Estimates of Biomass Density for Tropical Forests

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Abstract

An accurate estimation of the biomass density in forests is a necessary step in understanding the global carbon cycle and production of other atmospheric trace gases from biomass burning. In this paper we summarize the various approaches that we and colleagues have developed for estimating aboveground biomass density of tropical forests relying for the most part on forest inventory data and modeling in a geographic information system (GIS). Biomass density estimates from forest inventory data range from about 50 to >550 Mg ha^{-1} in tropical Asia and America and from about 25 to 380 Mg ha^{-1} in tropical Africa. This range of values for all regions reflects differences in climate and intensity of human disturbances. To capture the spatial distribution of biomass density, we have developed a geographic information system (GIS) model of the biophysical parameters that influence the distribution of biomass density. This model was combined with forest inventory and human population density data to produce a spatially explicit estimation of biomass density both under natural conditions and with the influence of human activity. These estimates are more representative of the landscape as a whole and are better suited to regional or global analysis. To date, this approach has been applied to the tropical regions of Africa and Asia.

Introduction

The role of tropical forests in global biogeochemical cycles, especially the carbon cycle and its relation to climate change, has heightened interest in estimating the biomass density of tropical forests. Forest biomass density provides estimates of the carbon pools in forest vegetation because about 50% of biomass is carbon. This pool is the potential amount of carbon, as carbon dioxide, that can be added to the atmosphere when the forest is cleared and/or burned. Attempts to estimate the biomass density of tropical forests have been made by the scientific community for use in models that assess the contribution of tropical deforestation and biomass burning to the increase in atmospheric carbon dioxide and other trace gases (Brown et al., 1989; Crutzen and Andreae, 1990; Hall and Uhlig, 1991; Houghton et al., 1987).

Estimates of the biomass density for many of the world's forests have been made. For example, a detailed summary of biomass density studies in tropical forests, from lowland to montane and from wet to very dry zones, was made by Brown and Lugo (1982). A later study by Olson et al. (1983) produced a global map of the biomass density of all ecosystem types, including disturbed and undisturbed forests, at a 0.5° x 0.5° grid-scale of resolution. These summaries of biomass density were based on ecological studies creating several problems with their use for global-scale analyses. Ecological studies are generally designed to characterize local forest structure and the study sites are usually not truly randomly located nor represent the population of interest (Brown and Lugo, 1992). These type of studies are suitable for studying local forests but not for making inferences about larger populations (Brown et al., 1989). Furthermore, the total area covered by these studies is a very small fraction of the total forest area (e.g., less than 0.00001% for tropical forests; Brown and Lugo, 1984).

A further problem with using biomass data from ecological studies for national to global analyses is the inherent bias of ecologists to adjust placement of plots based on the notion of what a mature forest should look like, i.e., one with many large diameter trees (Brown and Lugo, 1992), The effect of adjusting plot placement to include large diameter trees is to overestimate biomass density of the forests because biomass per tree increases geometrically with increasing diameter. The result of this bias is to yield high biomass density estimates for forests (Brown et al., 1989). Thus data from ecological studies must be used with caution as they may not represent the biomass density of the forest over large areas.

Biomass density estimates for tropical forests have also been made by the Food and Agriculture Organization (FAO, 1993) based on the FAO FORIS data base (Forest Resources Information System-- a computerized data base) of volume over bark (VOB, commercial volume to a minimum tree diameter of 10 cm) often measured in forest inventories. On the positive side, VOB data from forest inventories are based on a large number of plots, generally collected from large sample areas using a planned sampling design from the population of interest. However, very few national or subnational inventories that report VOB have been done in the tropics. The compilation of the VOB data base by the FAO required much educated guesswork to produce estimates on a tropic-wide country-level basis. This approach is, therefore, of unknown reliability and any errors in VOB estimates were compounded during the conversion of these data to biomass density values. Clearly, new efforts to estimate biomass density more directly from forest inventory data are needed to provide more reliable data for national to global assessments of the quantity of forest resources.

