Importance of biomass in the global carbon cycle

R. A. Houghton,[1] Forrest Hall,[2] and Scott J. Goetz[1]

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[1] Our knowledge of the distribution and amount of terrestrial biomass is based almost entirely on ground measurements over an extremely small, and possibly biased sample, with many regions still unmeasured. Our understanding of changes in terrestrial biomass is even more rudimentary, although changes in land use, largely tropical deforestation, are estimated to have reduced biomass, globally. At the same time, however, the global carbon balance requires that terrestrial carbon storage has increased, albeit the exact magnitude, location, and causes of this residual terrestrial sink are still not well quantified. A satellite mission capable of measuring aboveground woody biomass could help reduce these uncertainties by delivering three products. First, a global map of aboveground woody biomass density would halve the uncertainty of estimated carbon emissions from land use change. Second, an annual, global map of natural disturbances could define the unknown but potentially large proportion of the residual terrestrial sink attributable to biomass recovery from such disturbances. Third, direct measurement of changes in aboveground biomass density (without classification of land cover or carbon modeling) would indicate the magnitude and distribution of at least the largest carbon sources (from deforestation and degradation) and sinks (from woody growth). The information would increase our understanding of the carbon cycle, including better information on the magnitude, location, and mechanisms responsible for terrestrial sources and sinks of carbon. This paper lays out the accuracy, spatial resolution, and coverage required for a satellite mission that would generate these products.

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1. Introduction

[2] Biomass is of interest for a number of reasons. It is the raw material of food, fiber, and fuelwood. It is important for soil, fire and water management. It is related to vegetation structure, which, in turn, influences biodiversity. It determines the magnitude and rate of autotrophic respiration. And, finally, biomass density (the quantity of biomass per unit area, or Mg dry weight ha^{-1}) determines the amount of carbon emitted to the atmosphere (as CO_2, CO, and CH_4 through burning and decay) when ecosystems are disturbed.

[3] The purpose of this paper is to offer the scientific rationale, from the perspective of the carbon cycle, for accurate measurement of biomass density and changes in it. We define the objectives and measurement requirements for a satellite mission designed to measure biomass density and changes in biomass density. Why, from the perspective of the carbon cycle, do we need to quantify biomass density and changes in it? The paper will consider a number of subsidiary questions, such as where do we need to measure biomass density? At what resolution? How accurately? And how often? The answers define the observational (and modeling) requirements for meeting the objectives for understanding the role of terrestrial ecosystems in the carbon cycle.

[4] The paper consists of three parts. Part 1 focuses on the amount of carbon in the biomass of terrestrial ecosystems and the reason we need to know its spatial distribution more accurately. Part 2 focuses on understanding changes in biomass density, summarizing current understanding of the global carbon cycle and the processes that control changes in biomass density. Part 3 considers the requirements for a satellite-based system designed to determine terrestrial sources and sinks of carbon.

2. Amount of Carbon in the Biomass of Terrestrial Ecosystems

[5] Biomass is not consistently defined. It is usually defined to include the mass of living plants and/or animals, for example trees, shrubs, grasses, herbs, and microbes, although it is sometimes defined to include dead plant material as well. Belowground components (roots, rhizomes, and microbes in soil) are sometimes included, as well as aboveground material, although generally soil organic matter (SOM), which consists of plant parts that have decayed beyond recognition, are not included. The boundaries between dead biomass and litter, and between dead biomass and SOM, are somewhat arbitrary.

[1]Woods Hole Research Center, Falmouth, Massachusetts, USA.
[2]NASA Goddard Space Flight Center, Greenbelt, Maryland, USA.

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Table 1. Mean Living Biomass, Area, and Total Living Biomass of the World's Major Terrestrial Ecosystems[a]

Ecosystem Type	Area (10^6 ha)	Total Biomass (Pg)	Mean Biomass Density (Mg/ha)
Tropical forests[b]	1,750, 1,850	680, 350	390, 190
Temperate forests	1,040	280	270
Boreal forests	1,370	110	83
Temperate + boreal forests[b]	2,410, 2,450	390, 185	160, 75
Arctic tundra	560	4	7
Mediterranean shrublands	280	34	120
Croplands	1,350	8	6
Tropical savannas and grasslands	2,760	160	57
Temperate grasslands	1,500	12	8
Deserts	2,770	20	7
Ice	1,550	0	0
Total	14,930, 15,070	1,300, 773	87, 51

[a]From *Houghton and Goetz* [2008].

[b]For tropical forests and for temperate and boreal forests, combined, the first number in each column is from *Saugier et al.* [2001], and the second is from *Food and Agriculture Organization* (*FAO*) [2001] for tropical forests and from *Goodale et al.* [2002] for temperate and boreal forests.

[6] This review concerns the role of biomass in the carbon cycle (biomass, as dry weight, is about 50% carbon). We emphasize the biomass of woody plants, focusing on forests (forests hold 70–90% of terrestrial aboveground and belowground biomass) and focusing in particular on aboveground forest biomass, which accounts for 70–90% of total forest biomass [*Cairns et al.*, 1997], most of it in trees. Estimates of the amount of biomass in the world's terrestrial ecosystems range from 385 to 650 PgC (Table 1). Soil organic matter, globally, holds two to three times more carbon than biomass does, but much of the carbon in soils is physically and chemically protected and not easily oxidized [*Davidson and Janssens*, 2006] (the burning of peat is an exception). In contrast, biomass, particularly aboveground biomass, is vulnerable to fire, logging, land conversion, storms, pests, etc., and thus its carbon is easily released to the atmosphere.

[7] Biomass density varies spatially and temporally. Living biomass ranges over two to three orders of magnitude, from less than 5 MgC/ha in treeless grasslands, croplands, and deserts to more than 300 MgC/ha in some tropical forests and forests in the Pacific Northwest of North America. Biomass density also varies considerably within ecosystem types. This variability results in part from limitations of the environment (for example, soil nutrients or the seasonal distribution of precipitation and temperature), and in part from disturbance and recovery. The aboveground living biomass density of a recently burned forest may be nearly zero, but it increases as the forest recovers (Figure 1). Forests do not accumulate biomass indefinitely, however, because stand-replacing disturbances keep turning old forests into young ones. However, most forest stands are in the process of recovering from natural or human-induced disturbances and, thus, are accumulating carbon, albeit generally at lower rates as they age.

