

RFF REPORT

Forest Measurement and Monitoring

Technical Capacity and
“How Good Is Good Enough?”

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Preface

This report is part of a series of studies carried out under an initiative at Resources for the Future (RFF) to consider the economic, technical, and institutional issues associated with the goal of improving global forest measurement and monitoring. Companion studies under this initiative include an RFF discussion paper documenting uncertainties and discrepancies in existing forest measurement (Waggoner 2009) and another RFF report providing details on existing and near-term remote-sensing technology and its implications for improving measurement and monitoring (Fagan and DeFries 2009). The financial support of the Alfred P. Sloan Foundation is gratefully acknowledged for all studies under this initiative.

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Executive Summary

The international community lacks an understanding of the state and quality of the world’s forests that is commensurate with their economic and environmental importance. Measures of deforestation in tropical countries are often unreliable, and rates of reforestation and afforestation in temperate countries are usually overlooked. Methods for forest measurement are inconsistent across country borders and at times are wholly incompatible with each other. Advances in remote-sensing and satellite technology present a new opportunity to generate a worldwide forest “census” that can use more accurate, precise, and consistent measurements for forests across the globe. This report considers the quality of data sufficient for the various uses of forest measurements. The report also summarizes the advances in collection and reporting that are technically possible. Our investigation of how good is good enough is organized according to the four categories of forest measurements as established by the Forest Identity (Kauppi et al. 2006): forest area, timber volume, forest biomass, and carbon.

Users of forest area data, including researchers, conservation organizations, forest certification agencies, and national government assessors, have different requirements for data. Researchers, specifically modelers, focus on the supply of forest outputs derived from area measurements and give priority to consistent, regularly updated landscape data on net primary productivity or species and age classes available in grid cells of 30 square meters. Conservation organizations have similar data requirements but with more emphasis on remote-sensing data. Large-scale conservation plans by many of these organizations often require broad, coarse-scale, and consistent coverage. Small-scale, species-specific projects require finer-resolution data.

Like conservation organizations, forest certification agencies favor remote-sensing data, but they do not use it for their own assessments. Instead, they supervise accredited assessors who survey forests according to the protocol established by the agency. Remote-sensing data are a substitute for on-the-ground observations to a degree; better data may help decrease the costs of certification, which may increase the use of certification standards. Additionally, advanced national forest assessments, such as the USDA Forest Service’s Forest Inventory and Analysis, can harness remote sensing to generate very fine-scale resolution maps of targeted priority areas and coarser-resolution maps of less-critical areas. Assessments conducted by the U.N. Food and Agriculture Organization (FAO) consist mostly of self-reported data from countries and have, up to now, only included a limited role for remote sensing of area measurements. The FAO is including in its 2011 assessment a remote-sensing survey that will complement the national surveys currently collected but these data will primarily consist of already-existing Landsat data. Current technology allows for

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the construction of better estimates with newer remote-sensing data. Moderate-resolution mapping of forests can achieve up to 80 to 90 percent accuracy. Moreover, the use of radar and light detection and ranging (LIDAR) technology can exceed the accuracy of optical sensors. Improvements in coverage and data quality, however, will be somewhat expensive and will require an expansion of data processing capacities.

Timber volume, measured in cubic meters or board feet and also called growing stock, is of primary importance for the timber industry. Typically, volume data are obtained through on-the-ground measurement coupled with equations derived from regression models to estimate volumes for entire stands. New technologies like LIDAR are being incorporated into industry measurements and can help reduce the costs of direct ground-level studies. As a subset of the timber industry, forest certification agencies have similar uses for volume data, such as tracking long-term sustainable production. Easily accessible remote-sensing data may facilitate more forest certification in areas that are difficult to access. National forest assessments can also use volume data to survey the timber resources of a country. Industry experiences suggest that current data standards for measuring volume work well for timber management, but the data are probably not sufficient as a proxy for measuring carbon or other important attributes.

Biomass, the dry weight of the forest, is related to volume and varies substantially depending on tree species and other specific attributes of forests. Current biomass measures are used to estimate the fuel potential of energy production for biofuels and wood pellets, and measures are sufficient for these purposes. Scientific researchers use biomass to study its relationship to biodiversity. LIDAR technology can measure biomass more accurately than other techniques and can yield local estimates with greater than 80 percent accuracy, though typically at a coarse spatial resolution.

The accuracy of biomass measurements has major implications for forest carbon. Aboveground carbon is generally accepted to be 47–50 percent of aboveground biomass, though the actual value may vary somewhat. Carbon measures have become critically important to international climate negotiations because of the rising prominence of reducing emissions from deforestation and forest degradation (REDD). Major tropical forested countries like Brazil intend to use REDD practices to meet ambitious emissions goals, and developed countries like the United States view forest carbon offsets as a significant opportunity to help reduce the costs of domestic climate legislation. A major hurdle to incorporating forest carbon offsets into future carbon markets and REDD projects into international climate agreements, however, is ensuring veracity of measurement, monitoring, and verification. Problems like poor country-level and local-level data and leakage must be overcome for forest carbon to be an effective tool to combat climate change. Strengthened domestic and international institutions with a focus on measurement and monitoring will alleviate some problems and help determine the level of quality that is good enough for forest carbon. Levels already established in the voluntary carbon markets may set future forest carbon data quality norms.

In addition to the uses highlighted above, accurate maps of the world's forests have a role in informing society about forests as valuable natural resources. Satellite and remote-sensing technology combined with appropriate on-the-ground measurements form the backbone of an ideal data collection system, but this system is far from being a reality. Generating a world forest census will require some changes in funding, institutional coordination, and the priorities of the international community.

Introduction

Despite the economic and environmental significance of forests, we have only imprecise measurements of the physical variables that determine their valued attributes, whether for timber, carbon management, habitat, or other purposes. The global community lacks systematically collected and verified data with which to construct a reasonably good map of the world's forests or to document changes in forests. Deforestation of tropical forests is poorly measured, and even less attention is devoted to reforestation and forest preservation occurring in boreal and temperate forests (Waggoner 2009), making a shaky foundation of the measurement and monitoring of forest inventories, including forest carbon sequestration, in climate policy design (U.S. Government Accountability Office [GAO] 2008). The paucity of trades of forest carbon credits on the Chicago Climate Exchange and under the auspices of the Clean Development Mechanism is, in part, a result of poorly auditable measurement.