The purpose of this paper is to summarize the various approaches that we and colleagues have developed over the past decade or so for estimating biomass density of tropical forests, relying for the most part on forest inventory data and modeling in a geographic information system (GIS). Estimates of biomass density for a variety of tropical forests from different parts of the tropics are presented in tabular form and spatially distributed. We also discuss the factors that affect biomass density and show that it is not a static parameter but rather a moving target.

Definition of Biomass

A complete estimation of forest biomass density requires that the biomass of all forest components be estimated, including the above and below ground living mass of trees, shrubs, palms, saplings, other understory components, vines, epiphytes, etc. and the dead mass of fine and coarse litter. In this paper we consider only the total amount of aboveground organic matter present in trees including leaves, twigs, branches, main bole, and bark, expressed as oven-dry tons per hectare (referred to as biomass density). For most forests or tree formations, biomass density estimates are based only the biomass in trees with diameters greater than or equal to 10 cm, the usual minimum diameter measured in most inventories of closed forests. However, for forests or trees of smaller stature, such as those in the arid tropical zones, degraded forests, or secondary forests, the minimum diameter could be as small as 2.5 cm.

Most efforts on biomass estimation to date have generally focused on the aboveground tree component because it accounts for the greatest fraction of total biomass density and the methods are straightforward and generally do not pose too many logistical problems. However, a few estimates of these other components of tropical forests do exist, but they must be used with caution as the data base on which they are built is limited.

The amount of biomass in small diameter trees, understory shrubs, vines, and herbaceous plants can be variable but generally about 3-5% or less of the aboveground biomass of more mature forests (Jordan and Uhl, 1978; Tanner, 1980; Hegarty, 1989; Lugo, 1992). However, in secondary forests or disturbed forest, this fraction could be higher (e.g., up to 30%; Brown and Lugo, 1990; Lugo 1992) depending on age of the secondary forest and openness of canopy. Palms are common in many tropical moist forests are they are also often ignored in forest inventories. Their contribution to total biomass density can be very variable, from almost a 100 percent in almost pure palm forests to less than a few percent where they are a minor component of the forest (Brown and Lugo, 1992).

The biomass of roots in tropical forests varies considerably among tropical forests depending mainly upon climate and soil characteristics (Brown and Lugo, 1982; Sanford and Cuevas, 1995). Root biomass is often expressed in relation to aboveground biomass, such as a root-to-shoot ratio (R/S ratio). From a recent review of the literature, R/S ratios for lowland to montane forests range from 0.04 to 0.85 (Sanford and Cuevas, 1995). These estimates are based on only a few studies (about 30) and not all of them are consistent with respect to depth of sampling and whether all coarse roots were included.

The amount of dead plant material in a forest , or detritus, is composed of fine litter on the forest floor, (leaves, fruits, flowers, twigs, bark fragments, branches less than 10 cm diameter, etc.), standing dead trees and snags, and lying dead wood greater than 10 cm diameter; the last two components are referred to as coarse woody debris (CWD). The biomass density of fine litter ranges from about 2 to 16 t/ha (average of 6 t/ha or less than 5% of aboveground biomass), with higher values generally in moist environments although no clear trend is apparent in the data base (Brown and Lugo, 1982). The amount of fine litter on the forest floor represents the balance between inputs from litterfall and outputs from decomposition, both of which vary widely across the tropics.

The amount of CWD in tropical forests is poorly quantified but extremely variable. It is potentially a large pool of organic carbon, perhaps accounting for an amount equivalent to 10 to more than 40 percent of the aboveground biomass of a forest (Saldarriaga et al., 1986; Uhl et al., 1988; Uhl and Kauffman, 1990). Lack of data on this significant forest component obviously can lead to underestimates of the total amount of biomass in a forest.

It is clear from the above discussion that ignoring these other forest components can seriously underestimate the total biomass of a forest by an amount equivalent to about 70% or more of aboveground biomass. It is apparent that logistically and economically feasible methods and approaches must be developed to estimate this significant quantity of biomass, especially for improving estimates of terrestrial sources and sinks of carbon and other greenhouse gases.