[8] The estimation of forest biomass density depends, in part, on spatial scale. At a resolution of <0.1 km, biomass density varies with individual canopy trees, including spe-

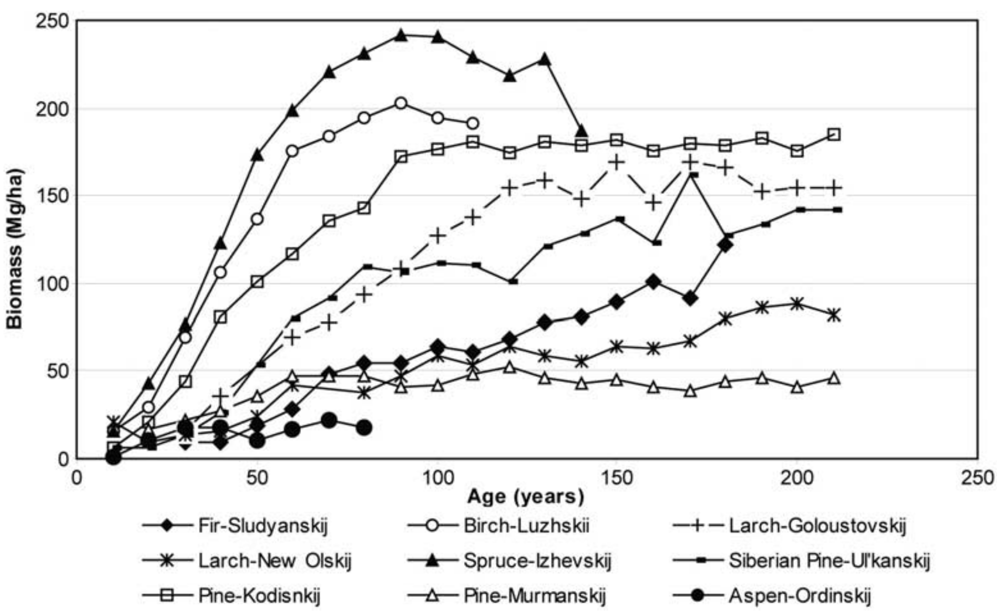

Figure 1. A sample of changes in the biomass density (Mg/ha) of forests in Russia following disturbance (for example, fire or logging). Each disturbance removes living biomass, which subsequently reaccumulates as a consequence of growth. See *Krankina et al.* [2005] for details. © 2005 NRC Canada or its licensors. Reproduced with permission.

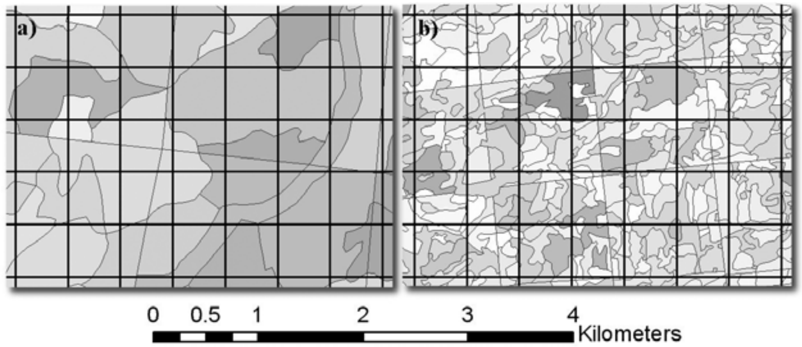

Figure 2. Forest stands in (a) Krasnoyarsk-Yartsevsky and (b) Novosibirsk. The different shades indicate variations in biomass density. The grid represents 500 m × 500 m cells [from *Houghton et al.*, 2007]. © Institute of Physics.

cies and natural mortality, which creates canopy gaps. At the level of a forest stand (an area relatively homogeneous in age and species composition) (0.1 – 1 km), biomass density varies through time as a result of disturbances and recovery. At the landscape scale (composed of different stands) (1 – 100 km), biomass density varies across space because the ages (since the last disturbance) of stands vary across the landscape. Figure 2 shows the distribution of forest stands across two landscapes in Russia. The remarkable feature of these landscapes is that they are not at all homogeneous, but, rather, a mosaic of different stands of biomass.

[9] There are two aspects to quantifying biomass density from in situ measurements: those at specific sites and those using methods for extrapolating the results from such sites to large areas. The ‘‘Gold Standard’’ of biomass density measurement at a sample plot is an extremely labor intensive, destructive technique. It involves harvesting all plant material within the plot, drying it to a constant weight, and weighing it [e.g., *Brown*, 1997]. In practice, this type of destructive measurement becomes more difficult if the belowground portions are included and if the vegetation includes large trees. Sorting roots from the soil-root matrix is difficult. The size of the plot is also important: small plots will either overestimate or underestimate average biomass density if they include or exclude large trees, respectively. Achieving accuracies of 10 MgC/ha over multihectare regions in tropical forests using a sampling approach with destructive samples is impractical, and repeating those measurements so that changes can be monitored is not feasible.

[10] To obviate these problems, foresters and ecologists have developed indirect methods for estimating biomass density. The most common approach uses empirically based allometric equations based on destructive samples that allow the estimation of tree biomass density from more easily measured properties, such as diameter at breast height (dbh) and height [*Whittaker and Woodwell*, 1968; *Brown*, 1997]. Systematic sampling (forest inventories), including both measurements and allometric equations, allows the biomass density (or commercial wood volumes) to be obtained over large areas. The approach requires sampling of ‘‘representative’’ trees to ‘‘calibrate’’ the allometric equations. How robust the approach is when extended beyond the ‘‘calibration’’ region is not well understood [see, e.g., *Nogueira et al.*, 2008], but the quality of allometric equations is generally better for northern forests in industrial countries than for tropical forests, in part because of the greater number of tree species in the tropics.

[11] The biomass of most temperate zone and boreal forests has been systematically inventoried at least once. Accuracies vary among regions and countries, but they are generally high for wood volumes. In the southeastern U.S., for example, the error calculated for the total wood volume was within 1.1% [*Phillips et al.*, 2000]. The error for aboveground carbon is somewhat greater because of variability in wood density and carbon content. The errors are larger in tropical forests because the paucity of systematic surveys, together with the large spatial variability and greater number of tree species, has severely limited the ability to estimate the distribution or total amount of woody biomass [*Clark et al.*, 2001].

