USE OF FOREST INVENTORIES AND GEOGRAPHIC INFORMATION SYSTEMS TO ESTIMATE BIOMASS DENSITY OF TROPICAL FORESTS: APPLICATION TO TROPICAL AFRICA

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Abstract. One of the most important databases needed for estimating emissions of carbon dioxide resulting from changes in the cover, use, and management of tropical forests is the total quantity of biomass per unit area, referred to as biomass density. Forest inventories have been shown to be valuable sources of data for estimating biomass density, but inventories for the tropics are few in number and their quality is poor. This lack of reliable data has been overcome by use of a promising approach that produces geographically referenced estimates by modeling in a geographic information system (GIS). This approach has been used to produce geographically referenced, spatial distributions of potential and actual (circa 1980) aboveground biomass density of all forests types in tropical Africa. Potential and actual biomass density estimates ranged from 33 to 412 Mg ha^{-1} (10^6g ha^{-1}) and 20 to 299 Mg ha^{-1}, respectively, for very dry lowland to moist lowland forests and from 78 to 197 Mg ha^{-1} and 37 to 105 Mg ha^{-1}, respectively, for montane-seasonal to montane-moist forests. Of the 37 countries included in this study, more than half (51%) contained forests that had less than 60% of their potential biomass. Actual biomass density for forest vegetation was lowest in Botswana, Niger, Somalia, and Zimbabwe (about 10 to 15 Mg ha^{-1}). Highest estimates for actual biomass density were found in Congo, Equatorial Guinea, Gabon, and Liberia (305 to 344 Mg ha^{-1}). Results from this research effort can contribute to reducing uncertainty in the inventory of country-level emission by providing consistent estimates of biomass density at subnational scales that can be used with other similarly scaled databases on change in land cover and use.

1. Introduction

Concern over increasing amounts of greenhouse gases in the atmosphere and their potential to influence global climate change has produced a number of initiatives, including the United Nations Framework Convention on Climate Change. Country-level activities under this framework agreement include estimations of greenhouse gas emissions from all sources within that country. Carbon dioxide (CO_2) is an important greenhouse gas, and while fossil fuel burning is a major source of atmospheric CO_2, change in land cover and land use can be an important source, especially in the tropics (Dixon *et al.*, 1994).

The quantity of biomass carbon (C) in a given ecosystem is one of the most uncertain factors involved in estimating changes in C flux from terrestrial ecosystems (Brown *et al.*, 1989). While land-cover changes can be seen with remote sensing data, biomass-carbon density and actual land-use changes can only be inferred. Very few studies have actually measured the biomass in tropical forest ecosystems (Brown and Lugo, 1982), and although it is possible to estimate biomass from a complete forest inventory (Brown *et al.*, 1989), the lack of sufficient, reliable inventory data is a significant factor in limiting biomass estimates for tropical forests.

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What is needed is a method that can extend the few reliable biomass-carbon density estimates to larger, national and regional scales. Brown *et al.* (1993) and Iverson *et al.* (1994) developed such a method for forests in tropical Asia. This modeling approach used a geographic information system (GIS). The results of this work demonstrated that it is feasible to produce a spatial distribution of biomass densities for tropical forests.

The purpose of this paper is to report on efforts to develop a spatial distribution of aboveground biomass density of woody vegetation in tropical Africa using the methodology described by Brown *et al.* (1993) and Iverson *et al.* (1994). This methodology was used to estimate biomass-carbon density for closed forests, open forests, woodlands, and savannas. Aboveground biomass density is reported by country and by ecological zone. This paper also shows how the approach can be used to provide estimates of biomass density for subnational units within the larger countries of tropical Africa.

2. Methods

2.1. Study Area

The African land mass is primarily tropical, with a wide variety of vegetation communities. Deserts bracket extensive areas of savanna and woodland, which are the characteristic vegetation communities of Africa. The central core of the continent (the Zaire River Basin and Western Africa) contains large areas of moist tropical forests. Variations in the distribution of potential ecological communities depend primarily on climatic factors, topography, and soils. The actual distribution of vegetation communities is very much related to density and type of human activity. Most human activity is concentrated in the seasonal forests, woodlands, and savanna ecosystems. The study area for this research effort included those countries that for the most part are located in tropical Africa. Nontropical Southern Africa (South Africa, Lesotho, and Swaziland) and Mediterranean Africa (Egypt, Libya, Algeria, Morocco, and Western Sahara) were excluded.