Estimating Biomass Density from Inventory Data

Use of forest inventory data overcomes many of the problems present in ecological studies as discussed above. Data from forest inventories are generally more abundant and are collected from large sample areas (subnational to national level) using a planned sampling method designed to represent the population of interest. However, inventories are not without their problems (Brown and Iverson, 1992). Typical problems include:

- Inventories tend to be conducted in forests viewed as having commercial value, i.e., closed forests, with little regard to the open, drier forests or woodlands.
- The minimum diameter of trees included in inventories is often greater than 10 cm, thus excluding smaller trees which can account for more than 30% of the biomass (Gillespie et al., 1992).
- The maximum diameter class in stand tables is generally open ended, with trees greater than 80 to 90 cm in diameter often lumped into one class; the actual diameter distribution of these large trees significantly affects aboveground biomass density (Brown and Lugo, 1992; Brown, 1995).
- Not all tree species are included.
- Many of the inventories are old 1960s to 1970s or earlier and he forests often no longer exist or at least are not the same now as they were at the time of the inventory.

Despite the above problems, many inventories are very useful for estimating biomass density of forests. During the last decade or so two main approaches for estimating the biomass density of forests based on existing forest inventory data have been developed. One uses existing volume estimates (VOB per ha), converted to biomass density (Mg/ha) using a variety of "tools" (Brown et al., 1989; Brown and Lugo, 1992; Gillespie et al., 1992). A second approach directly estimates biomass density from the application of an appropriate allometric regression equation (biomass per tree as a function diameter) selected on the basis of climate regime (dry, moist, or wet) to stand tables (number of trees /ha in a given diameter class) often reported in forest inventories. The advantage of this second method is that it produces biomass estimates without having to make volume estimates and then to apply various expansion factors to account for non-commercial tree components. The disadvantage is that a fewer number of inventories report stand tables to small diameter classes for all species, thus not all countries in the tropics are covered by these estimates.

Biomass density estimates

The above approaches have been used with inventories from many tropical Asian (9) and American (10) countries encompassing about 30 million ha. The resulting estimates of aboveground biomass density for moist forests range from less than 50 Mg ha^{-1} to more than 550 Mg ha^{-1} (Fig. 1) with an arithmetic mean of 230 Mg ha^{-1} for both tropical regions. In the wet zone of tropical America (mostly Panama), biomass density estimates range from less than 50 to about 300 Mg ha^{-1}, with an average of 150 Mg ha^{-1}. Forests in the wet zone tended to have lower biomass densities for a given basal area as has been shown before (Brown and Lugo, 1982).

The range of biomass density estimates for moist tropical American forests is practically identical to that for moist tropical Asian forests (Fig. 1). As was the case for the topical Asian forests (cf. Brown et al., 1991), many of the tropical American forests were identified as being disturbed (e.g., commercial harvesting, harvesting by indigenous communities, young to late secondary, shifting cultivation; Brown 1995).

Biomass density estimates for tropical moist forests of central and west Africa (Cameroon, Gabon, Cote d'Ivoire and Ghana) based on inventories range between 187 to 378 Mg ha^{-1} (ongoing research by Brown and Gaston). In the drier zones of west and east Africa where open forests or savanna woodlands dominate, biomass densities range from 22 to 196 Mg ha^{-1}. No inventory data for African moist forests available to date has produced biomass density estimates as high as those for tropical Asia or America, even though estimates from ecological studies show a similar range of values for all three tropical regions.

Estimating Biomass Density by Modeling in a GIS

Brown et al. (1993) and Iverson et al. (1994) developed a modeling approach using a GIS to produce spatial distributions of biomass densities for tropical forests. The method was developed to extend the few reliable, inventory-based biomass density estimates to regional scales in tropical Asia. The overall approach to making aboveground biomass density estimates was based on the assumption that the present day distribution of biomass is a result of a combination of the potential biomass density, based on prevailing climatic, edaphic and geomorphologic conditions, and the cumulative impacts of human activities which reduce biomass. We have used this approach to generate biomass density estimates for forests and woodlands of tropical Africa (Brown and Gaston, 1995, and ongoing research)

The modeling approach (described in detail in Iverson et al., 1994) first estimates potential biomass density by using a weighted overlay of input layers: precipitation, a climatic index, elevation and slope, and soil texture. Weighting factors were adjusted through an iterative process by comparing results to known localities (see Brown et al. 1993 and Iverson et al. for more details). The final iteration produced a raster grid with each pixel (5 km x 5 km) containing a potential biomass density (PBD) index ranging in value from about 40 to 100.

