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Spatial distribution of biomass in forests of the eastern USA

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Abstract

We produced a map of the biomass density and pools, at the county scale of resolution, of all forests of the eastern US using new approaches for converting inventoried wood volume to estimates of above and belowground biomass. Maps provide a visual representation of the pattern of forest biomass densities and pools over space that are useful for forest managers and decision makers, and as databases for verification of vegetation models. We estimated biomass density and pools at the county level from the USDA Forest Service, Forest Inventory and Analysis database on growing stock volume by forest type and stand size-class, and mapped the results in a geographic information system. We converted stand volume to aboveground biomass with regression equations for biomass expansion factors (BEF; ratio of aboveground biomass density of all living trees to merchantable volume) versus stand volume. Belowground biomass was estimated as a function of aboveground biomass with regression equations. Total biomass density for hardwood forests ranged from 36 to 344 Mg ha^{-1}, with an area-weighted mean of 159 Mg ha^{-1}. About 50% of all counties had hardwood forests with biomass densities between 125 and 175 Mg ha^{-1}. For softwood forests, biomass density ranged from 2 to 346 Mg ha^{-1}, with an area-weighted mean of 110 Mg ha^{-1}. Biomass densities were generally lower for softwoods than for hardwoods; ca. 40% of all counties had softwood forests with biomass densities between 75 and 125 Mg ha^{-1}. Highest amounts of forest biomass were located in the Northern Lake states, mountain areas of the Mid-Atlantic states, and parts of New England, and lowest amounts in the Midwest states. The total biomass for all eastern forests for the late 1980s was estimated at 20.5 Pg, 80% of which was in hardwood forests. 1999 Published by Elsevier Science B.V.

Keywords: Aboveground biomass; Belowground biomass; Biomass distribution; Carbon cycle; Disturbance; Hardwood forests; Softwood forests; USA

1. Introduction

Forests play an important role in regional and global carbon (C) cycles because they store large quantities of C in vegetation and soil, exchange C with the atmosphere through photosynthesis and respiration, are sources of atmospheric C when they are disturbed by human or natural causes, become atmospheric C sinks during regrowth after disturbance, and can be managed to sequester or conserve significant quantities of C on the land (Brown et al., 1996). Because of their importance in the global C cycle, there is an increasing need to improve the accuracy of estimates

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of the amount of C (or biomass of which ca. 50% is C; Brown and Lugo, 1982; Birdsey, 1992) forests contain. The outcome of the 1997 Kyoto meeting on climate change affirms the importance of forests for meeting greenhouse gas emissions targets during commitment periods for signatory countries of the UN Framework Convention on Climate Change. Emissions and removals of greenhouse gases, including carbon dioxide, from land-use change and forestry are included in these targets. Forest biomass represents the potential amount of C that can be added to the atmosphere or conserved or sequestered on the land when forests are managed for meeting emission targets (Brown et al., 1996).

The quantity of biomass in a forest is the result of the difference between production through photosynthesis and consumption through respiration, mortality, harvest, and herbivory. Forest biomass changes as a result of succession; direct human activities such as silviculture, harvesting, and clearing for conversion to non-forest use; natural disturbances caused by wildfire or pest outbreaks; and changes in climate and atmospheric pollutants. Thus, biomass is a useful measure for assessing changes in forest structure and a useful measure for comparing structural and functional attributes of forest ecosystems across a wide range of environmental conditions.