The imprecision in forest measurement is a consequence of including nonstandard reporting methodologies and a patchwork of substandard tools and techniques. Nations report forest inventory data but differ in the priority given to accurate assessment; they also vary widely in their capability to measure forests. Data are updated only every five years or so and even then are often extrapolated from past trends.

The enhanced use of global satellite measurement and monitoring capabilities holds promise as a means of significantly improving measurements by providing the basis for an accurate, periodic, and cost-effective global forest census. The use of satellite technology has some shortcomings and risk, but the unique advantages include the potential for improvement in temporal and spatial resolution;¹ standardization of measurement protocols; regular updating of global observations; and transparent, replicable methodology. Yet few forest inventories incorporate satellite-based measurement and doing so will come at some cost.

This report considers the question, how good is good enough? In other words, to what extent must forest measurement and monitoring be improved, and what is the state of the technology available now and in the next few years for enabling these improvements? Better data can improve the accuracy and precision² of the mapping, but the desired enhancements depend, of course, on the requirements of those who use the measures.

Part of the answer to “how good is good enough” requires estimates of willingness to pay for improved information about forests. After all, improved information comes at a cost, and how much additional cost is worth bearing? In this report, we do not estimate the value of improved information about forests for several reasons. The value of information is derived from the value of the associated goods or services. With the exception of the commercial forest products inventory,

¹ *Resolution* refers to the amount of detail in the data. Temporal resolution defines how frequently a given location is observed and its attributes (for example, land cover) recorded by a sensing device, such as a camera or other instrument on an Earth-orbiting satellite. Temporal resolution is directly related to how often the satellite passes over the same location on a daily, weekly, or monthly basis. Spatial resolution defines detail in the object or phenomenon being observed. Coarse spatial resolution typically means an area of about 1 kilometer by 1 kilometer or larger. Medium resolution is typically about 30 meters by 30 meters. High resolution can range from 5 meters by 5 meters to as small as 0.3 meters by 0.3 meters (approximately the very highest spatial resolution available outside of national security capabilities).

² *Precision* essentially refers to the reduction in the variability of estimates.

the services of forests are not typically exchanged in markets. Forests providing services such as watershed protection, species habitat, and natural beauty are “public goods” for which the challenges of valuation are well known. If markets eventually develop for the carbon sequestration of forests, as suggested in some climate policies reviewed below, then this market could serve as a basis from which to estimate the value of improved forest carbon measures. (Some estimates suggest that the value of this market could be quite large; see US Energy Information Administration 2009 and US Environmental Protection Agency 2009). Another confounding factor in considering “how good is good enough” is that data on forest attributes have historically been provided at low cost or without charge by government agencies. “Free” data have tended to be “good enough” for many uses. Yet discrepancies and uncertainties abound in these data (Waggoner, 2009), motivating our analysis in this paper.

We also ask a complementary question, drawing heavily from Fagan and DeFries (2009), about what improvements are technically possible. Our determination of how good is good enough is partly informed by ascertaining how much better we *can* be—that is, what improvements could be enabled by the enhanced use of existing and new technology? In some sense, better data are always preferable to poorer data, other things being equal. But other things are not always equal. In remote sensing, for example, coarse data covering a large area may provide more useful information than narrowly focused data covering just a small area.

Finally, we must consider the need for cooperation among countries to realize improved forest measurement and monitoring at the global scale, beyond individually reported country inventories. A forest is a nation’s sovereign resource. For this reason, if understanding of global forests is to improve, then worldwide cooperation and coordination in measuring forests are necessary. The imperfections in national forest inventories mean that we cannot simply “add up” these country-level data to give us a good picture of the world’s forests. The global reach of satellites is a technical advantage in this regard. Principles established in 1986 by the United Nations provide for remote sensing of Earth from space, but aerial remote sensing or on-the-ground field studies require the permission of the country or forest landowner. Even with the technical advantage enabled by satellites, however, questions remain as to who should pay for the satellites and the processing of their data and whether countries will agree to provide the complementary ground-based measures with which to calibrate satellite data.

We organize the remainder of our discussion around four attributes of forests—area, timber volume, forest biomass, and carbon (see Kauppi et al. 2006 for further description of these measures). We discuss each in turn along with a brief overview of the technological issues. As noted, our technology discussion draws extensively from a comprehensive survey of forest remote sensing by Fagan and DeFries (2009). We offer a few concluding thoughts in the final section.

Area

Forest area refers to the amount of land that is covered by forest. Even this seemingly straightforward definition is problematic, however, because different organizations have different definitions of *forest*. For example, the U.N. Food and Agriculture Organization (FAO), the only organization at present that routinely collects and compiles forest inventory data from countries, defines a forest as land with 10 percent tree crown cover. Yet not all countries use this definition in their inventory, and many of the inconsistencies in reported forest inventories are, in fact, the result

of differing definitions (Irland 2009; Waggoner 2009; Matthews and Grainger 2002). A common definition may be desirable for comparative purposes, but requirements of users of the measurements often vary and specialized definitions may sometimes be necessary.

Measures of forest area typically help answer questions such as the following.

- How much land area is covered by forest compared with nonforest?
- Within the forested area, how much land is covered by various forest subtypes?
- How does total forest area (or forest subtype area) change over time?

The simple distinction between forest and nonforest appears to be relatively straightforward, although it is sometimes complicated by differences in the desired level of accuracy and precision.³

At present, the responsibility for collecting information about global forest area rests with the FAO inventories, the Forest Resource Assessment (FRA). FAO compiles the FRA every five years or so largely from the individual country self-reported data. However, FAO is increasing its efforts to collect data using remote-sensing approaches. When data are missing, FAO typically relies on linear extrapolations from existing data and expert judgement. Many developing countries lack resources to maintain regular forest assessment programs, and a few countries, notably Canada and Russia, have assessment systems that are incompatible with those of other countries. This has led some experts to question the usefulness of FRA data (for example, see the perspectives of users of the FAO data summarized in Matthews and Grainger 2002). We examine the FAO FRA in more detail below.

Forest area data are used by several organizations and groups, and their requirements determine what is good enough. The accuracy that these groups require, as well as any improvements they would like in the future, is discussed below.

Groups Interested in Forest Area

Researchers

Forest area data are a starting point for scientists conducting research related to forests. Area data are used in land-use modeling and related research associated with agricultural and forest products, biofuels, water supply, and other land-based outputs. Additional topics of interest include the response of forests to climate change, the ecological impact of deforestation and forest fragmentation, and changes in forest dynamics over time.