[12] In the absence of systematic surveys, plot-level measurements of biomass density are interpolated, extrapolated, or mapped over large areas by one of three approaches: (1) classification of land covers, each assigned an estimated average value of biomass density based on estimates from the literature or forestry data [*Brown and Lugo*, 1992; *Fearnside*, 1992; *DeFries et al.*, 2002; *Achard et al.*, 2004], (2) calculation of biomass density from regressions based on environmental parameters that are mapped (for example, mean annual temperature and the seasonal distribution of precipitation) [*Brown et al.*, 1993; *Iverson et al.*, 1994], and (3) determination of relationships between in situ biomass density and remote sensing characteristics that can be consistently mapped over large regions [*Myneni et al.*, 2001; *Baccini et al.*, 2004, 2008; *Houghton et al.*, 2007; *Saatchi et al.*, 2007; *Blackard et al.*, 2008]. Figure 3 shows an example of the latter, produced using MODIS imagery and field data sets across central Africa. The map was assessed using lidar canopy height metrics and reserved field data, providing 25 MgC/ha error estimates for biomass values ranging up to 180 MgC/ha. Maps of this sort advance our understanding of the spatial distribution of carbon stocks, and are thus a substantial departure from more traditional methods of ascribing plot-level biomass measurements to land cover maps, but different biomass mapping methods do not yield consistent results [*Goetz et al.*, 2009]. A comparison of seven estimates of biomass for the Brazilian Amazon, for example,

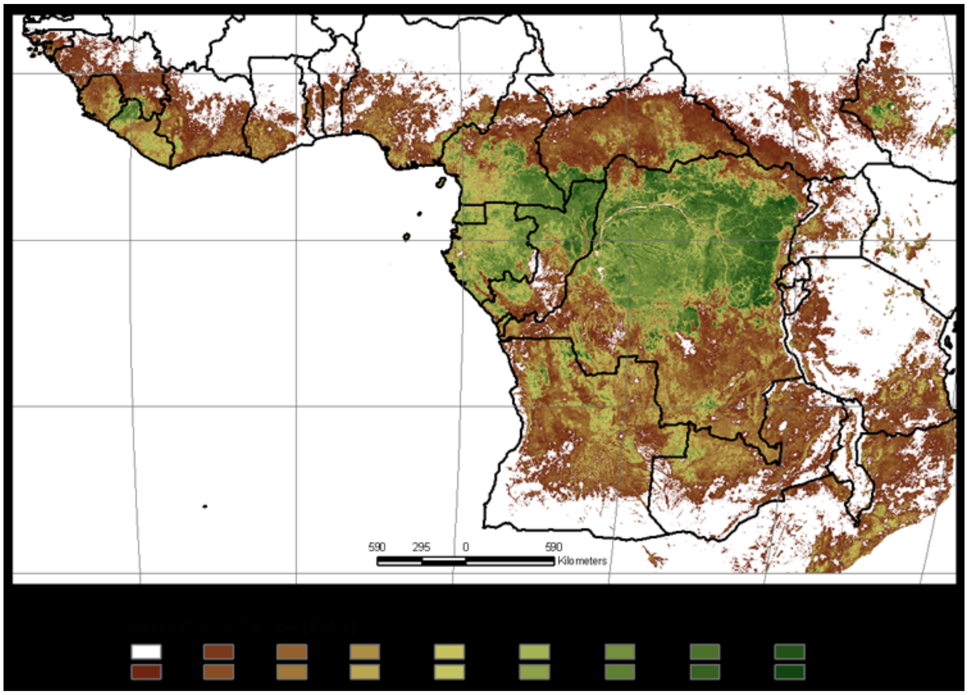

Figure 3. Biomass map derived from MODIS imagery and field data across central Africa. See *Baccini et al.* [2008] for details.

revealed not only a wide range (greater than a factor of two between the lowest and highest estimates of total biomass), but also no agreement as to where the forests with the highest and lowest biomass densities were located [*Houghton et al.*, 2001]. More recent investigations of Amazonian biomass have produced additional estimates [*Malhi et al.*, 2006; *Saatchi et al.*, 2007] but determining their accuracy is difficult due to a paucity of accurate in situ estimates. At present, estimates of both total biomass and the spatial distribution of biomass density are not well known, especially for tropical forests, where large areas have never been inventoried. Many regions are simply inaccessible for geographic and political reasons.

[13] Two recent reviews of global biomass are shown in Table 1. Although the estimates for forest area are reasonably similar, estimates of forest biomass density vary by nearly a factor of two. The higher estimate is a compilation of site-specific measurements in different types of ecosystems [*Saugier et al.*, 2001]. It suggests a global total of approximately 650 PgC, of which forests account for more than 80%. The lower estimate (385 PgC; 70% in forests) is based on forest inventories with a much larger number of measurements (of commercial wood volumes).

[14] The fact that estimates of forest biomass vary by more than a factor of two for temperate and boreal forests is remarkable, given that wood volumes are generally measured with an accuracy of 1% in national forest inventories [*Noble et al.*, 2000]. Some fraction of the discrepancy results from scaling commercial wood volumes to total biomass, including not only roots, leaves, and branches, but also understory vegetation, noncommercial species, and trees smaller than those generally inventoried. Some of the difference between estimates may also result from site selection. And, finally, some of the uncertainty in estimates of forest biomass results from inconsistent definitions of forest, which are often based on fractional tree cover to distinguish them from savannas and other woody lands [*Noble et al.*, 2000].

[15] In sum, recent reviews of global terrestrial biomass vary from <800 to 1300 PgC (±25%). Errors result from (1) inconsistent definitions of forest, (2) uncertain estimates of forest area (despite the agreement in Table 1), particularly in tropical regions and developing countries, (3) a paucity of ground measurements, particularly in forests with high biomass density, and (4) the lack of reliable mechanisms for extrapolating ground measurements to large areas. We note that a repeated "direct remote sensing approach" would overcome three of these errors (errors 1, 2, and 4).

[16] The first objective for a biomass observing system is to determine the spatial distribution of biomass density over the earth. Besides resolving current uncertainties and providing a baseline, such a map would provide guidance as to where forests might be preserved to maintain their stores of carbon, and where changes in land use would minimize carbon emissions. The spatial distribution of biomass would also enable ecosystem models to more accurately simulate plant (autotrophic) respiration.

3. Changes in the Amount of Biomass in Terrestrial Ecosystems

[17] Perhaps more important than biomass to the global carbon cycle, is change in biomass. Biomass is dynamic. Although average biomass density over large regions or biomes may change little over time, the biomass density of individual stands and plots is continuously changing (Figure 1). The sum of these changes is largely responsible for the net sources and sinks of terrestrial carbon. A one-time

Table 2. Global Carbon Budget[a]

	1990–1999	2000–2006
Fossil fuel emissions	6.5	7.6 ± 0.4
Net flux from land use change	1.6	1.5 ± 0.5
Total anthropogenic emissions	8.0	9.1 ± 0.6
Increase in atmosphere	3.2	4.1 ± 0.04
Oceanic sink	2.2	2.2 ± 0.4
Residual terrestrial sink	2.6	2.8 ± 0.7
Net terrestrial sink	1.0	1.3 ± 0.7
Airborne fraction	0.40	0.45

[a]From *Canadell et al.* [2007]. Units are PgC a^{-1} except for the airborne fraction, which is without units.

measurement of global biomass, though useful for a baseline, is thus inadequate for defining the biomass density of individual plots in the years following that measurement. Monitoring for change requires repeat measurements.

[18] Changes in biomass result from three different processes: (1) changes in land use and management can affect the area of forests, their age structure, community composition, and hence rates of carbon accumulation and loss; (2) natural disturbances and recovery have similar affects on the age of forests, their structure, community composition, and hence rates of carbon accumulation and loss; (3) physiological or metabolic changes, driven by environmental change, affect rates of photosynthesis, respiration, growth, decay, and, hence, rates of carbon accumulation and loss.