2.2. Geographic Information System Tools and Data

Spatial analysis, modeling, and overlay of spatial data were important tools in this research effort. This section briefly describes the spatial data and tools used. The GIS software used was ARC/INFO, with a heavy reliance on the raster overlay and modeling capabilities of the GRID module. The projection was a rectangular equal-area projection, with a pixel size of 5000 m by 5000 m.

Spatial databases for Africa came from the following of sources:

1. Population density for 1960, 1970, 1980, and 1990 for nations and subnational units (the area of a subnational unit is generally larger than the area of a pixel) were provided by the Food and Agriculture Organization's (FAO) Tropical Forest Resource Assessment 1990 Program (FRA90) (M. Lorenzini and K.D. Singh, 1995).
2. Elevation data were taken from a global digital elevation database (referred to as ETOPO5), which originated at the U.S. National Geophysical Data Center. The elevation

data were rescaled into 15 m increments and all bathymetry data were calculated to zero.

3. Soils data came from the FAO Soils Map of the World (FAO, 1971–81). This map was reclassified into simplified maps of five soil texture classes, five slope classes, and two soil depth classes.
4. The FAO agrometeorological database was used to develop climate surfaces. Various climatic parameters such as mean monthly precipitation, maximum temperature, minimum temperature, day-night temperature differential, evapotranspiration, and vapor pressure were recorded for each station. Using the spatial coordinates for each station, it was possible to create two interpolated surfaces: annual precipitation and an integrated climatic index, which incorporated precipitation and length of the growing season (Iverson *et al.*, 1994).
5. Distribution of vegetation was obtained from a vegetation map, circa 1980, which was produced by the FAO in collaboration with the International Institute of Vegetation Mapping, Toulouse, France (Lavenu, 1987). The original vegetation classes were simplified to produce a map showing closed forest, woodland and wooded savanna, grassland savanna, and other classes, which included agriculture. A map of ecofloristic zones (EFZ), developed for the FAO FRA90 program (Sharma, 1986), was used with various reclassification options as a verification tool and for summarizing results. Sixty-four EFZs were distinguished for Africa based on floristic composition and climatic, edaphic, and physiographic factors.

2.3. Modeling Potential Forest Biomass

The current distribution of forest biomass is assumed to be a combination of the potential biomass density, which is based on prevailing climatic, edaphic, and geomorphological conditions; natural disturbances; and the cumulative impact of human activities that reduce biomass. For the African forests, natural disturbances such as tropical cyclones or storms were assumed to be minimal. Wildfires in woodlands and wooded savannas do occur and are assumed to be part of the human disturbance regime (Goldammer, 1993). They are implicitly dealt with later in the analysis. The model used to estimate potential biomass (described in detail in Brown *et al.*, 1993, and Iverson *et al.*, 1994) performed a weighted overlay of input layers: precipitation, climatic index, elevation and slope, and soil texture. Each of the four input layers was assigned a maximum score of 25 points and a scaled relationship depicting how biomass is affected by a given layer alone. Initial weighting factors were based on published information, and results were compared to values at known localities and were evaluated by colleagues familiar with the region. Initial weightings were adjusted through an iterative process. The final iteration produced a raster grid for tropical Africa with each pixel containing a potential biomass density (PBD) index ranging in value from about 40 to 100.

The above methodology is designed to generate biomass density estimates for *woody* formations only, so the next step was to remove nonwoody formations from the map of potential biomass density indices. To accomplish this, the FAO vegetation map was reclassified (Lavenu, 1987). All woody formations, including all classes of disturbed forests, woodlands, and mosaics, were classed into either closed forests or woodland/ wooded savanna; all nonwoody formations were removed. The map of PBD indices for tropical Africa was then overlain with this map to remove nonwoody formations.