Forest biomass also provides valuable information for many global issues, however estimating this quantity at suitable scales is not without its problems. The use of remote sensing techniques has been investigated, but as yet this approach has met with little success for multi-age, multi-species forests, and only with limited success in forests with few species and age classes representing a broad range of biomass distributions (Wu and Strahler, 1994; Hall et al., 1995). We believe that, at present, the best approach for estimating forest biomass on a national or regional scale is to use existing data from national forest inventories. This is an appropriate method for broad scale studies because inventory data are generally collected at regional scales from the population of interest and are designed to be statistically valid. Such data are collected on the ground on a regular basis in many countries, particularly industrialized countries. The most common reporting unit is forest wood volume ($m^3 ha^{-1}$) that is derived from field measurements and summarized by forest types, administrative unit (e.g., county), and/or stand age or size class. Inventories of forest wood volume, however, do not characterize all forest biomass; they report only the commercially valuable wood and exclude non-merchantable species and other important components such as branches, twigs, bark, stumps, foliage, roots, and seedlings and saplings. Methods and factors have been developed for converting inventoried forest volume to total biomass for a range of forest types (e.g., Brown, 1997; Cairns et al., 1997; Schroeder et al., 1997; Brown and Schroeder, in press). Forest volume inventories have provided the basis for several national-level C budgets (e.g., Birdsey, 1992; Krankina et al., 1996; Kurz and Apps, 1993).

The forests of the eastern USA have been subject to human disturbance for longer than any other forests on the continent, and virtually all of the forest landscape that we see today has been altered by humans to some degree at some time in the past (Perlin, 1991). While some disturbances were likely caused by the indigenous human population, widespread human disturbance began with the arrival of European colonists. They cleared forests for farming, and logged them for lumber and building materials, railroad expansion, and fuelwood (Perlin, 1991). In this century, large areas of land have reverted to forests as marginal farmlands were abandoned and forests naturally regenerated or were converted to plantations (Williams, 1988; Turner, 1990). The timing of these activities varied by state, with the eastern most states being disturbed earlier than more western ones of the region. Today, most forests in the eastern US are managed for the variety of goods and services that humans value. The biomass of the eastern forests is thus likely to vary widely across the region because of differences in past and present use and management of the land.

The US has an extensive forest inventory database, and data for eastern forests are readily available on the World-Wide Web at various levels of detail. We have previously developed methods for converting US inventory volume data to above and belowground biomass (Cairns et al., 1997; Schroeder et al., 1997; Brown and Schroeder, in press). The main goal of this paper is to use these previously developed methods and apply them to the eastern US forest inventory database to produce spatially explicit estimates of the biomass density (above plus belowground biomass per unit area) and pools of eastern forests (hardwoods and softwood; encompassing 33 states) at the county scale of resolution. Maps not only provide a vivid visual representation of the pattern of forest biomass densities and pools over space that are useful for forest managers and decision makers, but they also serve as databases for verification of vegetation models (e.g., BIOME—Prentice et al., 1992; CENTURY—Parton et al., 1988; MAPSS—Neilson et al., 1992).

2. Methods

Our overall approach was (1) to use the USFS Forest Inventory and Analysis (FIA) database retrieval system to download data on growing stock volume and area by forest type and stand size-class for each of the 2009 counties of the 33 eastern states. (2) We converted these volume data to estimates of aboveground biomass density using previously developed methods (Schroeder et al., 1997; Brown and Schroeder, in press). (3) Belowground biomass densities were estimated from a regression equation relating belowground biomass (coarse and fine roots) to aboveground biomass (Cairns et al., 1997). (4) Biomass pools were the product of biomass density and area, summed by stand-size class. Area-weighted biomass densities were calculated for each county. (5) Biomass pools were mapped in a geographic information system (GIS) by county. For biomass density, we made a forest distribution map by reclassifying a map of US forests based on satellite data (advanced very high resolution radiometer – AVHRR, 1 km resolution; Powell et al., 1993) into two classes: hardwood and softwood forests. This two-class map was then used with the forest biomass density data to clip maps of biomass density at a resolution of 4 km × 4 km to show biomass density at its mapped location.