[19] A system for measuring global biomass should be designed to quantify the contributions of at least the first two of these three processes, those that involve structural changes [*Shugart*, 2000; *Running*, 2008]. Although some metabolic processes, such as photosynthesis, are observable from space [*Sellers*, 1987; *Myneni et al.*, 1995; *Goetz and Prince*, 1999], others, such as respiration, are not, and thus net changes in carbon density must be calculated with models.

[20] Clearly, metabolic and structural processes occur simultaneously and are not always distinguishable. Nevertheless, they often operate at different temporal scales. Structural changes reflect longer-term, integrative properties of ecosystems. Unlike metabolic changes, they may not be accurately predicted with models based on short-term measurements of metabolism (photosynthesis, respiration) or short-term variations in atmospheric CO_2 concentrations, and thus need to be addressed independently of short-term processes. Structural changes may account for a large portion (perhaps all) of the net flux of carbon between the atmosphere and terrestrial ecosystems, and a biomass satellite mission would provide direct information on such changes. Even a mission as short as 3–5 years is long enough to identify where major structural changes have occurred and the magnitude of carbon involved.

3.1. Changes in Carbon Density From Land Use Change and Management

[21] Over the period 2000–2006 terrestrial ecosystems released an estimated 1.5 PgC/a to the atmosphere as a result of changes in land use (largely tropical deforestation) (Table 2). The error of this estimated global carbon source is itself uncertain, ranging from ±0.5 PgC/a [*Canadell et al.*, 2007] to ±1.0 PgC/a [*Denman et al.*, 2007]. The major source of uncertainty is the aboveground biomass density of the forests converted to other land uses.

[22] Although the net annual flux of carbon from land use change, globally, has always been a net source of carbon to the atmosphere over the last 155 years [*Houghton*, 2003], a number of regions have been and are carbon sinks. Emissions result from the conversion of forests to cleared lands. Sinks result from the recovery (growth) of forests following harvest, abandonment of agricultural lands, and afforestation. Globally, the sources of carbon from land use change have always exceeded the associated sinks.

[23] The sources and sinks are calculated with carbon-tracking models based on two types of information: rates of land use change and per hectare changes in carbon pools (plants, soil, wood products, and detritus) following a change in land use [*Woodwell et al.*, 1983; *Detwiler and Hall*, 1988; *Hall and Uhlig*, 1991; *Fearnside*, 2000; *DeFries et al.*, 2002; *Achard et al.*, 2002, 2004; *Houghton*, 2003]. Ecosystems models have also been used to calculate fluxes from land use change and disturbance [*Potter et al.*, 2009], and other models have calculated the emissions from fires [*van der Werf et al.*, 2003; *DeFries et al.*, 2008] or fires and insects [*Kurz et al.*, 2008]. All of the estimates of flux suffer from the lack of spatially specific estimates of biomass density. Consequently, accurate estimates of aboveground biomass density at a spatial resolution equivalent to the resolution of land use change would enable more accurate estimates of carbon flux from land use change.

[24] Improving the estimated net flux of carbon from changes in land use is important for both policy (emissions inventories) and science (understanding feedbacks in the carbon-climate system). Over the last ~155 years, about half of the anthropogenic emissions of carbon to the atmosphere (from burning fossil fuels and from land use change) has remained in the atmosphere, and half has accumulated on land and in the oceans [*Field et al.*, 1998; *Houghton*, 2007]. As annual emissions of carbon have grown, the annual accumulations in atmosphere, land, and oceans have also grown. The annual increase in atmospheric carbon relative to the annual emissions (the airborne fraction) has remained remarkably constant. In other words, land and oceans have been taking carbon out of the atmosphere in proportion to emissions. If the uptake had not remained proportional to emissions (if the sinks had not increased), the airborne fraction would have increased (and atmospheric concentrations of CO_2 would be higher).

[25] The past behavior of land and oceans in taking up carbon is not guaranteed for the future, and understanding the carbon cycle and, in particular, the mechanisms responsible for sources and sinks of carbon on land and in the ocean, is critical. Changes in the airborne fraction may be the first indication of feedbacks between global warming and the carbon cycle. Recent evidence suggests that the airborne fraction, over the last 48 years, may have increased by 10% (0.25 ± 0.21%/a) [*Canadell et al.*, 2007]. The increase suggests that the relative strengths of terrestrial and/or oceanic sinks have been declining.

[26] It is difficult to discern a trend in the airborne fraction because, first, year-to-year variability in the airborne fraction is large, and, second, trends in the emissions of carbon from land use change are uncertain. In particular, it is unclear whether the emissions of carbon from land use change have increased, decreased, or stayed approximately the same over the last 30 years. The uncertain trend in

emissions from land use change precludes the ability to determine with confidence whether or not the airborne fraction is changing in a manner consistent with weakening sink strengths.

[27] At least half of the uncertainty in estimates of the emissions of carbon from land use change results from uncertain estimates of biomass density [*Houghton*, 2005] (Table 1). Even where estimates of regional means of forest biomass density are known with confidence, as in most developed countries, the spatial distribution is not well known; and the possibility that deforestation occurs in forests with biomass density systematically different from the regional mean suggests that this potential bias may also contribute to systematic errors in flux estimates [*Houghton et al.*, 2001; *Helmer et al.*, 2008]. A wall-to-wall measurement of aboveground biomass density for the world's terrestrial ecosystems at accuracies and resolutions described below (section 3) could reduce the errors of estimates of this flux to levels similar to other global terms. Wall-to-wall measurements would also provide valuable information for land use planning. Carbon storage is one of many competing uses of land, and a map of its spatial distribution would help in choosing among land uses.

[28] The first objective for a biomass observing system (to determine the spatial distribution of biomass density over the earth) is applicable here, for it would define the initial (predisturbance) biomass densities of those ecosystems converted from one use to another (thus improving the accuracy of calculated emissions).

3.2. Changes in Carbon Density From Natural Disturbances and Recovery

[29] Over the years 2000–2006, when changes in land use and management were releasing an average of 1.5 PgC/a to the atmosphere, other terrestrial ecosystems are inferred to have been a global sink of 2.8 ± 0.7 PgC/a [*Canadell et al.*, 2007]. The value of this 'residual terrestrial sink' is determined by the difference between total emissions (fossil fuel + land use change) and the total 'known' sinks (atmosphere and oceans) (Table 2). The 'residual terrestrial sink' has never been measured; its location and the mechanisms responsible for it are uncertain [*Gurney et al.*, 2002; *Stephens et al.*, 2007]. If the source from land use change is overestimated, the residual sink will also be overestimated.