Spatially explicit data on forest resources are one key to the successful development of economic models of land use. Historically, modelers have made use of datasets collected by individual countries (see Sedjo and Lyon 1990, Sohngen et al. 1999, and Sohngen et al. 2009 for descriptions of how country datasets have been applied to global forestry models) and data provided by the periodic FAO FRA. As noted earlier, most countries do not systematically collect data and report it in a format that is easily accessible to the global land-use modeling community. The USDA Forest Service Forest Inventory and Analysis (FIA) dataset is the most comprehensive and easily accessible dataset, given its Internet-based format, but this approach to data collection and assembly has not been widely reproduced in other regions.

³ *Accuracy* is how close a measured value is to the actual (true) value; *precision* is how close measured values are to each other.

Table 1 illustrates several models of forestry land use that have been developed to assess forestry markets and land-use changes. The models require a range of data, including the following.

- Forest area by ecosystem type
 - Measures of the quantity or proportion of forest in fixed land units (e.g., 0.5° grid cells, 30-meter grid cells) that are repeated over time (e.g., once per year, once every five years) using consistent measurement techniques (e.g., satellite measurements with groundtruthing).
 - Measures of the types of ecosystem present in the fixed land units. The more specific the information on ecosystem types, the better. Information on the specific forest types, such as deciduous versus evergreen or oak–hickory versus aspen–birch, would be useful. However, more detailed data on forest types and conditions for each land unit would provide more detail and could be more useful for many purposes. Modelers in general would benefit from more specific and detailed data, as they could then scale the data for their own purposes.
- Estimates of forest productivity
 - Purely ecological measures, such as net primary production, are a good first step, but more advanced measures of net ecosystem production or net biological production that would account for soil respiration losses and losses from disturbances would also be beneficial if collected in a repeated approach at a fixed spatial unit. (We discuss this attribute of forests below in our section on biomass).
- Forest stock
 - Information on the inventory volumes, species, and age classes of trees within fixed land units (e.g., 0.5° grid cells, 30-meter grid cells).
 - Information on the distribution of forest tree sizes or crown classes would be useful if age class information is not available.

These data types focus on the land-based measures that are used by modelers. In particular, these data are useful for understanding the supply of forest outputs. Supply depends critically on the area of land in forests (and in specific types of forests), the age class of those forests (e.g., the stock), and the annual growth of those forests. Maintaining a database with these pieces of information is one of the most important and difficult tasks of any modeling effort.

Efforts to put together globally consistent databases are underway but incomplete. For example, the Global Trade Analysis Project at Purdue University has compiled datasets on global land uses so that land use can be better modeled within the context of computable general equilibrium models. The forestry data in that dataset rely heavily on data from the Timber Supply Model/Global Timber Model database described in Table 1. Information on this effort, and the role of land-use modeling within the context of general equilibrium modeling can be found in a recently released book by Hertel et al. (2009b) What becomes clear in their analyses is the desirability for substantially improved data on forest stocks and productivity globally.

Table 1. Global Models of Timber Markets and Land Use

Model	What does the model do?	Data needs	Regional detail
GTM/TSM (Sedjo and Lyon 1989; Sohngen et al. 1999)	Dynamic optimization model used to project forest land use, timber harvests, and biomass stock for the globe	Forest area and age class Forest yield functions Forest inventory	Globe divided into around 250 ecosystem types, which are aggregated into 16 geographical regions
CINTRAFOR (Kallio et al. 1987; Perez-Garcia and Lippke 1992; Perez-Garcia et al. 2002)	Projects timber harvests for the globe	Forest yield and inventory (stock)	Globe divided into 43 log-producing regions and 33 log-consuming regions 400 bilateral trade flows monitored
IIASA/DIMA/ G4M/GLOBIOM (Gusti et al. 2008)	Projects global land use in forests and agriculture (including biofuel crops)	Land use, forest inventory (stock), and forest productivity (e.g., NPP)	Gridded spatial resolution, so includes all regions of the world
GFPM (Buongiorno et al. 2003)	<ul style="list-style-type: none"> Equilibrium model of market output, prices, and trade in timber products 	Forest area, harvest, inventory (stock) Forest prices and trade	180 countries
GTAP (Hertel 1997; Hertel et al. 2009b)	<ul style="list-style-type: none"> General equilibrium model of market output, prices, and trade in all products, including forestry and agricultural products 	Forest area, harvest, inventory (stock) Forest prices and trade data	>150 countries, but users can specify the level of aggregation
GTEM (Ahammad and Mi 2005; see also ABARE n.d.)	<ul style="list-style-type: none"> General equilibrium model of market output, prices, and trade in all products, including forestry and agricultural products 	Forest area, harvest, inventory (stock) Forest prices and trade data	User-specified, but could be more than 150 countries

Conservation Organizations

Conservation groups use forestry and land-use data, often from the vantage point of remote sensing, to move away from a view of conservation that emphasizes a narrow focus on individual locations to a broader, regional perspective (Wiens et al. 2009). Examples include improving understanding of the regional dynamics of various ecosystems and creating conservation plans to preserve important ecological processes at this scale. For instance, The Nature Conservancy (TNC) has used remote sensing to create an ecological protection plan for the Connecticut River watershed (Wiens et al. 2009). By mapping stands within the floodplain, TNC determined the areas that would be most ecologically effective to protect.

Conservation groups also use forest area measures from remote sensing to monitor the effectiveness of conservation strategies (Wiens et al. 2009). For example, these measures inform

the assessment of the conservation status of and effects of deforestation on rare and endangered bird species in the tropics (Buchanan et al. 2008). This application of remote sensing is seen as particularly important in many regions that may be otherwise very difficult to access.

Conservation groups make use of a wide array of data at a spatial resolution of about 15 to 30 meters, a level of detail that is consistent with the average quadrant sizes used by representatives of conservation groups working in the field (Wiens et al. 2009).

The quality of data that is “good enough” depends on the particular objective. For broad-scale projects, coarser resolutions are adequate. Very fine resolutions, such as 1 meter or better, might be necessary when dealing with a specific small-scale conservation goal like the protection of a very rare tree species. But fine-resolution data are presently more expensive than the coarser resolution available at low to no cost from U.S. government agencies, and conservation groups have limited budgets. An organization such as TNC would prefer broad, consistent coverage rather than very fine spatial resolution when creating a conservation plan (Wiens et al. 2009). For some applications, such as monitoring selective logging in the tropics, existing coarse-resolution data are adequate; in addition, new algorithms and other geospatial techniques have been developed to improve the analysis of the data (for example, to improve analysts’ ability to classify types of land cover; Asner et al. 2005).