2.1. Forest inventory data

Data were extracted from the USDA Forest Service FIA unit database for all states from FIA's website: *http://www.srsfia.usfs.msstate.edu/scripts/ew.htm.* We acquired data on area of all timberland and total growing stock volume by forest type (e.g., oak–hickory, maple–beech–birch, spruce–fir, loblolly–shortleaf pine) and stand size-class (seedling/sapling, poletimber, and sawtimber) for each county in the eastern US. Timberland is defined by the Forest Service as land producing or capable of producing in 'excess of 20 cubic feet per acre per year (or ca. 1.4 m^3 ha^{-1} $year^{-1}$) of industrial roundwood products'. With respect to the eastern US, this definition accounts for 94% of all forest land (or 145×10^6 ha out of a total of 154×10^6 ha; Powell et al., 1993). Of the forest lands not included, ca. 3% are wilderness areas, parks, and other lands withdrawn from use for timber by statute or administrative regulation (mostly in the states of New York, Pennsylvania, and Minnesota) and 3% in other forest lands of low primary production such as post oak and blackjack oak forests in Texas and Oklahoma (Powell et al., 1993). Growing stock volume is defined as under-bark volume of main stem to a 10 cm top for trees 12.7 cm diameter and larger, excluding unmerchantable (cull) trees. Details of plot design, field data collection, subsequent manipulation, and the FIA database itself are available at the website or by referring to Hansen et al. (1992).

The database contains information from inventories of forest resources conducted on a cycle of $\approx$10 years. The year of the most recent inventory varied by state, from as far back as 1985 to as recent as 1996 (Table 1). However, about two-thirds of the eastern states had their most recent inventory in the 1990s.

2.2. Estimation of biomass

We estimated the total above and belowground (oven dry mass) of all living trees with a minimum breast-height diameter of 2.54 cm. After downloading the data from the web site, we first summed the growing stock volume and area by three categories of forests—hardwoods, pines, and spruce–fir—for each stand size-class and county. We then divided the total growing stock volume by the corresponding area to generate estimates of growing stock volume per unit area (GSVD; m^3 ha^{-1}). This resulted in a possible nine values of GSVD per county.

To convert GSVD to aboveground biomass, we used functions that related biomass expansion factors (BEF) to GSVD for hardwood, pine, and spruce–fir forest types (Schroeder et al., 1997; Brown and Schroeder, in press). The BEF (Mg m^{-3}) is defined as the ratio of aboveground biomass density of all living trees of DBH $\geq$2.54 cm to GSVD for all trees of

Table 1
Dates of current inventory (from data on the USDA Forest Service FIA unit's website)

State	Current inventory
Alabama	1990
Arkansas	1995
Connecticut	1985
Delaware	1986
Florida	1995
Georgia	1989
Illinois	1985
Indiana	1986
Iowa	1990
Kentucky	1988
Louisiana	1991
Maine	1995
Maryland	1986
Massachusetts	1985
Michigan	1993
Minnesota	1990
Mississippi	1994
Missouri	1989
New Hampshire	1983
New Jersey	1987
New York	1993
North Carolina	1990
Ohio	1991
Oklahoma	1993
Pennsylvania	1989
Rhode Island	1985
South Carolina	1993
Tennessee	1989
Texas	1992
Vermont	1989
Virginia	1992
West Virginia	1989
Wisconsin	1996

DBH $\geq$12.7 cm. Our previous work (Schroeder et al., 1997; Brown and Schroeder, in press) presented a general approach to convert GSVD to total aboveground biomass of all living trees for hardwood and softwood forests. Our approach accounted for non-commercial tree species, non-merchantable commercial tree species (e.g., cull trees), non-commercial tree components (branches, twigs, and leaves), and all trees of diameter $\geq$2.5 and <12.5 cm, and estimated aboveground biomass density of the tree component (AGBD, Mg ha^{-1}) directly from growing stock volume density (m^3 ha^{-1}).