To calibrate the PBD indices into biomass density values required the assignment of biomass density estimates across the range of index values. The most critical values were those that identified the upper and lower biomass limits. A very limited set of ecological studies that gave biomass estimates for mature forests, woodlands, and wooded savannas were used to establish the upper and lower limits of biomass density (Brown and Gaston, 1995). The process of establishing the linkage of PBD index values to biomass density was iterative that relied heavily on prior field experience, experts in the area, and published information.

A variety of natural and anthropogenic factors reduce biomass in any system from its potential. Long-term human use has a dramatic effect on the density of biomass in forest ecosystems. Fuel-wood gathering, sanctioned and unsanctioned logging (Callister, 1992), grazing, shifting cultivation, and anthropogenic burning all reduce the amount and density of biomass present. As these practices are continuing and ongoing as population pressure increases, the biomass density of forests becomes a "moving target". Past research has shown that population density is a good empirical indicator to quantify the long-term human impact on biomass density (cf. Brown et al., 1993). Using the methods described above, we estimated actual forest biomass density from the available forest inventories. The amount of biomass reduction as measured by the degradation index was calculated as the ratio of biomass density estimated from forest inventories to the modeled potential biomass density for the inventory location at the scale of a sub-national unit or administrative unit such as a state. We then paired this degradation index to the population density of the subnational unit for the decade of the inventory and stratified the data base into two forest types: closed forest and open forest/woodland (Brown and Gaston, 1995). We were able to identify only eight inventories for the whole of Africa for this step, four in the closed forest zone and four in the open forest/woodland zone.

We have shown that we can combine the African data base with a similar one for tropical Asia and develope statistically significant regression equations of degradation ratio versus population density for the closed forest and open forest/woodland zones (Brown and Gaston, 1995 and ongoing research). We used these two regression equations with the population density map to produce a map of degradation ratios. The spatial distribution of "actual" biomass was produced as the product of the potential biomass density map and the degradation ratio map. The estimates of actual biomass density were calculated on a pixel by pixel basis.

The spatial distribution of the actual biomass density for tropical African forests generally follows expected trends (Fig. 2). As so few forest inventory data are available in the region, we were forced to use most of them to develop the degradation model. Only two inventories were not used and these were used for one step in the validation process. Results from a national forest inventory for the West African country of Guinea gave a weighted average biomass density estimate 135 Mg ha^{-1}. The weighted mean for this country from the modeling approach is 140 Mg ha^{-1}, almost equal to the measured estimate (Brown and Gaston, 1995). Similarly for the wooded part of Mali, the inventory gave a range of 55 to 65 Mg ha^{-1} and the model gave a somewhat lower weighted mean of 45 Mg ha^{-1}. Furthermore, we used the process described in Brown et al. (1993) as a further check for our results. We used a reclassified map of the ecofloristic zones of Africa (something akin to a life zone map). Results of this step confirmed expected patterns. For example, actual biomass density decreased from about 300 Mg ha^{-1} in the lowland moist zone to 140, 60, and 20 Mg ha^{-1} in the lowland seasonal, lowland dry and lowland very dry zones, respectively.

Highest estimates (>300 Mg ha^{-1}) are for dense humid forests located in parts of the west African countries of Liberia and Cote d'Ivoire and the central African countries of Congo, Equatorial Guinea, and Gabon (Fig. 2). Biomass densities decreased with increasing distance from these wetter areas to a low of <50 Mg ha^{-1} in the dry open woodlands of countries in the Sahel and East Africa. Area weighted, country -level estimates of actual biomass density were also produced (Table 1). Low coefficients of variation (CV) were obtained for those countries with the highest biomass density estimates suggesting a relatively homogenous environment and lower population pressure (Brown and Gaston 1995, and ongoing research).