Forest Certification Agencies

Forest certification agencies provide the general public with the means to support sustainable forestry practices. The major certification agencies—the Forest Stewardship Council (FSC), the Programme for the Endorsement of Forest Certification (PEFC), and the Sustainable Forestry Initiative (SFI)—all work in similar ways. Generally, a plot of forest land is certified according to a set of sustainability guidelines. After harvest, the wood must pass through a rigorous chain-of-custody certification process to ensure that certified wood is not mixed with uncertified wood between harvest and the point of sale. Demand for certified wood has been increasing over the past few years, partially because of environmentally aware niche markets and the LEED building certification program (FSC 2006).

Certification agencies use several criteria that require the measurement of forest area and that can be monitored using remotely sensed measures (FSC 1996; SFI 2008; World Wildlife Fund [WWF] 2006). The conservation of biodiversity is a requirement for forest certification, and although biodiversity cannot be measured directly and accurately from a satellite, the existence of representative samples of existing ecosystems protected from logging operations may be detectable. In addition, afforestation and reforestation of clear-cuts can be detected.

Forest certification agencies do not conduct assessments themselves, but rather oversee accredited groups that conduct the assessments. Prices for certification audits vary, with assessments of smaller forests costing much more per acre than those of larger ones. One study in North Carolina found that initial FSC certification would have cost \$30,439 for the 42,000 acres managed by the North Carolina Division of Forest Resources (DFR; \$0.72 per acre), \$23,378 for the 8,000-acre Duke forest (\$2.92 per acre), and \$24,594 for 4,500 acres of North Carolina State University (NCSU) forests. SFI total costs would have been \$0.54 per acre for the DFR lands, \$4.18 per acre for the Duke forests, and \$9.32 per acre for the NCSU forests (Cubbage et al. 2003). If remote sensing can be performed more quickly than in-the-field observations, it may reduce the

cost of certification. This approach might help small landowners because fewer on-the-ground assessments translate to cost savings from fewer trips and reduced transportation time.

Remotely sensed area measures might make certification easier and less expensive in tropical regions and other hard-to-reach locations, possibly encouraging more landowners to certify their land. It is unlikely that remote sensing could entirely eliminate on-the-ground assessments in the near future, but the data could make certification less expensive and assist in monitoring compliance.

Governmental Forest Assessments

Most countries have a forest assessment program to record national forest resources. In the United States, the U.S. government's forest assessment program is the FIA National Program administered by the USDA Forest Service. FIA tracks a number of forest parameters—how much forest is in the United States, where it is, whether any changes in forest area and forest health have occurred over time, as well as who owns forests and how they are being managed (USDA Forest Service 2007). Remote sensing is already a part of the FIA: the assessment protocol is divided into three phases, and remote sensing is used as part of Phase 1, for forest area estimates. Phases 2 and 3 are based on on-the-ground sample plots. The FIA originally used aerial photography as the method of remote sensing; now this is being replaced by satellites.

The Forest Service also creates maps of U.S. land and has recently updated its existing vegetation mapping and classification standards at four hierarchical levels, from the national level to the most detailed, or base, level. A base-level map is at a scale of 1:24,000 to 1:60,000 and is less than 50,000 acres in extent (Schwind et al. 2004). These new protocols create standards that are consistent across the country, with a goal of classifying all land and water surfaces (Tart et al. 2005). In creating the new standards, the Forest Service considered existing projects and programs that use remote sensing to help determine the feasibility of the standards. These other projects tended to use a mix of coarse- and fine-resolution satellite data and aerial photography (Warbington et al. 2002). At a test site adjacent to Yosemite National Park, the dominant tree type, as well as a number of other forest attributes, could be identified with an acceptable degree of accuracy (Schwind et al. 2004).

Ideally, the Forest Service would be able to conduct forest assessments at fine enough spatial resolution to create highly detailed and accurate base maps for all U.S. forested lands. Creating maps of forests at this level of spatial resolution would be very expensive at present costs of the required data relative to the agency's budget, and Forest Service representatives currently doubt that this would ever be possible (Warbington et al. 2002). However, the remote-sensing technology necessary to create such a map is within existing technological capabilities. Price-per-scene is the limiting factor. Until costs decline for obtaining highly detailed remote-sensing data, the Forest Service must create a list of priorities for those areas that need to be mapped with the highest-resolution sensors available and supplemented with ground sampling, and for those areas for which coarse maps would be sufficient.

As noted above, the FAO FRA is the most comprehensive international compendium of forest data, and many researchers use data from the FRA in their research (e.g., Kindermann et al. 2008). FAO acknowledges limits in the FRA as a firm foundation for other forestry research or conservation work. The FRA is composed of inventories that are self-reported by countries.

Developing countries often lack resources to conduct regular forest assessments. Some countries only report data for one point in time; in other cases, data are often old or incomplete. FAO relies on linear extrapolations from existing data and expert opinion. In tropical regions, FAO estimates forest change using a 10 percent sample of forest area from satellites. However, the statistical validity of this method has been questioned; a much larger sample may be necessary to obtain deforestation data within an appropriate range of accuracy (Tucker and Townshend 2000).

The FAO Support to National Forest Assessments (NFA) program helps developing countries that do not otherwise have adequate resources improve the quality of their data by implementing field assessments and organizing regional workshops to facilitate dialogue on particular forest issues. In addition, the NFA methodology ensures that all participating nations have compatible data (FAO 2009). As of June 2009, the NFA had been completed for 8 countries (Bangladesh, Cameroon, Costa Rica, Guatemala, Honduras, Lebanon, Philippines, Zambia) and was in progress for 14 more nations.

Until recently, remote sensing has had a limited role in the NFA program. Aerial photography and satellite imagery are used to generate land-use maps and vegetation classifications, but only for the countries for which recent images are already available. Aerial photography is currently too costly an undertaking even for small sample plots in many regions, and data from high-resolution satellite sensors are often unavailable for developing, tropical countries (Saket et al. 2002).

The FRA for 2010 includes a remote-sensing survey that will be complementary to national surveys. This survey is intended to address many of the problems with earlier surveys. The remote-sensing portion of FRA 2010 primarily makes use of already-available Landsat data, augmented by data from other sensors and from past field inventories (Ridder 2007).