In our previous work (Schroeder et al., 1997; Brown and Schroeder, in press), we developed BEFs that were based on: oak–hickory and maple–beech–birch forests for hardwoods, and spruce–fir and loblolly/shortleaf pine forests for softwoods. We aggregated the database into these three broad forest categories because it was not practical to attempt to formulate BEFs for every forest type in the eastern US. The relationship between BEF and GSVD for hardwoods was based on the oak–hickory and maple–beech–birch forests that account for ca. 50% of all eastern hardwood forests. As there was no significant difference in the relationships between BEF and GSVD for these two forest types, the data were pooled and a single regression equation was developed (Schroeder et al., 1997). We assumed that this regression equation was applicable for all hardwood forests reported in the FIA databases. Statistically significant regression equations between BEFs and GSVD were obtained for aggregated hardwoods and spruce–fir forests. The equations are:

Hardwoods:

$$\mathrm{BEF} = \exp\{1.91 - 0.34 \times \mathrm{Ln(GSVD)}\};\quad r^2 = 0.85,\ n = 208,\ \mathrm{SE} = 0.109 \qquad (1)$$

for GSVD >200 m^3/ha, BEF = 1.0.

Spruce–fir:

$$\mathrm{BEF} = \exp\{1.77 - 0.34 \times \mathrm{Ln(GSVD)}\};\quad r^2 = 0.88,\ n = 49,\ \mathrm{SE} = 0.095 \qquad (2)$$

for GSV >160 m^3/ha, BEF = 1.0.

Biomass expansion factors decrease with increasing GSVD for both forest categories, a pattern consistent with theoretical expectations (Schroeder et al., 1997). At high GSV, the slopes approach zero, beyond which point the BEFs approach a constant.

No significant relationship between BEF and GSVD was obtained for pine forests. Because of the general similarity of pine forests in the eastern US, and their common structural characteristics and branching patterns, we assumed that they would have similar BEFs. The only other comparable analysis of pine data that we are aware of (Brown, 1997) also found no relationship between GSVD and BEF, which further demonstrates the similarity of pine forests. Thus, we used the following median BEFs for the indicated range in GSVD:

$$\mathrm{GSVD} < 10\,\mathrm{m}^3\,\mathrm{ha}^{-1};$$

$$\mathrm{BEF} = 1.68\,\mathrm{Mg\,m}^{-3}(n = 72,\ \mathrm{SE} = 0.13)$$

$$\text{GSVD} = 10\text{–}100\,\text{m}^3\,\text{ha}^{-1};$$
$$\text{BEF} = 0.95(n = 86,\ \text{SE} = 0.02) \tag{3}$$
$$\text{GSVD} > 100\,\text{m}^3\,\text{ha}^{-1};$$
$$\text{BEF} = 0.81(n = 16,\ \text{SE} = 0.03)$$

For each forest category and stand size-class, we calculated aboveground biomass density as the product of GSVD and BEF. We used Eqs. (1)–(3) to convert volume estimates to aboveground biomass for the hardwood, pine, and spruce–fir forest categories.

We estimated belowground biomass density (BGBD = fine and coarse roots) for each forest category and stand size class from AGBD by using the following regression equation for temperate forests (from Cairns et al., 1997):

$$\text{BGBD} = \exp\{-1.059 + 0.884 \times \text{Ln}(\text{AGBD}) + 0.284\};$$
$$r^2 = 0.84,\ n = 151$$

Estimates of belowground biomass density were then added to the aboveground estimates to produce a total biomass density estimate. An area-weighted average total biomass density was then calculated for hardwood and softwood (pine plus spruce–fir) forests for each county. Biomass pools were estimated as the sum of the products of total biomass density, by forest category and stand size-class, and the corresponding area for each county. We combined the data for hardwoods and softwoods for each county to generate an estimate of total forest biomass.

2.3. Mapping biomass

We produced and displayed all maps using version 7.0 of the ARC/INFO GIS software (ESRI, 380 New York St., Redlands, CA 92373). We used the Albers conic equal-area projection with standard parallels at 29° 30′ and 45° 30′, the central meridian at −96° and the latitude of origin at 23°.