[30] The residual terrestrial sink presumably results from the two general processes not included in analyses of land use change; namely, changes in biomass density resulting from natural disturbances and recovery, and metabolic changes resulting from environmental change. Studies have estimated the local and regional effects of disturbance and recovery on carbon density [e.g., *Zeng et al.*, 2009], but a global analysis has not been attempted [see *Frolking et al.*, 2009]. It is unclear whether the sources and sinks from disturbance and recovery, globally, would be a source of carbon or a net sink at any time. Over the long term, the sources and sinks of carbon from disturbance and recovery should be in balance. Over years to a few centuries, however, the net flux may be either a source or sink for carbon. Fire frequency has increased recently in the western U.S., Alaska, and Canada, but in the preceding 150 years fires in the northern hemisphere seem to have been less frequent [*Marlon et al.*, 2008], suggesting that some portion of the current sink in northern midlatitudes might be a result of this change in disturbance regime. There are at least two ways in which a biomass satellite mission might help determine the sources and sinks of carbon from natural disturbances.

[31] First, a biomass mission would focus on identifying disturbances (whether anthropogenic or natural) (the second objective, below). A terrestrial ecosystem model would use (1) derived information on rates of disturbance (hectares/year from this objective) and (2) spatially explicit estimates of biomass density (from the first objective) to calculate sources and sinks of carbon attributable to natural disturbances.

[32] Second, the magnitude and distribution of changes in aboveground biomass density might be determined directly (the third objective, below). This objective focuses on the direct measurement of changes in aboveground biomass density, either increases from growth or decreases from deforestation or degradation. A terrestrial carbon model would not be required except to estimate changes in pools other than aboveground biomass; however, changes in aboveground biomass density could be used as an independent validation of terrestrial carbon models.

[33] The second objective of a biomass mission is to identify disturbance, both anthropogenic and natural. As explained above, previous studies have calculated the net flux of carbon attributable to changes in land use and management. This second objective would add natural disturbances to the calculation. For the biomass mapping/monitoring system proposed here, we do not require that direct anthropogenic effects be differentiated from natural disturbances. Rather, we include both in the general category of 'disturbance and recovery'.

[34] Identification of disturbance would enable us to define (within the limits of error) (1) the fraction of a region's surface that is disturbed over a 3- to 5-year interval [see *Frolking et al.*, 2009], and (2) the contribution of year-to-year variability in disturbance rates (e.g., fire) to the atmospheric growth rate of CO_2. At present it is unclear whether anomalies in metabolism (photosynthesis and respiration) or anomalies in disturbance rates (fires) drive the anomalies in CO_2 growth rates.

[35] This objective is to obtain the information needed to quantify the role of natural disturbances (and recovery) in the terrestrial flux of carbon. Including natural as well as anthropogenic disturbances in the calculations may or may not reduce the magnitude of the residual terrestrial sink, but it will help restrict it to metabolic mechanisms. An unambiguous distinction is unlikely because both metabolic and disturbance/recovery processes occur simultaneously. For example, climatic change (drier conditions) in high-latitude forests may reduce productivity (metabolism) and, at the same time, lead to changes in disturbance regimes [*Goetz et al.*, 2005, 2007]. Despite the difficulties in separating metabolic responses from disturbance and recovery, if we can identify natural disturbances as well as anthropogenic management, we will likely be able to put much greater constraints on the residual terrestrial sink.

[36] The third objective of a biomass mission is to determine changes in biomass directly with repeated measurement of aboveground biomass density. The sources and sinks of carbon from changes in land use, management, and

natural disturbances are calculated with a carbon tracking model. For this third objective the carbon tracking model is secondary. Direct measurement of changes in aboveground biomass density has the advantage over model-based analyses in that it does not require classification of forest area and does not require definitions of deforestation or degradation. Repeated measurements of biomass density at the same location will indicate reductions and accumulations of biomass density no matter how the cover is classified and no matter how deforestation or degradation are defined. Direct observation of change in carbon stocks eliminates the ambiguities and arbitrariness of definitions [*Houghton and Goetz*, 2008]. A carbon-tracking model would still be required to calculate changes in the stocks of dead biomass, wood products, and soil carbon, but it would not be required for calculating changes in aboveground carbon (biomass).

[37] 'Direct' measurement of change in aboveground biomass needs qualification. State of the art in-space lidars are samplers, not imagers, so measurement of biomass change at high spatial resolution based on direct observations of biomass change alone, will not be possible. Sampled changes will need to be combined with other imagers (e.g., radar, optical) to measure change contiguously over a landscape.

[38] This section describes the use of direct measurement of change in aboveground biomass density rather than a model to determine sources and sinks of carbon. The direct measurement of change in biomass density does not require classification of land cover (except as such classification helps improve the algorithms for biomass density measurement). Rather, the changes in biomass density will reveal both increases (from growth) and decreases (from disturbance or degradation), in either case providing a more accurate estimate of flux than one based on models of disturbance. Degradation has been documented in many case studies in the tropics, but its extent and effects globally are unknown. Estimates of carbon emissions from degradation vary regionally from 5% to 132% of the emissions from deforestation [*Flint and Richards*, 1994; *Gaston et al.*, 1998; *Houghton and Hackler*, 1999; *Achard et al.*, 2004]. Similarly, the rate at which carbon is accumulating (growth) in different regions of the globe is also poorly known. *Grainger* [2008], for example, has hypothesized that rates of tropical deforestation are matched by rates of tropical reforestation, such that forest area is unchanged. If so, one should be able to observe areas of growing forests.

[39] What fraction of the world's forests is measurably changing (i.e., being disturbed or recovering)? What proportion of a region's forests is either accumulating or losing biomass at a rate high enough to be 'observed'? We do not know because maps of biomass change are restricted to small areas. We do not know what fraction of the earth's surface is responsible for the major sources and sinks of carbon. For that part of earth's surface where growth is not observable, carbon models will still have to be used to calculate the changes in carbon stocks resulting from growth, perhaps documenting past disturbances with the 35-year Landsat archive [*Cohen et al.*, 2002; *Goward et al.*, 2008]. But we do not know whether that fraction is 90% or 10% of the earth's terrestrial ecosystems. This question is elaborated in more detail below.

3.3. Changes in Carbon Density From Environmentally Influenced Changes in Metabolism

[40] Physiological or metabolic processes include increased or decreased rates of growth that result from changes in the environment (for example, increased CO_2 concentrations, increased deposition of nitrogen, or changes in climate). Such changes have long been hypothesized to explain the 'residual terrestrial sink' [*Schimel et al.*, 1995], but there is no consensus as to the relative importance of them, either individually or collectively.

[41] Distinguishing 'recovery' processes (including land use change) from metabolic processes is important for predicting the permanence of the current terrestrial sink. Nevertheless, it is not a feasible objective of a biomass mission to observe the residual terrestrial sink. Some changes in biomass density will be too small to be observed, yet potentially occurring over very large areas. At best, the mission will determine what fraction of the world's woody lands is observed to be changing in biomass.