Next, the PBD indices were converted into biomass density. This required the assignment of biomass density estimates across the range of index values. The most critical values are those that identify the upper and lower biomass limits. A limited set of ecological studies that provided biomass estimates for mature forests, woodlands, and wooded savannas was used to establish the upper and lower limits of biomass density (Brown and Lugo, 1982; estimates from data in Pierlot, 1966; Iverson *et al.*, 1994).

2.4. The Degradation Ratio

In any system, a variety of natural and anthropogenic factors reduce biomass from its potential. Long-term human use such as fuelwood gathering, logging (both sanctioned and unsanctioned), agricultural clearing, grazing, shifting of cultivation, and anthropogenic burning all reduce the amount of biomass present (Brown *et al.*, 1991). Indeed, in Africa long-term human use has produced a suite of ecosystems that may no longer contain a "natural" (non-human-impacted) ecosystem.

Population density has been identified as an index that can be used to quantify the long-term impact of human actions on the biomass density of forests in tropical Asia (cf. Brown *et al.*, 1993). While there is some disagreement about the relationship of population density and biomass reduction, in most areas of tropical Asia where the population lives in close contact with forests and other wooded areas there seems to be a significant, direct relationship between population density and a reduction in the potential biomass density. The percentage of forest cover in tropical regions has also been shown to correlate closely with population density at subnational levels when stratified into ecological zones (FAO, 1993). Although population density seems to work well as an explanation for trends in biomass and forest area reduction, it does not account for all of the variability. Other socioeconomic factors such as the state of industrialization, the ratio of rural to urban population, the importance of subsistence use of land, and the export or import of timber and agricultural products also contribute to a reduction in biomass and forest cover (Flint and Richards, 1994). However, continued increases in population density do not necessarily cause continued decreases in biomass and forest cover. Eventually a population density is reached beyond which there is no further decrease in forest cover and biomass change. At this point other factors come into play, and forest cover and biomass density may even increase with increasing population density, such as is occurring in many of the industrialized countries of the temperate zone. However, for most tropical countries this limit appears not to have been reached.

The amount of biomass reduction (degradation) has been estimated by comparing biomass density estimates from forest inventories conducted at the subnational to national scale with the modeled estimate of potential biomass density for the same inventory location (Brown *et al.*, 1993; Iverson *et al.*, 1994). This comparison produced "degradation ratios," unitless factors that relate the reduction of potential biomass density to the actual biomass density (see Figure 1). Data on the corresponding population density

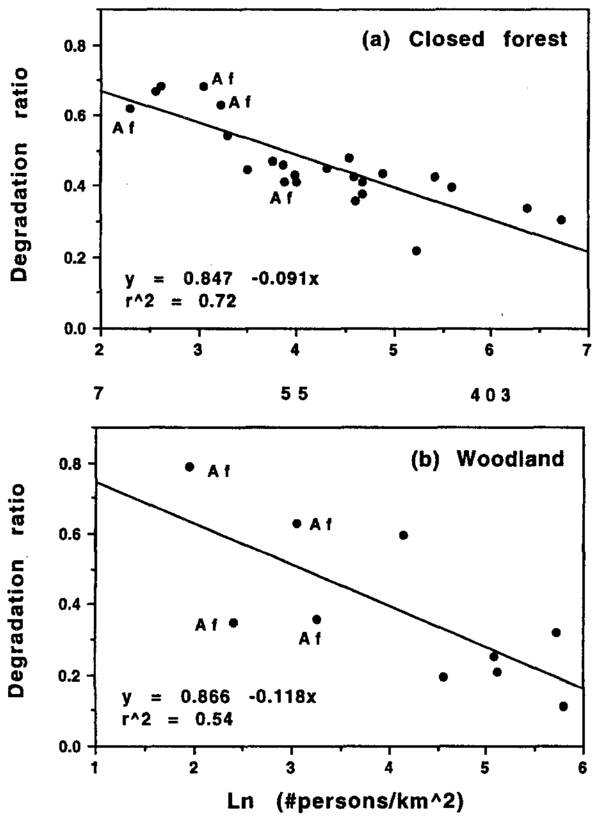

Figure 1. Relationship between degradation ratio and natural log of population density for (a) closed forests (n = 25) and (b) woodlands/savannas (n = 10).

for the decade of the inventory was also obtained from the population data set (see Section 2.2). This database was then stratified into climatic zones (for example, moist or dry).