We first made a forest distribution map by reclassifying a map of the forests of the US (Powell et al., 1993), based on 1 km AVHRR satellite data, into two classes: hardwood and softwood forests. This two-class map was then used as a template with the forest biomass density data to generate maps at a resolution of 4 km × 4 km to convey the biomass density at its mapped location. This resulted in hardwood forests being mapped in all counties except a few with an extremely small area of forest. The results were not as complete for softwood forests; many counties had data for softwood biomass but no area according to the forest cover map. This was due to interpretation differences between field-based forest inventory and a relatively coarse satellite-based map. We added a 4 km × 4 km pixel in the center of any county that had softwood biomass data but no mapped softwood forest. This was for display purposes only and did not affect the maps of total biomass. Maps of total biomass per county were not clipped by the two-class map because the area of forest by county was already included in the calculation.

2.4. Error estimation

The FIA program uses a statistically based sampling scheme designed to provide growing stock volume estimates with a sampling error of 5% for $28.3 \times 10^6\,\text{m}^3$ (billion cubic feet), and forest area estimates with a sampling error of 3% for 0.4×10^6 ha (million acres) (Noel Cost, USDA Forest Service, 1998, personal communication). Larger forest areas and volumes have smaller relative standard errors, and vice versa. The sources of error in volume or biomass estimation are measurement error, sampling error, and regression error; the sampling error has been shown to be the largest component of the total error (Phillips et al., 1998). Analysis of the data at the county level, as done in this paper, would result in a larger total error, mostly due to the increase in sampling error at this smaller scale. For example, the sampling errors for volume at the state level for Virginia and North Carolina increased by about a two to three-fold factor or more at the county level (Brown, 1993; Thompson and Johnson, 1994). How the various sources of error compound into total error for biomass at the county level is not known, and indicates an area deserving more attention.

3. Results and discussion

3.1. Distribution of biomass densities

Hardwood forests with the highest biomass densities (>200 Mg ha^{-1}) are mostly located in the