Conclusions

The biomass density of tropical forests is one of the most important variables that influences the magnitude of the terrestrial carbon flux and other trace gas fluxes. We have shown that a variety of tools are available to estimate biomass density at country to regional scales, yet still capturing the heterogeneity of the environment. We have also suggested that estimates produced by these approaches are more suitable for regional-scale models because they are more representative of the larger landscape and attempt to encompass the human component. Finally, the GIS modeling approach has the advantage of producing biomass density maps that can be matched to similar ones produced by high resolution satellite imagery that show the actual forest areas undergoing change.

Acknowledgments

Research reported on here was partially supported by a grant from the US Department of Energy (DOE DEFGO2-90ER61081) to the University of Illinois (S. Brown P.I.).

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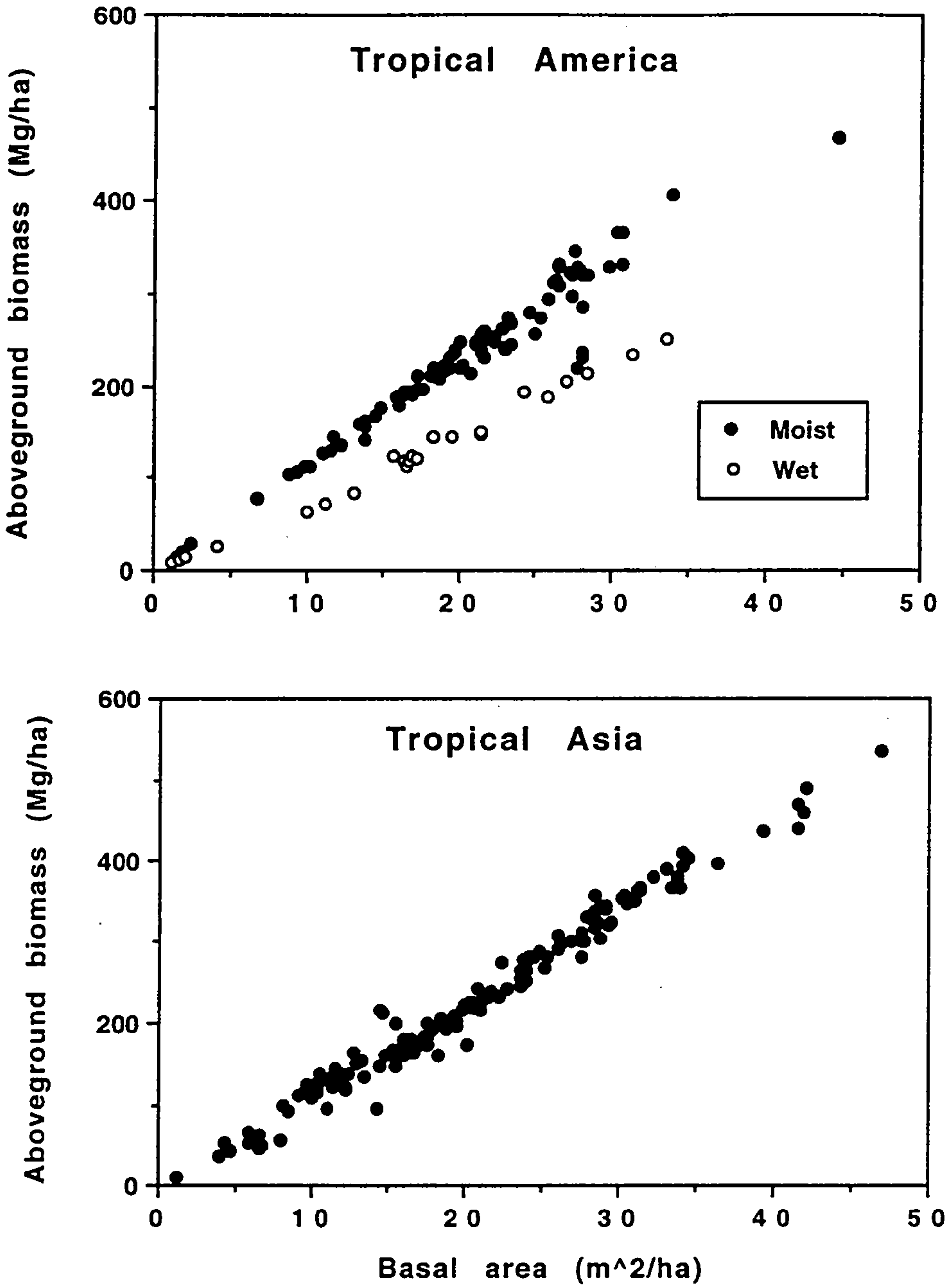
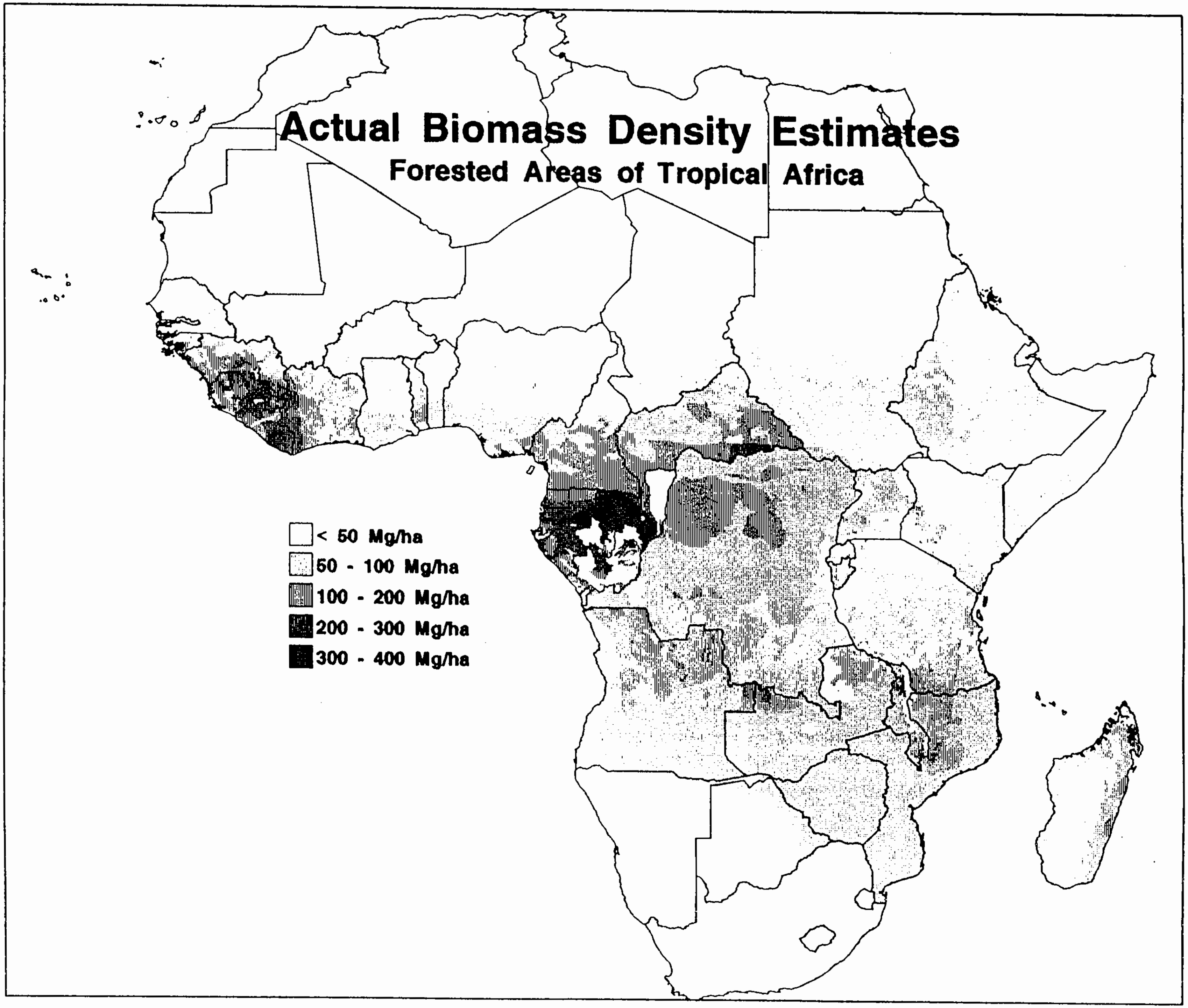
Figure 1. Aboveground biomass density estimates for forests of tropical America and Asia (from Brown 1995). The estimates are plotted against basal area as a way of showing the range of values; a high correlation is expected (see text).