Based on twenty-seven inventory units, Brown *et al.* (1993) compiled a database of degradation ratios and corresponding population densities for moist forests and dry forests of tropical Asia. We identified eight reliable inventory-based data sets for estimating actual biomass density in tropical Africa. Four were located in the moist closed forest zone: Gabon (Clement and Nouvellet, 1978), northern and southern Cote d'Ivoire (Development and Resources Corporation, 1967; Republique de Cote d'Ivoire, 1975), and Sierra Leone (United Nations Development Program, 1972), and four in the dry woodland/wooded savanna zone of Cameroon, Mali, Tanzania, and Zambia (FAO, 1989). Using a variety of methods described in Brown *et al.* (1989), Brown and Iverson (1992), and Brown and Lugo (1992), we estimated the actual biomass density from these African inventories.

The data for the closed forest zone of Africa were combined with the moist forest data from Asia. The African data appeared to fit well with the Asian database, and combining the data slightly improved the fit of a linear regression line of degradation ratio versus natural log (ln) of population density (from adjusted $r^2 = 0.70$ for Asia alone to adjusted $r^2 = 0.72$ for Asia and Africa; Figure 1). Similarly, the data for the dry woodland/savanna in Africa were combined with the data for the dry Asian forests. Again, the overall fit of the points was good and improved the adjusted r^2 of the linear regression (from 0.41 for Asia alone to 0.54 for Asia and Africa; Figure 1).

2.5. Actual Biomass Density Map

The actual biomass map was the product of the potential biomass density map and the distribution of degradation ratios. The population density map at the subnational level for 1980 was stratified by forest type (closed forest and woodland/wooded savanna) and a degradation ratio calculated for each pixel by using the regression equations in Figure 1. While each pixel of a subnational unit has the same population density value across the unit, the forest strata may vary. Thus, the calculated degradation ratio could also vary within a unit. The estimates of actual biomass density were calculated on a pixel-by-pixel basis, with the value in each pixel reflecting the predicted estimate of potential biomass density, the forest-type stratification, and the population density for 1980 from each subnational unit.

3. Results and discussion

Because forest inventories in tropical Africa are limited and because most of these were used to calibrate the model, regionwide verification of the results was difficult. The few inventories that were not used in the calibration gave the following comparisons (ongoing research by authors):

- Guinea—the model gave a national weighted mean biomass density of 140 Mg ha^{-1}; and the inventory, a value of 135 Mg ha^{-1}.
- Gambia—the model gave a national weighted mean biomass density of 29 Mg ha^{-1}; and the inventory, a value of 36 Mg ha^{-1}.
- Mozambique—the model gave a national mean weighted biomass density of 55 Mg ha^{-1}; and the inventory, a value of 57 Mg ha^{-1}.
- Burkina Faso—the model gave a regional weighted mean biomass density for the tree savannas of 34 Mg ha^{-1}; and the inventory, a value of 21 Mg ha^{-1}.

Although only a few countries are compared here, the comparisons are in the right direction, with most model results practically the same as the inventory results.

To see if the results of the modeling seemed reasonable and yielded expected trends across the continent, the biomass density estimates were aggregated by EFZ. The EFZ map was reclassified to show four lowland zones and two montane zones akin to the Holdridge life zone system. This map served as an independent check because it had not been used in any stage of the analysis. Estimated potential biomass densities were summarized for each zone (Table I). As expected, the estimates are highest in the lowland moist zone (412 Mg ha^{-1}) and decrease with increasing aridity. The lowest biomass density was obtained for the lowland very dry zone (33 Mg ha^{-1}). Montane zones have slightly

TABLE I

Mean potential and actual aboveground biomass density (Mg ha^{-1}), coefficients of variation (CV in %), and degradation ratios (DR) for tropical forests of Africa by ecofloristic zone.