[42] Further, identifying disturbances directly, and determining the flux of carbon attributable to disturbance and recovery (the three objectives for the mission), will indirectly provide a more accurate estimate of the metabolic (or residual) effects. In the extreme case, past disturbances and land use change may account for the entire terrestrial sink. Past disturbances may have loaded the landscape with numerous secondary forests, where the accumulations of carbon in growth exceed the emissions from decay. In this extreme case, the residual terrestrial sink would be reduced to zero.

4. Requirements of a Biomass Observing System to Measure Aboveground Carbon Stocks and Changes

[43] In this section we define and rationalize the requirements for a biomass observing system, including spatial resolution and coverage, accuracy, and temporal resolution. The requirements are broadly similar to those indicated by the 'Decadal Survey' [*National Research Council* (*NRC*), 2007], but the three objectives outlined above do not always have the same requirements.

4.1. At What Spatial Resolution Do We Need to Know Biomass Density or Biomass Density Change?

[44] All three objectives call for a spatial resolution consistent with the scales of the factors underlying the variability in biomass density. Furthermore, data on vegetation structure must be obtained at the same scale or finer than the underlying heterogeneity that influences that structure. Changes in land use, natural disturbances, and the environmental variables that influence rates of growth and decay all operate at scales of 10–1000 m. There is no clear cutoff that defines the upper limit to resolution, but homogeneous forest stands are generally not larger than 1000 m (Figure 2). A recent paper by *Thomas et al.* [2009] and generalized simulations (G. C. Hurtt et al., Linking models and data on vegetation structure, submitted to *Journal of Geophysical Research*, 2009) show that to achieve the desired biomass and biomass change performance, the required resolution ranges from tens to hundreds of meters, depending on the resolution of the factors driving biomass

change and the resolution of the remotely sensed model input values. At coarser resolution, we lose the ability to accurately predict carbon dynamics due to averaging. This, in turn, implies that coarse resolution measurements of change will be difficult to attribute to underlying mechanisms. We might have a precise estimate of change in carbon stocks, but we risk losing the ability to know whether this change resulted from deforestation, degradation, disturbance, or a combination of these processes together with growth. We might determine the net changes but not the gross changes that are associated with mechanisms. If the primary interest is changes in carbon stocks, measurement at coarse scales is sufficient; for understanding and prediction, however, mechanisms are important.

[45] Changes in land use occur over a range of patch sizes, from tenths of a hectare in the densely populated landscapes of India, China, and Africa [*Ellis*, 2004; *Ellis et al.*, 2006; *Wu et al.*, 2008] to thousands of hectares in the agricultural lands in the American midwest and large cattle ranches of Brazil. Spatial resolution also varies for disturbances, including forestry activities. In Novosibirsk, Russia, where population density is relatively high, management occurs in smaller units than it does in Krasnayorsk-Yartsevsky, where human density is lower (Figure 2). Because biomass density varies at scales of tens of meters, and because humans do not choose lands randomly, it is important to measure biomass density at the same resolutions as changes in land use; i.e., <100–1000 m. Average values of biomass density for areas larger than 100 m run the risk that the forests actually harvested or converted to other uses are systematically different from that 'average'.

[46] Repeated measurements at the same location will indicate either (1) an increase in biomass density, (2) equilibrium, or (3) a decrease. For an increase or a decrease, we will know where and how much the biomass density (carbon) has changed (within error). For the area that appears not to have changed, the user might forfeit spatial resolution (and the capacity for attribution) for accuracy and look at a larger (aggregated) area (500–1000 m). However, changes may be as apparent at fine resolution (∼100 m) as at coarse resolution. For example, repeated coverage with airborne lidar in an old-growth tropical forest in Costa Rica over a 7-year interval revealed both increases and decreases in aboveground carbon stocks at 100m resolution. Similarly, losses and gains in aboveground biomass density with fire disturbance have been observed with lidar in boreal forests (S. J. Goetz et al., Synergistic use of spaceborne LiDAR and optical imagery for assessing forest disturbance: An Alaska case study, submitted to *Journal of Geophysical Research*, 2009).

[47] The different rates of change expected for different processes suggest a dual approach for defining spatial resolution. For the large, abrupt changes associated with deforestation (and subsequent recovery) a fine spatial resolution should be used, for greater accuracy in both area affected [*Zheng et al.*, 2008] and biomass change [*Strand et al.*, 2008]. The changes after deforestation and during the first part of recovery (∼30 years) include the largest (most rapid) changes in biomass density. On the other hand, tracking growth in older stands might best use coarser resolution data. Late in succession the changes are smaller (slower) and more likely to allow 1 km scales for observation.

4.2. Where Should We Measure Biomass Density?

[48] Biomass density is sufficiently variable within [*Brown et al.*, 1991; *Houghton et al.*, 2001] and between ecosystems [*Whittaker and Likens*, 1973; *Olson et al.*, 1983; *Brown et al.*, 1989; *Dixon et al.*, 1994] that if we were to cover only selected ecosystems, we would not obtain estimates of global biomass accurate enough to meet the objectives. Currently we have very poor a priori information on the global distribution of land use change, disturbance regimes, and thus age structure and recovery rates of forests in different regions of the world. To obtain such data for future inventories, the first inventory must include all woody land covers as well as those nonwoody lands with the potential for woody encroachment.

[49] The distribution of deforestation is patchy and (some of it) in small patches (<1 ha). On the other hand, deforestation and the harvest of wood have the potential to occur in essentially all forests. Because deforestation and logging are often clumped [*Tucker and Townshend*, 2000; *Asner et al.*, 2005] and their distribution is not well known, there is no a priori reason for restricting where one should look to obtain an accurate estimate of change. We do not have sufficient knowledge to identify strata of different rates of change, except, perhaps via "hot spot" detection [*Hansen et al.*, 2008]. We need wall-to-wall measurements because we cannot anticipate where change will occur.

[50] Furthermore, there is little a priori data to suggest where the residual terrestrial sink is, even broadly. *Gurney et al.* [2002] suggested it was largely in the northern midlatitudes, whereas *Stephens et al.* [2007] suggested it was largely in the tropics, offsetting emissions from deforestation. The magnitude of carbon sinks depend upon the frequencies and extent of disturbances, from tree falls to fires and massive disturbance events, whose location cannot be predicted in advance. Any system of monitoring other than complete coverage is likely to miss critical carbon sinks and sources [*Fisher et al.*, 2008].

[51] Spatially complete sampling also removes the need for assumptions about the spatial distribution of deforestation and captures explicitly (if acquired at <100 m spatial resolution) the heterogeneity of site factors that affect carbon dynamics, such as decay and growth rates.