Even some developed nations use methodologies for national forest assessments that are incompatible with those used by other countries in the FRA. Notably, Russia and Canada use different definitions for forest cover and forest change. The forests in these two nations are characterized as temperate and boreal forest. They include about 65 percent of all forests in developed countries and, as a result, their data have probably skewed the FRA data for developed countries as well as for boreal and temperate forests (Matthews and Grainger 2002).

How Good Is Good Enough?

Remote sensing of forest area, primarily using optical satellites, is more complex than simply mapping where forest exists and where it does not exist. Groups interested in forest area data seek accurate maps of forest and nonforest in very fragmented environments and maps of different types of forest as well as the ability to gather these data in areas that experience near-constant cloud cover. In Box 1 below, we summarize the current state of technical capability to measure forest area. It appears that current technology allows for the achievement of much better estimates of forest area than are currently available. One could also argue that the current estimates are not good enough for most uses to which they are put. The problem relates partly to the priority given to forest measurements by national governments. In addition, the instruments on satellites are not optimized for observing forests; rather, they are designed for many purposes, including observing land use more generally. A related problem is whether willingness to pay for instruments dedicated to forest measures is sufficient; high-resolution data could improve forest area measures, but at present, many users of forest area data indicate that the costs of these data are too large. These

problems lead to insufficient global coverage and differences in standards and definitions in forest measures.

Box 1. Measuring Forest Area

Measures of forest area have been based on data collected on the ground or from remote sensing carried out by aerial photography or satellite instruments. The data have usually been assembled on a one-off basis for an individual study of a particular geographic area or for a national inventory. As noted in the text, national inventories vary widely in their methodology and thus have been of limited use in assembling global forest area measurements.

The workhorse of all satellite-based measures has been the U.S. Landsat program, the first civilian satellite system to observe Earth. The U.S. Geological Survey manages the Landsat program. The Landsat program began in the early 1970s and remains the longest continuously operating satellite land remote-sensing system. FAO is assembling a sample of Landsat data from 1990 to 2000 to provide a set of baseline data as part of its next FRA. It is not clear what provision will be made to incorporate satellite data routinely into future FRAs.

Though researchers can and do use data from other satellites, protocols for using Landsat data to assess forest dynamics have been in place for a long time. There is a considerable body of research on interpreting Landsat data, as well as a large archive of historical data (Hall et al. 1991). These factors allow scientists to use well-understood and accepted protocols and to include historical data in their research. Landsat data have also been the least expensive data available. By U.S. law, the data have been available at prices set close to the cost of processing the data. In January 2008, standard Landsat data became available at no cost (fees are charged to process nonstandard data requests). At present, however, the availability of data in the future is in question. Whether the U.S. government will continue the Landsat program is unclear given federal budgetary limits (Behrens 2009).

Other remote-sensing data that are often used instead of or with Landsat data include data from SPOT, the Satellite Pour l'Observation de la Terre, operated by SPOT Image based in Toulouse, France, and Quickbird. All of these systems use optimal imaging devices to produce data that are akin to photographs. The spatial resolution of these systems ranges from 0.5 to 10 meters and the temporal resolution is 3 to 16 days.

In current maps, forest area is measured with medium accuracy of about 70 to 80 percent in discerning forested and nonforested land. Recent improvements in analytical techniques for distinguishing types of land cover and the combination of different types of satellite imagery (imagery *fusions*) have allowed moderate-resolution mapping of forest with 80 to 90 percent accuracy.

A global scheme reliant on the highest available optical resolution would have significant technical and economic challenges at present. Very high-resolution images are relatively more expensive than medium-resolution data, involve a large volume of data, and may have limited temporal resolution (Boyd and Danson 2005). In addition, optical sensors cannot obtain data on areas frequently covered by clouds or smoke. The ability to monitor changes also becomes difficult. Data acquisition is intermittent under the best circumstances and all but impossible for several months of the year (Asner 2001; Sano et al. 2007). Rainforests are often covered in clouds and are therefore difficult to sense.

Wall-to-wall coverage is relatively expensive, ranging from about \$250,000 for extremely coarse resolution (about 100 meters) to several hundred million dollars for high resolution (about 1 meter or

better; see Fagan and DeFries 2009). In addition, the use of high-resolution data requires substantial amounts of data processing capacity. For instance, wall-to-wall mapping of the globe at 1.65-meter spatial resolution requires nearly 600,000 images. An alternative is to use statistical models to analyze a random sampling of data, as FAO is now doing in its use of Landsat. However, statistical sampling may be inadequate when measuring deforestation (Sanchez-Azofeifa et al 1997; Tucker and Townshend 2000). In one study, a sampling rate of 80–90 percent was necessary to estimate deforestation within a range of 20 percent error 90 percent of the time, demonstrating that wall-to-wall coverage may be necessary to avoid excessive over- or underestimation (Tucker and Townshend 2000).

The most recent advances in forest area measurement are those from the use of radar and light detection and ranging (LIDAR). The accuracy of these data can be very high, rivaling or exceeding that of optical sensors. These data are more expensive to acquire and to process, but these challenges may be offset if the data are used in conjunction with optical data (Fagan and DeFries 2009). Radar and LIDAR are particularly useful for measures of forest volume. We discuss both techniques further below.

Volume

The volume of merchantable timber in a forest—growing stock, which we abbreviate as volume—is central to the timber industry. Multiplied by the density of cubic meters of growing stock per hectare, the two-dimensional area of a forest becomes its three-dimensional volume of timber. Measured internationally in cubic meters, timber volume is also measured in board feet. Although the concept suggests simply the volume of a one-foot length of a board one foot wide and one inch thick, which equals 0.00236 cubic meters, indeed the amount of board feet obtainable from a log depends on its diameter and thus varies with log dimensions as well as log volume. The log volumes and other characteristics, such as size and species, are used to estimate a timber price, and thus are related to company revenues. The most accurate method of measuring standing forest volume is to measure the diameter at breast height (1.4 meters) and the height of each tree. For a large stand of forest, sampling methods are used together with complex equations derived from regression models to estimate timber volumes (Schreuder et al. 1993). However, for very large heterogeneous forests, this method can be prohibitively expensive and time consuming.

Traditionally, the forest industry has had a major interest in forest volumes and forest volume data. The industry generally obtains these data through on-the-ground estimates using site sampling procedures. However, remote sensing using a new technique, LIDAR, is becoming increasingly common.⁴ Although the costs of LIDAR data are significant, so, too, are those of ground-based inventory techniques. Improved volume measures can also be used to estimate biomass weight and, in turn, levels of carbon sequestered in the forest. Changes in forest volume can be a good proxy for changes in forest carbon. Hence, volume may ultimately provide the most reliable estimates of deforestation and forest carbon changes (we return to a discussion of biomass and carbon below).