Ecofloristic	Potential	CV	Actual	CV	DR
Zone					
Lowland moist	412	15	299	22	0.73
Lowland seasonal	211	60	141	71	0.67
Lowland dry	92	96	60	112	0.65
Lowland very dry	33	112	20	110	0.61
Montane moist	197	55	105	61	0.53
Montane seasonal	78	123	37	111	0.47

Note: Aboveground biomass estimates are based on 1980 population densities.

less biomass than their lowland counterparts, as previously observed by Brown and Lugo (1982). These expected patterns of potential biomass density by EFZ are convincing evidence that the methodology used for generating a biomass density map of Africa produces reasonable estimates at a continental scale, as was the case for tropical Asia (Brown *et al.,* 1993).

The variability in potential biomass density, as expressed by the coefficient of variation (CV), is lowest in the lowland moist zone (15%), where moisture is generally not limited, and one can reasonably expect a relatively homogenous landscape with small variations in biomass. As the climatic zones become arid, the heterogeneity of potential biomass density appears to increase across the landscape (high CVs), most likely the result of the differential effects of soils and slope on biomass in the fairly uniform dry environment.

3.1. Distribution of Potential and Actual Biomass Density Estimates

Examination of the potential biomass density map (Figure 2) shows that the overall distribution of biomass appears to match the expected patterns. High biomass densities (>300 Mg ha^{-1}) are found in the moist tropical forest zones of central (Zaire Basin) and west Africa. Moving away from these zones, biomass density decreases where woodland/savanna zones tend to dominate the landscape. Woody formations with the lowest potential biomass densities are located in the eastern and southern parts of tropical Africa and in countries of the Sahel.

The distribution of the biomass density of tropical African forests changes dramatically under the influence of human activities (Figure 3). Practically all forest areas with potential biomass density greater than 400 Mg ha^{-1} have disappeared in the map of actual biomass density (Figure 3). Furthermore, in the actual biomass density map, the

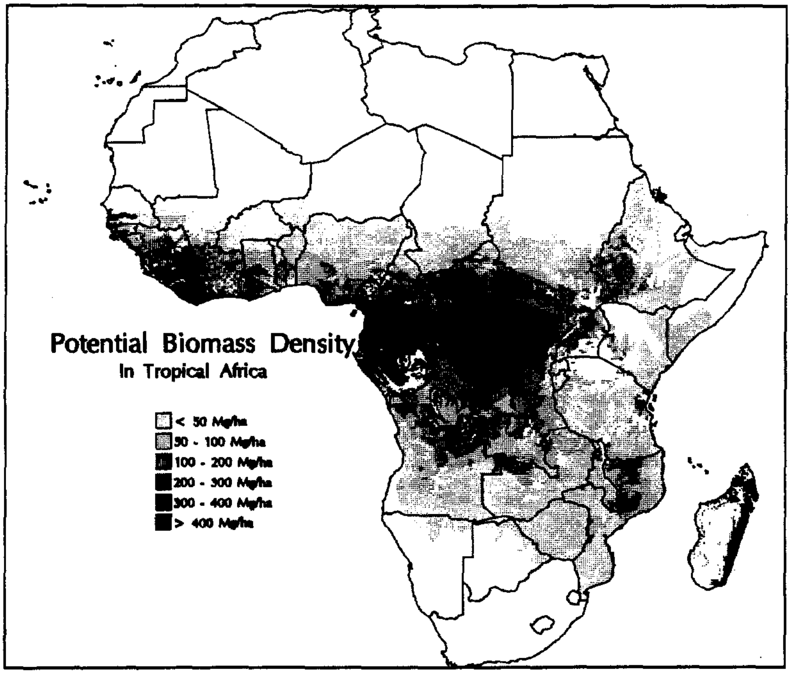

Figure 2. Map of potential biomass density for woody formations of tropical Africa.
The original map has 12 classes.
Note: A copy can be obtained from this paper's authors.