Figure 2. Spatial distribution of actual aboveground biomass density for forests and woodlands of tropical Africa for about 1980 (from Brown and Gaston, 1995). This map is available as a ARC/INFO data base; a color version with ten biomass density classes is available from authors.



Tropical America
Aboveground biomass (Mg/ha)
0
200
400
600
0
1 0
2 0
3 0
4 0
5 0
Moist
Wet
Tropical Asia
Aboveground biomass (Mg/ha)
0
200
400
600
0
1 0
2 0
3 0
4 0
5 0
Basal area (m^2/ha)



Actual Biomass Density Estimates
Forested Areas of Tropical Africa
< 50 Mg/ha
50 - 100 Mg/ha
100 - 200 Mg/ha
200 - 300 Mg/ha
300 - 400 Mg/ha

Table 1. Mean area weighted actual biomass density (Mg ha^{-1}) and coefficient of variation (CV) for forests of tropical Africa by country (from Brown and Gaston, 1995).

Country	Actual	CV(%)
Angola	73.3	81
Benin	58.0	53
Botswana	13.2	55
Burkino Faso	34.4	70
Burundi	42.7	49
Cameroon	217.4	54
CAR	199.6	44
Chad	42.8	58
Congo	343.6	29
Cote d'Ivoire	164.7	44
Equatorial Guinea	317.9	10
Ethiopia	51.5	100
Gabon	338.5	19
Gambia	29.2	55
Ghana	82.7	57
Guinea	139.6	58
Guinea Bissau	84.6	47
Kenya	33.0	80
Liberia	304.8	22
Madagascar	195.8	37
Malawi	47.1	65
Mali	44.9	57
Mozambique	57.3	75
Niger	8.6	50
Nigeria	49.0	88
Rwanda	33.7	40
Senegal	31.5	75
Sierra Leone	199.0	26
Somalia	12.5	40
Sudan	63.8	95
Tanzania	45.3	69
Togo	71.9	58
Uganda	102.2	43
Zaire	206.3	47
Zambia	46.8	85
Zimbabwe	13.6	71

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Estimates of Biomass Density for Tropical Forests

5. REPORT DATE

6. PERFORMING ORGANIZATION CODE

7. AUTHOR(S)
S.Brown, G. Gaston

8. PERFORMING ORGANIZATION REPORT NO.

9. PERFORMING ORGANIZATION NAME AND ADDRESS
EPA, NHEERL-Corvallis, OR

10. PROGRAM ELEMENT NO.

11. CONTRACT/GRANT NO.

12. SPONSORING AGENCY NAME AND ADDRESS
US EPA ENVIRONMENTAL RESEARCH LABORATORY
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Corvallis, OR 97333

13. TYPE OF REPORT AND PERIOD COVERED
Symposium Paper

14. SPONSORING AGENCY CODE
EPA/600/02

15. SUPPLEMENTARY NOTES
1995 Biomass Burning & Global Change, ed. Joel Levine, Mar 13-17, Williamsburg, VA

16. ABSTRACT

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17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
Tropical Forests, Biomass Estimation, Biomass Burning		

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