⁴ LIDAR uses scattered light to find the distance to an object.

Groups Interested in Forest Volume

Forest Products Industry

The forest products industry is interested in merchantable forest volume. An accurate estimate of the amount of wood available to sell—and thereby the potential value of the wood—allows landowners additional time for planning prior to harvest. The conventional method for determining forest volume involves assessing small plots and extrapolating values for the entire stand. Such assessments can be expensive. The Forest Inventory Group, a commercial company that provides landowners with timber inventory information, estimates that a conventional cruise to determine approximate timber volume would require five person-days of work and would cost \$1,946.00 per 100-acre polygon (Forest Inventory Group 2009). Using data from satellites that have been calibrated by smaller, on-the-ground, studies is much more cost-effective because much of it can be automated.

Temporal resolution is also a factor in the forest products industry if landowners need to measure the volume of their forests at a certain point in the growing season, assess damage after a major storm or other disturbance, or monitor changes in volume over time.

Sustainable Forestry Certification Agencies

Because sustainable forestry certification is largely a subset of the timber industry, the requirements of both groups are similar for the remote sensing of forest volume. At the same time, a purpose of sustainable forestry certification groups, such as FSC, SFI, and PEFC, is the conservation and long-term health of forest ecosystems. Certification agencies require monitoring of forest yield and growth rates to ensure sustainable productivity in the long term (FSC 1996; WWF 2006; SFI 2008).

As with the remote sensing of forest area, the remote sensing of forest volume would be particularly useful to the independent contractors that perform the forest assessments in tropical regions for organizations such as FSC. Because these regions are difficult to access, making these data more easily available (and more affordable) would facilitate forest certification in these regions.

National Governments

In addition to forest area, forest volume is of interest to national governments in their assessment of forest resources. In fact, the original purpose of the USDA Forest Service FIA beginning in the 1930s was to survey the timber resources of U.S. forests; the emphasis on long-term forest health, biodiversity, and sustainability is a much more recent development (USDA Forest Service 2005). FIA currently measures forest attributes by remote sensing, with levels of accuracy comparable to collecting data on the ground (USDA Forest Service 2007).

Currently, estimates of timber volume are part of Phase 2 of the FIA protocol, which takes place on the ground (USDA Forest Service 2007). If the Forest Service incorporated LIDAR or other technologies into the FIA to shift forest volume to Phase 1, the remote-sensing portion, the time it would take to conduct assessments could feasibly be shortened.

How Good Is Good Enough?

Estimates of forest volume using existing satellite technology receive a mixed assessment. In Box 2, below, we summarize the technology available for measuring forest volume and include a discussion of recently available LIDAR instruments (at present, carried on airplanes rather than satellites). Existing data appear adequate for estimating timber volumes of relatively homogeneous forest types for industrial wood management. Indeed, the forest industry has functioned successfully for decades with only on-the-ground measurement approaches. Although LIDAR technology is new and, at present, expensive, these data offer improved volume estimates today as well as the opportunity for lower costs eventually. Most firms have yet to use LIDAR, however, suggesting that traditional methodologies are good enough for most purposes now.

For more generally improving the measurement and mapping of global forests in three dimensions, current data are not good enough, although the further development of LIDAR gives promise of the capability of three-dimensional global mapping in the next decade. For the purposes of estimating carbon using information about volumes, the data are not yet good enough (we provide more discussion of this below).

Box 2. Measuring Forest Volume

Remote sensing can be used to obtain estimates for forest structure, both vertical and horizontal, and these estimates can, in turn, be used to estimate forest volume. Optical high-resolution data have provided 40 to 90 percent accuracy, with the lowest bound largely a result of closed mixed-species forests with tree canopy overlap (Fagan and DeFries 2009). Radar instruments, including synthetic aperture radar (SAR) and interferometric SAR (inSAR) tend toward greater accuracy of 50 to 95 percent, but only in low-biomass forests. The radar may fail to penetrate dense forests (see Fagan and DeFries [2009] for additional discussion).

LIDAR is a promising technology for accurate estimates of forest volume. LIDAR scanners are currently mounted on airplanes and measure the returning radiation from laser pulses. Unlike space-based optical sensors, LIDAR provides three-dimensional data. A LIDAR system can penetrate the tree canopy and obtain information on canopy height as well as the topography of the underlying terrain. LIDAR estimates of area range from 45 to 97 percent accuracy, with greater than 80 percent accuracy common (Fagan and DeFries 2009).

At present, radar is only a small part of the satellite fleet, and the first satellite-based LIDAR is not scheduled to be launched until 2015 or later. In addition to their limited availability, both radar and LIDAR are significantly more expensive data to acquire and process compared with optical data such as those from Landsat. Airborne LIDAR also requires permission for the right to fly over a country's airspace.

Biomass

Biomass refers to the dry weight of the forest. Although biomass is related to forest volume, the relation varies substantially, depending not only on tree species, but also on the peculiarities of the individual forest, such as elevation or provenance. The measurement of forest biomass can be used to estimate the carbon content of forests. Dry woody biomass is consistently about 50 percent

carbon, so estimates of forest carbon content can be obtained by multiplying the dry weight of a forest by 0.5 (Smith et al. 2003). Information on global forest biomass is of great interest in relation to global climate change. Estimates of how much carbon forests absorb are necessary for understanding the global carbon cycle, as well as providing necessary information for climate management policy involving carbon credits or offsets.

Forest volume-to-biomass models in the United States tend to use FIA data for information on forest volume. However, these models measure only the aboveground biomass of growing stock volume (i.e., Cost et al. 1990). To address the inadequacies of previous models, Smith and colleagues (2003) have developed a more comprehensive model for calculating forest biomass from FIA data. This model incorporates the biomass of standing dead trees, includes equations for whole trees (including root systems) as well as aboveground biomass, and accounts for differences in species composition of U.S. forests. An advantage of the approach used by Smith and colleagues (2003) is that their equations for an area at the scale of an FIA test plot can be expanded to cover much larger scales with only minimal error. Further research is needed to avoid over- or underestimation of dead trees, as well as to further refine equations based on forest structure and composition. In addition, more detailed global forest assessments, particularly biomass measurements, would allow researchers to calculate an estimate for global forest biomass content. This would also be a step toward creating an accurate, international carbon budget.