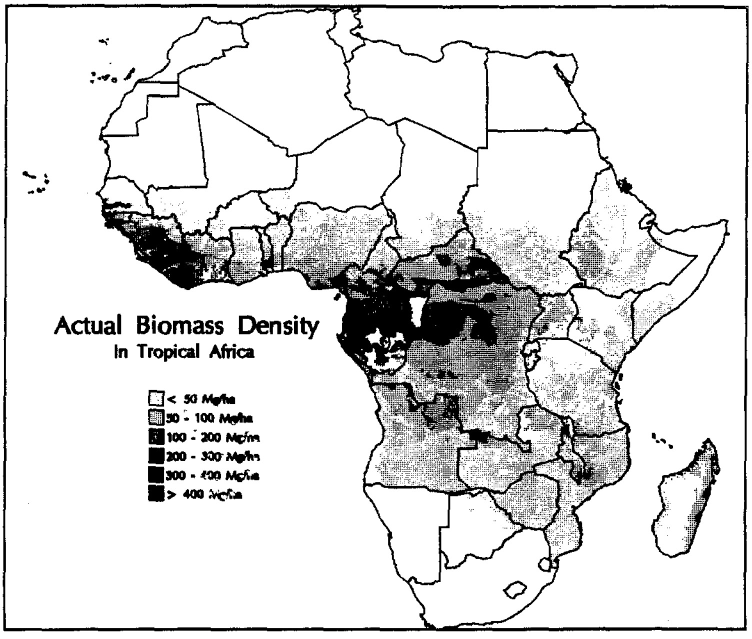

Figure 3. Map of actual biomass density for woody formations of tropical Africa. The original map has 10 classes (because of degradation, the highest classes of the potential biomass density map are missing).
Note: A copy can be obtained from this paper's authors.

distribution of the three biomass density classes greater than 200 Mg ha^{-1} has become severely limited.

Actual biomass density estimates range from about 300 Mg ha^{-1} in the lowland moist zone to 20 Mg ha^{-1} in the lowland very dry zone (Table I). Forest biomass was reduced or degraded more from its potential in montane zones (47%–53%) than in lowland zones (61%–73%). Adding human influence to the analysis, as reflected by the estimates of actual biomass density, results in a higher CV for the lowland moist, seasonal, and dry zones and for the montane moist zones, from a range of 15% to 96% to a range of 22% to 112% (Table I). The CVs for actual biomass density for the lowland very dry and montane seasonal zones decreased slightly (112% to 110% and 123% to 111%) (Table I).

3.2. Biomass Density Estimates at the Country Level

Biomass density estimates can be extracted on a country-by-country basis (Table II). The countries with the highest estimates of potential biomass density were Liberia (466 Mg ha^{-1}), Equatorial Guinea (442 Mg ha^{-1}), Sierra Leone (411 Mg ha^{-1}), Gabon (375 Mg ha^{-1}), and Congo (374 Mg ha^{-1}). These countries also had low CVs and are characterized as small to medium in size and dominated by the lowland moist climatic zone. The countries with the lowest potential biomass density estimates were Botswana (15 Mg ha^{-1}), Niger (16 Mg ha^{-1}), and Somalia (20 Mg ha^{-1}), all large countries dominated by the lowland very dry climatic zone.

Of the thirty-seven countries included in this study, more than half contained forests that had less than 60% of their potential biomass. The most degraded countries were Senegal (33% of potential), Burundi (36% of potential), and Rwanda (38% of potential). The least degraded countries were Congo (92%), Botswana (91%), and Gabon (90%). Spatial heterogeneity within a country, as reflected in CVs, appears to be related to its size, population density, and domination by dry climatic zones. High population and large size both favor high variability in biomass density estimates in dry countries such as Ethiopia, Sudan, and Kenya (Table II).

In many cases, the country level is the minimum spatial resolution at which biomass density estimates can be made with any degree of confidence because of the coarse resolution of several of the data layers (for example, FAO soil maps and elevation maps) used in making the map of potential biomass density. However, for some of the larger countries with large subnational units, biomass density estimates can be reported by subnational unit with some confidence. For example, Zaire, which is one of the largest countries in tropical Africa, is divided into nine major subnational units with corresponding biomass density estimates (Table III). The estimates for potential and actual biomass density are highest (424 Mg ha^{-1} and 321 Mg ha^{-1}) with the lowest CVs (16% and 17%) in Equateur, which, as the name suggests, is the province in Zaire that is along the equator and is dominated by the Zaire River basin. The lowest potential and actual biomass density estimates (146 Mg ha^{-1} and 100 Mg ha^{-1}) and highest CVs (45% and 56%) are in Shaba Province, which is farthest south and farthest from the core area of moist tropical forest. The effect of high population pressure on biomass estimates can be clearly seen in Kinshasa, where the high population density (215 persons km^{-2}) has reduced the potential biomass density by about two-thirds.