4.3. How Accurately Do We Need to Measure Biomass Density?

[52] The global net flux of carbon from land use change (deforestation) has an uncertainty estimated to range from ±33% [*Canadell et al.*, 2007] to ±70% [*Denman et al.*, 2007]. By contrast, the next most uncertain term in the global carbon balance is the net uptake of carbon by the oceans, with an uncertainty of ±18% [*Canadell et al.*, 2007]. Thus, to be at least as good as the next most uncertain term, the estimate of global emissions from land use change requires an uncertainty of ±18%.

[53] The relationship between biomass density and carbon emissions is approximately 1:1 for a given deforestation rate. That is, an uncertainty of ±18% in mean regional biomass density yields an uncertainty ±18% in the estimated carbon source from deforestation. The average global flux from terrestrial ecosystems is roughly 2 Pg/a, and ±18% would be equivalent to an uncertainty of ±0.36 Pg/a. A measurement error no greater than 2 Mg/ha over 25 ha

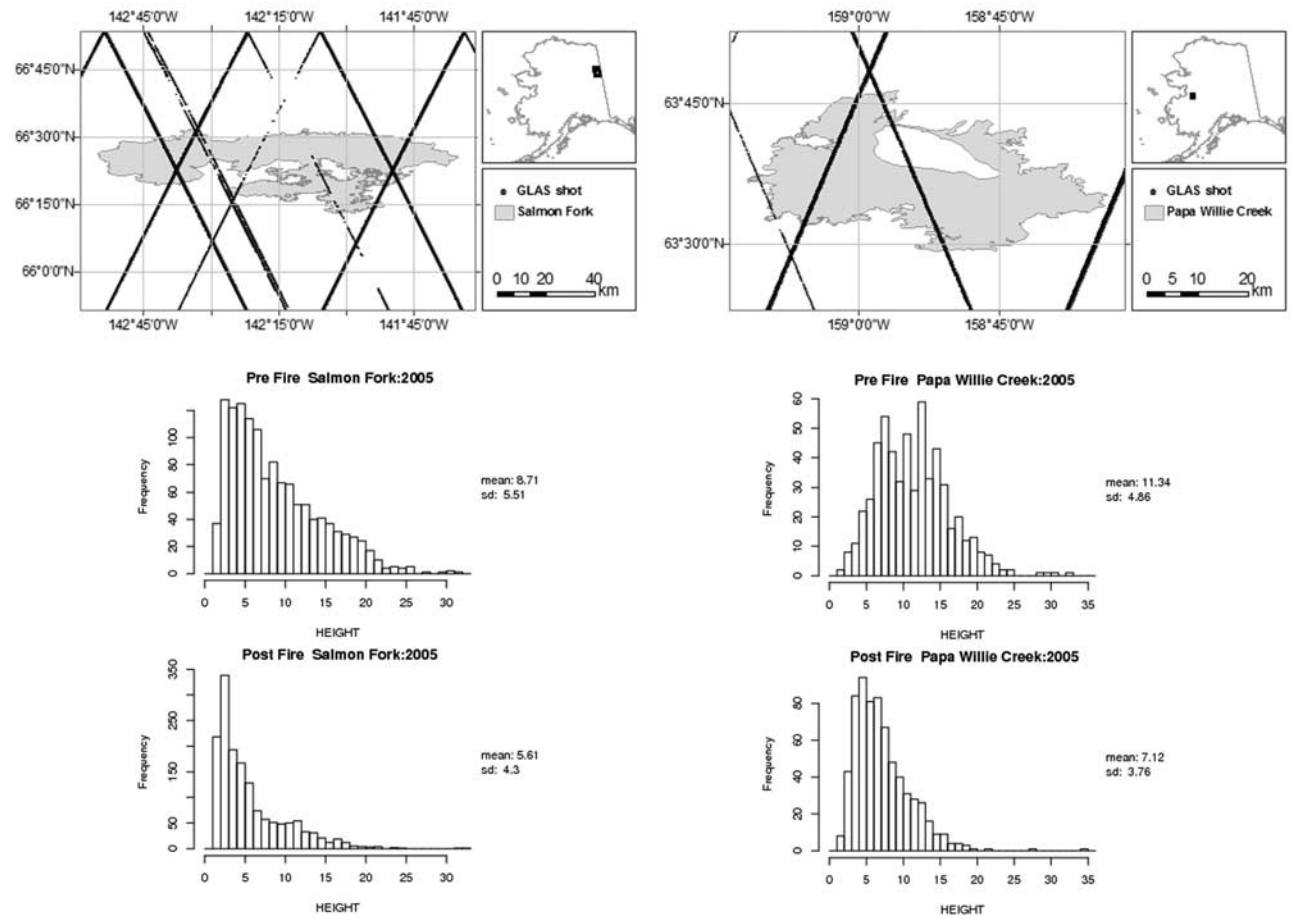

Figure 4. Frequency distribution of prefire and postfire canopy heights, as derived from ICESAT-GLAS, for two fires (Papa Willie and Salmon Fork) that took place in Alaska in 2005. See Goetz et al. (submitted manuscript, 2009) for details.

(including both noise and bias) would assure, in the worst case, that the bias in our global estimate for forests would be no worse than the 25 ha bias times the total global forested area (about 4 billion ha), or about ±0.32 Pg. This is a worst-case scenario. In reality, errors will be random and canceling to some degree across ecosystems, resulting in even smaller global errors. Forest inventories in the U.S. suggest that an accuracy of 2 MgC/ha/a would capture the growth of more than 90% of the counties in the eastern U.S. [*Brown and Schroeder*, 1999]. Such an accuracy would also probably require a spatial resolution of ∼25 ha.

[54] The accuracy for measuring increments of biomass density attributable to growth is higher than that required for measuring reductions in biomass density that follow disturbance because the reductions immediately following disturbance are generally large and rapid relative to the gains during recovery (see discussion of spatial resolution, above). For example, Figure 4 provides an example of changes in lidar canopy metrics following fire disturbance in a boreal forest. Again, there is a trade-off between accuracy and spatial resolution. To estimate the changes with deforestation to ±20% at a spatial resolution of 100–250 m, requires an accuracy of ±10 MgC/ha (±20 Mg biomass/ha, or 20%, whichever is lower). However, in forests with aboveground biomass density of 250 Mg/ha or more, a relative uncertainty of ±20% translates into an absolute uncertainty of ±50 Mg/ha or more, which is too high to enable accurate estimates of carbon flux. Thus, in high biomass forests the maximum error should not exceed ±50 MgC/ha.

[55] Clearly, changes will only be apparent where they exceed some yet-to-be-determined error, suggested here as 2–10 MgC/ha/a. But with each subsequent observation over 5 years, additional sites of deforestation, growth, and degradation within forests will appear. The fraction of a region's forests that show change is variable. We propose here that biomass data for deforestation and subsequent recovery be acquired a 1-ha resolution, but that data for observation of change in forests older than ∼30 years may allow coarser resolution observations. The relationship between spatial resolution and accuracy receives more attention below.