Industry

Biomass estimates are common in the pulp and paper industry and also in the biofuels industry, as when estimating biomass fuel potential for energy production, including electricity, biofuels, and wood pellets. At present, estimates of biomass are adequate for managing pulp and paper industrial wood requirements as well as most biomass and biofuel requirements.

Groups Interested in Forest Biomass

Researchers

Researchers are interested in forest biomass for a number of reasons, including the relationship between biomass and biodiversity (e.g., Liira and Zobel 2000). As noted above, researchers interested in measurements of forest biomass include groups that do work related to global climate change. Related research includes the impact of a carbon dioxide (CO₂)-enriched atmosphere on forest structure (e.g., DeLucia et al. 1999) and carbon flux models of forests (e.g., Dixon et al. 1994).

Many biomass studies rely on on-the-ground field sampling to measure biomass. Using remote-sensing technology, such as LIDAR, or even estimates for biomass derived from national forestry assessments, could allow biomass-related research to occur at a much larger scale than it does currently.

How Good Is Good Enough?

The data for forest biomass depend importantly on the ability to measure forest volumes and conversion factors to obtain biomass estimates from the volume measures. The operation of the pulp and biofuel industries suggests that the estimates of biomass are at present adequate for most industrial wood purposes. For other uses of biomass, particularly to assess global carbon stocks,

existing measures are not good enough. Box 3 provides a summary of technical ability to measure biomass.

Box 3. Measuring Forest Biomass

Remote sensing cannot directly measure wood density, but correlative forest inventory data can use species-specific or region-specific allometric equations to estimate the aboveground biomass of forests based on estimates of forest canopy width, structure, and/or height. Accordingly, improvements in these measures in the future can improve estimates of biomass. LIDAR has the potential to improve biomass estimates because of its ability to measure both forest canopy height and ground elevation (radar cannot measure both of these dimensions). In some cases, LIDAR has enabled estimates of local area forest biomass with accuracy greater than 80 percent. The direct measurement of forest canopy from LIDAR is a promising approach for estimating forest biomass for small geographic locations but is currently limited by the expense of data and data processing, as noted above. Another limitation is the narrow swath of airborne LIDAR sensors. This coverage limitation can be eased by integrating LIDAR data with other datasets that have greater-swath widths

Plans for future satellite systems include LIDAR but will trade off the advantages of LIDAR with coarse spatial resolution simply because of technology limits. Again, fusing or integrating data from different instruments is an approach with the potential to accommodate limits across all of the various technologies. Japan's Advanced Land Observing Satellite uses a related but different type of instrument, PULSAR, which is radar operating in a new region of the electromagnetic spectrum (the "p-band"). These data have offered possible new information about volume and biomass.

Carbon

The role of forests in the global carbon cycle has become a focus of increasing attention among both scientists and policymakers as these groups address actions to respond to a changing climate. Carbon dioxide is taken in by trees and other plants during respiration, and some of the carbon is sequestered in plant tissue and the surrounding soil. When trees are removed or killed, they release CO₂ through the decay or combustion of their tissues.⁵ Carbon sequestered in forest soil is similarly released through decomposition or fire.⁶ Terrestrial carbon sequestration projects, also called offsets to reflect their role in counterbalancing greenhouse gas (GHG) emissions, are dependent on these natural processes. The role of the world's forests in reducing global GHG emissions can be substantial. An estimated 7 to 30 percent of anthropogenic CO₂ emissions are attributable to deforestation and forest degradation (Denman et al. 2007; Houghton and Goetz 2008).

The amount of carbon in forests is not measured directly (see Box 4). Instead, estimates of forest carbon are derived from biomass measurements, which are, in turn, often derived from area

⁵ Significant carbon pools exist in aboveground biomass (trees, plants, and so on), belowground biomass (roots), soil organic matter, dead wood (fallen trees), and litter (leaves, branches, and so on). All of these pools must be accounted for to generate a realistic assessment of current carbon stocks and carbon sequestration potential. Aboveground carbon stocks are estimated to represent, on average, less than half of the total carbon in forests (although this varies greatly among forests; see Fagan and DeFries 2009).

⁶ Our discussion above focuses on carbon stocks. Measurement of carbon fluxes is also needed to accurately estimate carbon emissions from forests. Remote sensing can help to improve estimates of fluxes by measuring carbon gas uptake and release, vegetation productivity, and the extent and frequency of forest fires (Fagan and DeFries 2009 and references therein).

and volume measures. The default value of aboveground carbon in forests is generally accepted to be 47–50 percent of aboveground dry biomass value, though depending on the part of the tree and the forest climate, carbon values vary between 43 and 55 percent (Brown 2002; Fagan and DeFries 2009; Intergovernmental Panel on Climate Change [IPCC] 2006).

Uses of Estimates of Forest Carbon

Forest carbon estimates are of scientific importance to improve understanding of the quantitative role of forest carbon sequestration in Earth's climate system. Forest carbon estimates are also of intense interest to policymakers in shaping climate policy. For example, reducing emissions from deforestation and degradation (REDD) was a prominent section of the Bali Road Map established in 2007 and continues as a leading topic in international climate negotiations. The central government of Brazil, which has led major developments in REDD approaches and their institutional governance, announced in November 2009 that the country will reduce its GHG emissions by 2020 by roughly 40 percent, with half of the reductions obtained from efforts to reduce deforestation. In August 2009, Australia and Indonesia announced a joint agreement to develop REDD and forest offset projects. Australia also intends to improve capacity for deforestation monitoring in Southeast Asia by constructing a satellite receiving station near Darwin. These actions and others will probably serve as talking points at the Conference of the Parties negotiations in Copenhagen in December 2009.

REDD and forest carbon offsets have played a major role in U.S. congressional proposals. As of fall 2009, legislation approved by the U.S. House of Representatives (H.R. 2454) and a bill under consideration by the U.S. Senate (S. 1733) included provisions illustrating some of the issues with which legislators are wrestling.⁷ Both proposals establish a GHG emissions cap and trading regime as the primary means of controlling emissions. The proposals also call for domestic and international carbon markets with a cumulative cap of 2 billion offset credits, many of which are expected to come from forestry projects. Additionally, the bills allocate allowance value from the cap-and-trade system to reduce 6 billion cumulative tons of CO₂ emissions from deforestation and degradation in developing countries by 2025. Estimates of the economic significance of forest offsets in meeting the stabilization of atmospheric concentrations of GHGs targeted in the bills show the financial importance of forests. In analyses of H.R. 2454, the Energy Information Administration and the Congressional Budget Office (CBO) estimate that, by including forest offsets, the cost to the U.S. economy of meeting stabilization goals can be reduced by half or, in some scenarios, slightly more than half.