TABLE II

Area-weighted mean potential and actual aboveground biomass density (Mg ha^{-1}), coefficient of variation (CV in %), and the degradation ratio (DR, ratio of actual to potential biomass density) for tropical African forests, by country

Country	Potential	CV	Actual	CV	DR
Angola	100	83	73	81	0.73
Benin	112	59	58	53	0.52
Botswana	15	56	13	55	0.91
Burkina Faso	65	66	34	70	0.53
Burundi	119	48	43	49	0.36
Cameroon	307	46	217	54	0.71
CAR	243	43	200	44	0.82
Chad	63	57	43	58	0.68
Congo	374	21	344	29	0.92
Cote d'Ivoire	276	41	165	44	0.60
Equatorial Guinea	442	9	318	10	0.72
Ethiopia	101	99	52	100	0.51
Gabon	375	18	339	19	0.90
Gambia	64	62	29	55	0.45
Ghana	182	51	83	57	0.45
Guinea	259	56	140	58	0.54
Guinea Bissau	153	46	85	47	0.55
Kenya	58	104	33	80	0.57
Liberia	466	10	305	22	0.65
Madagascar	322	39	196	37	0.61
Malawi	108	64	47	65	0.44
Mali	75	65	45	57	0.60
Mozambique	96	77	57	75	0.60
Niger	16	49	9	50	0.53
Nigeria	128	87	49	88	0.38
Rwanda	103	47	34	40	0.33
Senegal	50	88	32	75	0.62
Sierra Leone	411	21	199	26	0.48
Somalia	20	39	13	40	0.63
Sudan	95	93	64	95	0.67
Tanzania	83	75	45	69	0.55
Togo	155	57	72	58	0.46
Uganda	237	43	102	43	0.43
Zaire	297	42	206	47	0.69
Zambia	67	76	47	85	0.70
Zimbabwe	26	73	14	71	0.51

Note: Aboveground biomass estimates are based on 1980 population densities.

TABLE III

Mean potential and actual aboveground biomass density of woody formations (Mg ha^{-1}), coefficients of variation (CV in %), and population density (PD in #/km^2) for subnational units of Zaire

Subnational	Potential	CV	Actual	CV	PD
Bas-Zaire	193	33	98	36	33
Kinshasa	161	29	49	43	215
Shaba	146	45	100	56	7
Bandundu	248	32	157	35	11
Kasai-West	280	29	169	29	18
Kasai-East	288	27	176	28	13
Equateur	424	16	321	17	8
Kivu	292	31	156	46	7
Haut-Zaire	378	21	277	26	8

4. Conclusion

Reliable estimates of biomass density for tropical forests are important variables in assessing terrestrial carbon fluxes, but because of their limited availability, it has been necessary to develop alternative methods of extrapolating biomass density across the landscape at regional and national scales. The methods described in this paper make use of simple and widely available spatial data sets to extend limited biomass data to regional and national estimates. It appears that it is possible to use the biomass density estimates from ecological studies and biomass density estimates derived from forest inventory data to produce reasonable patterns in the distribution of biomass density in tropical forests. The patterns of biomass density distribution in all cases are consistent with expected patterns. Using population density as an index to model anthropogenic effects on biomass density appears to be valid statistically and may allow for projections to be made both forward and backward over a moderate amount of time (one to two decades). The ability to project biomass based on population trends, within the social and economic limits previously mentioned, is a powerful tool in assessing changes in carbon flux from the tropical forests.

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References

Brown, S. and Iverson, L. R.: 1992, Biomass estimates for tropical forests, *World Resource Review* **4**, 366-384.

Brown, S. and Lugo, A. E.: 1982, Storage and production of organic matter in tropical forests and their role in the global carbon cycle, *Biotropica* **14**, 161-187.