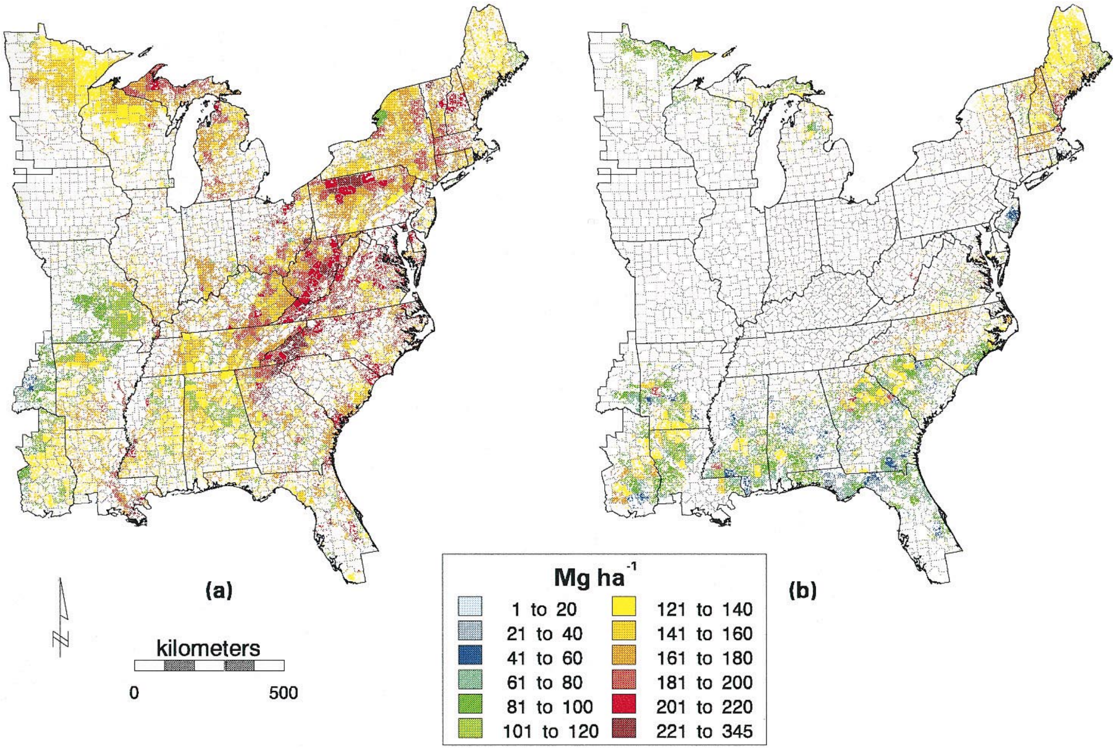

Fig. 1. Map of biomass density (above and belowground biomass, Mg ha^{-1}) for (a) hardwood and (b) softwood forests of the eastern US.

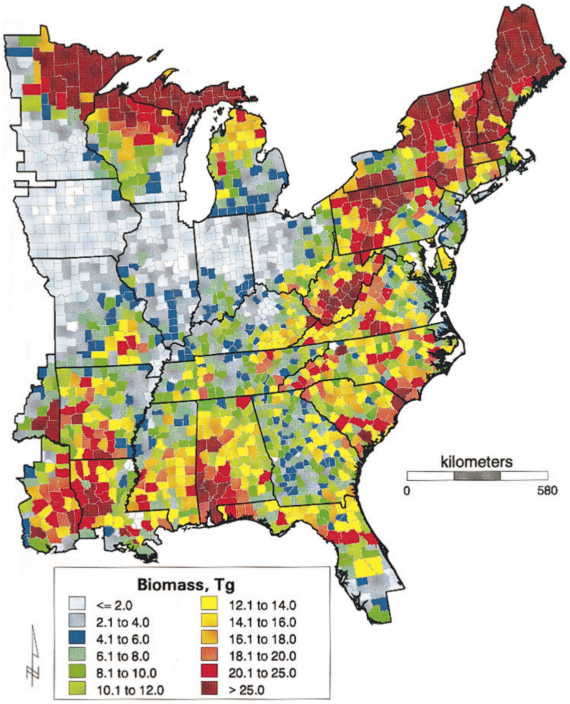

Fig. 4. Map of total biomass (hardwood plus softwood) for forests of the eastern US.

Appalachian Mountains, stretching from northern Georgia to as far north as the New England states; the coastal plain of North Carolina and Virginia; and in the upper peninsula of Michigan (Fig. 1(a)). Scattered counties in Illinois, Indiana, and Wisconsin also contain forests with biomass densities above 200 Mg ha^{-1}. Hardwood forests with some of the lowest biomass densities (<100 Mg ha^{-1}) are located in Iowa, Missouri, Oklahoma, and Texas.

States in the northeast have softwood forests with some of the highest biomass densities, while the southern states have forests with a wide range of biomass densities (Fig. 1(b)). The wide range of biomass densities in southern states most likely reflects the influence of more intensive management of pine plantations and natural forests (Birdsey, 1992), producing a mosaic of different age classes and thus biomass.

Biomass densities for hardwood forests, at the county scale of resolution, ranged from 36 to 344 Mg ha^{-1}, with an area-weighted mean of 159 Mg ha^{-1}. And, for softwood forests, biomass densities ranged from 2 to 346 Mg ha^{-1}, with a weighted mean of 110 Mg ha^{-1}. About 50% of all counties had hardwood forests with biomass densities between 125 and 175 Mg ha^{-1} (Fig. 2). Biomass densities were generally lower for softwoods than for hardwoods; ca. 40% of all counties had softwood forests with biomass densities between 75 and 125 Mg ha^{-1}.