[56] It is worth noting that radar often "saturates" at ∼100 MgC/ha (200 Mg biomass/ha). As much as 65% of the old-growth terra firme forests in the Amazon are >100 MgC/ha, and ∼23% are greater than 150 MgC/ha [*Saatchi et al.*, 2007, Table 5]. For the Democratic Republic of Congo, *Baccini et al.* [2008] report that 44% of the forest area exceeded 100 tC/ha and 5% exceeded 150 tC/ha. It is important to note that at a resolution of 1 km no forests

exceeded 200 MgC/ha, but that individual field plots with as high as 235 MgC/ha were measured. Similarly, in Russia, there were no 0.25 km^2 cells with biomass density >150 MgC/ha [*Houghton et al.*, 2007], although individual forest stands have higher values. Overall, at a resolution of 1 ha, we might expect that 5–15% of the world's forests have a biomass density >150 MgC/ha (see also Figure 1).

[57] As noted above, a measurement error no greater than 2 Mg/ha over 25 ha is based on a worst-case scenario that assumes the terrestrial sink is evenly distributed. In fact, carbon is not accumulating uniformly across the world's forests. The net global source of ~1.5 PgC/a from land use change includes gross emissions 2–3 times higher from deforestation and sinks of nearly the same magnitude in lands recovering from harvests, shifting cultivation, fires, etc. [*Houghton*, 1999]. The spatial distribution of the residual terrestrial sink of ~2.8 PgC/a is unknown but probably not distributed evenly throughout the forests of the world. Around 1990, for example, data from forest inventories indicate that biomass was increasing in the temperate zone forests of the U.S., Europe, and China, while it was decreasing in the boreal forests of Canada and Russia [*Goodale et al.*, 2002]. Such spatial variations at coarse scale suggest that some forests are growing rapidly, while others are growing hardly at all. The question is: What fractions of the world's forests can be observed to be increasing (or decreasing) in biomass? The answer depends not only on the accuracy with which biomass density can be measured, but also on the fraction of the world's forests in different stages of growth. Anything we learn about the spatial distribution of increases and decreases in biomass (i.e., sinks and sources of carbon) will represent an advance. Even if, say, only 1% (or 5% or 50%) of the world's forests are growing (or declining in biomass density) fast enough for change to be observed over 3–5 years, that information represents a significant advancement to our current understanding of forest (and carbon) dynamics. Such information exists for some developed countries in the northern midlatitudes, and for selected subnational regions [e.g., *Sloan*, 2008; *Redo et al.*, 2009], but for most forests of the world, that information is lacking.

[58] In tropical countries where forest inventories are rare, there are, nevertheless, permanent plots where aboveground biomass density has been observed to change, increasing in some areas and decreasing in others [*Phillips et al.*, 1998; *Baker et al.*, 2004; *Clark*, 2004; *Feeley et al.*, 2007; *Chave et al.*, 2008]. And, as discussed above, more than 50% of the 1-ha cells in an old-growth forest in Costa Rica showed a measurable change in biomass density over 7 years. Where biomass density has been remeasured at high spatial resolution, changes seem to be the rule rather than the exception, even in stands >30 years age. The observation seems counter to the argument above that coarser spatial resolution might suffice to observe changes in biomass density.

4.4. How Often Do We Need to Measure Biomass?

[59] The temporal resolution required to determine aboveground biomass density varies among the three objectives. A high-resolution, wall-to-wall, global map of biomass density obtained once over the course of 5 years would satisfy the first objective of mapping the spatial distribution of terrestrial biomass density. For the third objective (observing changes in forest biomass) at least two observations over a 5-year period is a minimum requirement. Intervals of less than a year are generally too short for accurate measurement of growth. Intervals greater than a year will miss the opportunity to attribute year-to-year variations in atmospheric CO_2 growth rates to disturbances (second objective).

[60] As a part of the second objective (determine changes in biomass attributable to disturbances), an important requirement is to quantify the role of disturbance in the year-to-year variation in growth rate of atmospheric CO_2. This year-to-year variation is largely a terrestrial signal (rather than oceanic) [*Patra et al.*, 2005; *Baker et al.*, 2006] and thought to result largely from variations in the residual terrestrial sink (rather than the land use source) [*Houghton*, 2000]. However, if the biomass measurement system identifies annual disturbances with global coverage at 1-ha spatial resolution, we will be able to distinguish whether year-to-year variation in disturbances (e.g., fire) [e.g., *van der Werf et al.*, 2008], as opposed to year-to-year variation in photosynthesis or respiration rates, is responsible for variation in atmospheric growth rates of CO_2. The first objective, assigning values of (predisturbance) biomass density to the areas disturbed, will enable accurate calculation of the net emissions from disturbance.

5. Conclusions

[61] The terrestrial terms in the global carbon balance are less certain than the oceanic, atmospheric, and fossil fuel terms. The net emissions of carbon from land use change are uncertain because neither current rates of deforestation in the tropics nor the biomass density of tropical forests are well known. Data from existing satellites can be used to increase the accuracy of deforestation rates in terms of land area cleared [*Hansen et al.*, 2008], but existing satellites cannot increase the accuracy of biomass density estimates at the resolution required to assign biomass density to many of the areas disturbed. These uncertainties are not unique to the tropics. The calculated net flux of carbon from changes in land use outside the tropics is uncertain for most of the same reasons.

[62] The residual terrestrial carbon sink is even more poorly constrained, in part because of uncertainty surrounding the emissions from land use change. If a biomass observing system enabled determination of the global distribution of aboveground biomass density once, the uncertainties of the land use flux could be reduced to 20% or less. Further, with a wall-to-wall monitoring of disturbances, a similar modeling approach could be expanded to include natural as well as anthropogenic disturbances, leaving the residual terrestrial sink more constrained (perhaps eliminated). And with repeat observations, changes in biomass density could be observed independent of carbon-accounting models. The observed changes, whether positive (growth) or negative (disturbance and degradation), would add considerably to knowing the magnitude and geographic distribution of the major sources and sinks of terrestrial carbon.

[63] The requirements of a biomass mission are that it provide global coverage, at a resolution of 10s to 100s of

meters, with accuracies of 20% (or a maximum of ±20 Mg biomass/ha). Higher accuracies at coarser resolution will be required for forests with low rates of change. A mission of 3–5 years would be adequate, but a longer mission is preferable in that it would enable rates of change to be observed in more forests.

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S. J. Goetz and R. A. Houghton, Woods Hole Research Center, Falmouth, MA 02543, USA. (rhoughton@whrc.org)

F. Hall, NASA Goddard Space Flight Center, Greenbelt, MD 20771, USA.