Brown, S. and Lugo, A. E.: 1992, Aboveground biomass estimates for tropical moist forests of the Brazilian Amazon, *Interciencia* **17**, 8-18.

Brown, S., Gillespie, A. J. R., and Lugo, A. E.: 1989, Biomass estimation methods for tropical forests with application to forest inventory data, *Forest Science* **35**, 881-902.

Brown, S., Gillespie, A. J. R. and Lugo, A. E.: 1991, Biomass of tropical forests of South and Southeast Asia, *Canadian Journal of Forest Research* **21**, 111-117.

Brown, S., Iverson, L. R., Prasad, A., and Liu, S.: 1993, Geographical distributions of carbon in biomass and soils of tropical Asian forests, *Geocarto International* **4**, 45-59.

Clement, J. and Nouvellet, Y.: 1978, *Inventaire Forestier dans la Zone d'Edenzork*, Republique du Gabon, Societe Gabonaise de Cellulose, Centre Technique Forestier Tropical, Nogent-sur-Marne, France.

Development and Resources Corporation: 1967, *Forestry Resources of the Southwest Region*, a report to the government of the Republic of Ivory Coast.

Dixon, R. K., Brown, S., Houghton, R. A, Solomon, A., and Wisnieski, J.: 1994, Carbon pools and flux of global forest ecosystems, *Science* **263**, 185-190.

Flint, E. P. and Richards, J. F.: 1994, Trends in carbon content of vegetation in South and Southeast Asia associated with changes in land use, in Dale, V. (ed.), *Effects of Land Use Change on Atmospheric CO Concentrations: Southeast Asia as a Case Study*, New York: Springer-Verlag, 201–300.

Food and Agriculture Organization, (FAO): 1971–81, *Soils Map of the World 1:5,000,000*, FAO-UNESCO.

FAO: 1989, *Studies on the Volume and Yield of Tropical Forest Stands 1. Dry Forest Formations*, FAO Forestry Paper 51/1.

FAO: 1993, *Forest Resources Assessment 1990 Tropical Countries*, FAO Forestry Paper 112.

Goldammer, J. G.: 1993, Historical biogeography of fire: tropical and subtropical, in Crutzen, P. J. and Goldammer, J. G. (eds.), *Fire in the Environment: the Ecological, Atmospheric, and Climatic Importance of Vegetation Fires*, Chichester, U.K.: John Wiley and Sons, 297–314.

Iverson, L. R., Brown, S., Prasad, A., Mitasova, H., Gillespie, A. J. R., and Lugo, A. E.: 1994, Use of GIS for estimating potential and actual biomass for continental South and Southeast Asia, in Dale, V. (ed.), *Effects of Land Use Change on Atmospheric CO_2 Concentrations: Southeast Asia as a Case Study*, Springer-Verlag, New York: ch. 3.

Lavenu, F.:1987, *Vegetation Map of Africa Scale 1:1,5000,000*, Institute de la Carte Internationale de la Vegetation, Universite Paul Sabatier, Toulouse, France, Distributed by FAO Forest Resources Assessment 1990 Project, Rome, Italy.

Pierlot, R.: 1966, Structure et composition de forets denses d'Afrique, especialement celles du Kivu, *Academie Royale des Sciences d'Outre-mer, Classes des Sciences Naturelles et Medicales*, N.S.–XVI–4, Bruxelles, Belgium.

Republique de Cote D'Ivoire, Ministere des Eaux et Foret: 1975, *Analyse et Commentaires des Resultats de l'Inventaire Forestier de la Region Nord-Ouest. Resultats de la Region du Nord-Ouest*, Inventaire Forestier National, Direction des Inventaire et Amenagement (SODEFOR), Abidjan.

Sharma, M. K.: 1986, *Ecofloristic Zones of Africa*, Institute de la Carte Internationale de la Vegetation, Universite Paul Sabatier, Toulouse, France, Distributed by FAO Forest Resources Assessment 1990 Project, Rome, Italy.

United Nations Development Program: 1972, *Forestry Inventory of the Gola Forest Reserves, Report to the Government of Sierra Leone*, FAO.