The present biomass density of eastern forests reflects their stage of recovery from the historical pattern of human use (Brown et al., 1997), the ongoing management for timber, and the variation in environmental factors that affect rates of biomass accumulation. For example, forests with some of the highest biomass density are most likely those that are older because they were either subject to less human disturbance or the lands were abandoned from agricultural use sooner and have had a longer time to regrow (e.g., Maine, upper peninsula of Michigan, Appalachian Mountains) (Perlin, 1991 Whitney, 1994). Rather than age or harvesting, environmental factors such as drier climate and shorter growing season are likely the main causes for the lower biomass density forests in counties at the western edge of the region (e.g. Iowa, Oklahoma, and Texas).

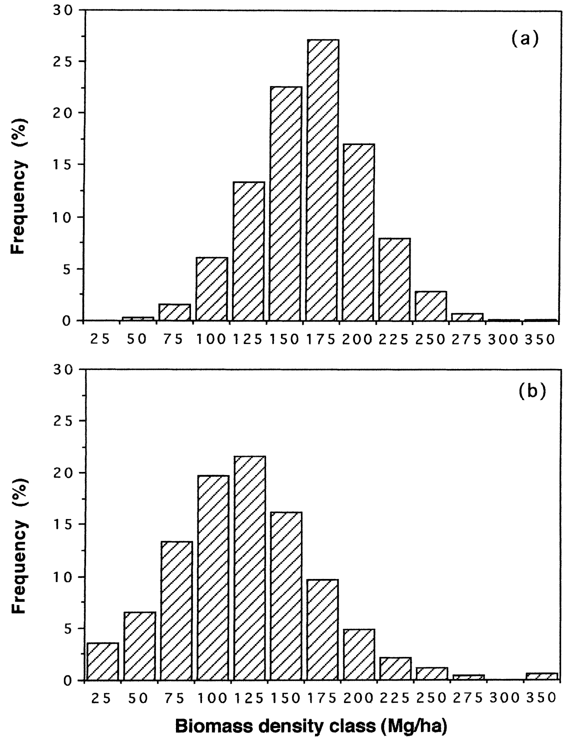

Fig. 2. Frequency distribution of biomass density classes for (a) hardwood and (b) softwood forests in the eastern US. The values plotted on the horizontal axis are the upper limit of the biomass density class.

3.2. Distribution of biomass pools

Pools of total forest biomass by county (Tg = 10^{12} g) range over two orders of magnitude in the eastern US (Figs. 3 and 4). Because most of the counties in this region are somewhat similar in size (except those in Minnesota and Maine which tend to be larger than average and those in Georgia which tend to be smaller), this range in pools reflects comparative amounts of forest biomass. More than 60% of the counties have biomass pools of $\leq$10 Tg, and only about 6% have biomass pools >25 Tg (Fig. 3). Counties with the smallest pool of forest biomass ($\leq$2.0 Tg) are those mostly located in midwestern states as might be expected, with additional low biomass counties scattered along the Mississippi valley and parts of Florida. Counties in New England, Maine, and the upper peninsula of Michigan have some of the highest

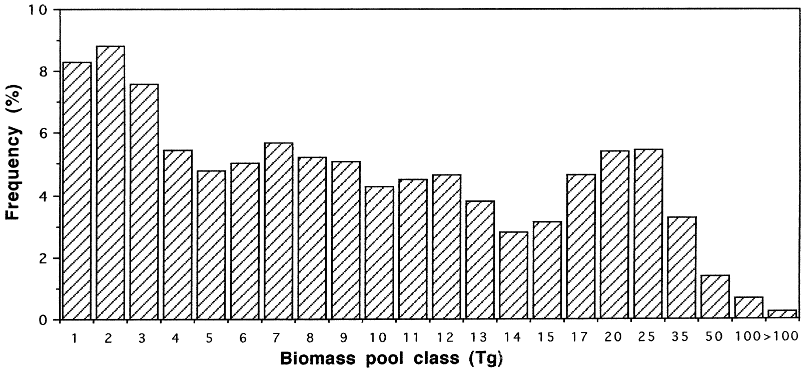

Fig. 3. Frequency distribution of total biomass pools for hardwood and softwood forests combined for all counties in the eastern US. Values plotted on the horizontal axis are the upper limit of the biomass pool class. Note that the scale is non-linear after the 15 Tg class.

biomass pools because they have forests with high biomass densities and large forest areas. The large pools in counties of northeastern Minnesota and northern Maine are mostly due to their large size as well as high forest cover; their biomass densities are in the mid-range.

The total biomass pool for all eastern forests is 20 500 Tg, 80% of which is in hardwood forests (Table 2). North Carolina and Georgia have the highest biomass pools (>1200 Tg), and ca. 65–75% of this is in hardwood forests. These two states plus an additional four (Alabama, Michigan, Pennsylvania, and Virginia), containing more than 1000 Tg of biomass each, account for more than a third of the total biomass in the eastern states. Delaware, Iowa, New Jersey, and Rhode Island each contain ca. 100 Tg or less of biomass. About 27% of the states had 25% or more of their biomass pool in softwood forests. Two states only (Louisiana and Maine) had more than 40% of their biomass in softwood forests.

The total biomass pool that we obtained is ca. 1.25 times higher than the 16 200 Tg reported by Birdsey (Birdsey, 1992; tree component only) for the same area. This difference in pool estimates could partly be due to the higher level of resolution that we used, and partly due to the various factors and approaches that the respective studies used in estimating tree components other than growing stock volume. However, with all the potential sources of uncertainty in the analysis, the difference may not be significant.

3.3. Potential for increased biomass-carbon storage

Although the total biomass density of eastern hardwood forests span a wide range, their average biomass density is less than half of what it could be because they lack numerous large diameter trees as is typical for old-growth forests (Brown et al., 1997). This lack of large diameter trees is because the forests are still either aggrading or are managed for commercial timber production. Eastern forests have the potential to accumulate significant quantities of additional biomass in living trees (at least an additional 20 000 Tg) if left unharvested, and thus storing atmospheric C into the future. As many of the forests in the eastern US are <100 year old, they would require a few hundred years more to attain the structure of old-growth forests (Brown et al., 1997). The biological possibility of storing additional C does not mean that this possibility will be realized because of the many competing uses and objectives for forest lands. Promoting C storage in existing forests by reducing harvesting or lengthening rotations are options to increase C sequestration, but ones that must be weighed against the benefits of conventional forest management, potential risks of catastrophic wildfires, and the costs of C emissions from the manufacture of materials to replace wood products. An alternative is to increase the area of forest lands by afforesting marginal farmland, a trend that is occurring in many parts of the eastern US under federal incentive programs such as the Conservation Reserve Program and the Wetlands Reserve Program.

Table 2
Total forest biomass pool and fraction of pool in hardwood forests by state

State	Biomass pool (Tg)	Fraction
Alabama	1054	0.75
Arkansas	876	0.79
Connecticut	128	0.91
Delaware	27	0.86
Florida	635	0.68
Georgia	1211	0.65
Illinois	249	0.99
Indiana	261	0.98
Iowa	95	1.00
Kentucky	787	0.97
Louisiana	751	0.59
Maine	970	0.58
Maryland	190	0.90
Massachusetts	199	0.74
Michigan	1210	0.81
Minnesota	771	0.76
Mississippi	915	0.77
Missouri	543	0.98
New Hampshire	336	0.66
New Jersey	107	0.87
New York	982	0.84
North Carolina	1284	0.74
Ohio	466	0.98
Oklahoma	168	0.78
Pennsylvania	1133	0.95
Rhode Island	21	0.94
South Carolina	668	0.67
Tennessee	806	0.93
Texas	565	0.65
Vermont	286	0.76
Virginia	1088	0.85
West Virginia	917	0.98
Wisconsin	791	0.86
Total	20 500	0.80

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