Although the proposals rely heavily on offsets, many analysts in the federal government remain skeptical of the veracity of forestry carbon as a source of offsets. The Congressional Research Service has identified integrity and credibility as the primary concerns related to forestry offsets (Gorte and Ramseur 2008). In a report requested by Republican members of the House of Representatives, GAO found that the voluntary carbon market lacks a consistent verification and measurement metric and suggested that the government may want to implement standardized

⁷ H.R. 2454 is titled the American Clean Energy and Security Act. It was introduced by Reps. Henry Waxman (D-CA) and Edward Markey (D-MA) and passed by the U.S. House of Representatives June 26, 2009. S. 1733, titled the Clean Energy Jobs and American Power Act, was introduced by Sens. John Kerry (D-MA) and Barbara Boxer (D-CA) September 30, 2009.

procedures to account for offset uncertainty (GAO 2008). The legislative proposals recognize that some level of uncertainty is involved with forestry and other types of offsets; after 2018, international offsets are discounted by 20 percent, meaning that 1.25 international offsets must be purchased to get 1 credit in the offset market. CBO advocates such an approach as a way to improve offset credibility (CBO 2009). Moreover, the legislation requires scientific reviews of offset protocols every five years and third-party verification for all projects.

The legislation does not address the level of accuracy in measurement and monitoring necessary to ensure that forest offsets are achieving their advertised carbon sequestration levels. Instead, the bill delegates responsibility for determining specific measurement protocols and uncertainty levels to the U.S. Environmental Protection Agency (EPA) and the U.S. Department of Agriculture (USDA).

The Problem of Leakage

One of the most significant risks that could prevent the forest carbon markets from functioning effectively to offset GHG emissions is the problem of *leakage*, which occurs where efforts to decrease deforestation in one area drive deforestation to another area. Forecasts of how much forested area may be protected may be incorrect if it is assumed that no leakage occurs. Murray et al. (2004) estimate leakage at 10 to 90 percent for various activities in the United States. Without adequate monitoring and enforcement of forest management agreements in all countries, the leakage potential could be quite high.

Forest Carbon Standards: How Good Is Good Enough Now?

Different stakeholders will not require the same types and quality of forest carbon data. For instance, the information related to the accuracy and uncertainty of measures required by an investor may not necessarily be the requirements of a government regulator or a forest scientist. To date, however, information requirements of users of forest carbon data have not been well documented. Current literature on the uncertainty of emissions factors is limited (IPCC 2006). Standards for uncertainty in forest carbon measurement standards set by private and government-sponsored voluntary protocols are somewhat heterogeneous, though they coalesce around ± 10 percent of the mean of likely CO₂ sequestration totals with a 90–95 percent confidence level. As many organizations in the voluntary carbon market seem to have informally agreed on this level of accuracy, it may be considered the current standard for good enough. Scientific assessments and inventories, such as the IPCC Agriculture, Forestry and Other Land Use (AFOLU) standards, include estimates of the uncertainty of their data but do not set goals or standards for obtaining a specific level of uncertainty.

Finally, GAO (2008, 37) warns “several factors contribute to challenges in understanding the market. First, although most markets involve tangible goods or services, the carbon market involves a product that represents the absence of something—in this case, an offset equals the absence of one ton of carbon dioxide emissions. Second, ensuring the credibility of carbon offsets poses challenges because of the inherent uncertainty in measuring emissions reductions or sequestration relative to a projected business-as-usual scenario. Any measurement involving projections is inherently uncertain.” Additionally, “many transactions do not involve a central trading platform, exchange, or registry system. These factors limit the market’s transparency and pose challenges for market participants, especially consumers.”

Table 2 summarizes a number of selected standards set by voluntary GHG offset protocols, programs, and scientific inventories.

Good Enough with Better Data

As forest offsets grow in prominence, either through their continued role in voluntary offset markets, or through their inclusion in carbon markets established by domestic legislation and international climate agreements, the need for consistent and transparent data standards will grow as well. Currently, no regulatory body has the authority to set uncertainty levels for forest offsets in the United States. These problems may be assigned to some future market oversight regime. For example, provisions in congressional proposals establish the Offset Integrity Advisory Board within EPA and give it authority to “make available to the Administrator its advice and comments on... methodologies to address the issues of additionality, activity baselines, *quantification methods*, leakage, *uncertainty*, permanence, and environmental integrity” of international offsets (emphasis added). H.R. 2454 gives similar authority for domestic offsets to USDA.

These agencies will probably receive some pressure from investors to make standards reasonably achievable at a low cost. Many voluntary protocols, including the Chicago Climate Exchange, currently require this level of precision. The standards of any of several existing voluntary approaches could provide a starting point for consideration as these approaches are already somewhat established and investors have experience using them. For instance, an initial level of good enough for carbon in a forest could be established as ± 10 percent of the estimated mean for that forest type at a 90 or 95 percent confidence level.

Eventually, policymakers would need provisions to establish “good enough” levels of accuracy for carbon in U.S. policy. These levels will not only determine what quality of offsets will be allowed in U.S. carbon markets, they will also influence the formation of standards for REDD established by the U.N. Framework Convention on Climate Change (UNFCCC). When federal government agencies and the UNFCCC set accuracy and uncertainty standards, they will do so based on the methods and quality of data available at the time, balancing market information demands and flexibility with scientifically sound methodologies. Reliable, high-quality forest data on a global scale will be a linchpin in shaping how good is good enough for carbon in the future.

Table 2. Standards for Accuracy and Precision of Forest Carbon Data

Source	Standard type	Users	Level of accuracy/precision (metrics are source-specific)
Climate Action Reserve – Forest Project Protocol (p. 85) http://www.climateactionreserve.org/how-it-works/protocols/adopted-protocols/forest/current-forest-project-protocol	Voluntary GHG offset reporting protocol	Offset suppliers, offset purchasers	For projects: up to 5% sampling error with 90% confidence level, no confidence deduction needed. Between 5 and 20% sampling error with 90% confidence level, amount over 5.1% confidence deduction required. At 20% sampling error with 90% confidence level, 100% risk contribution required.
Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2007: Land Use, Land Use Change, and Forestry (pp. 7–19) http://www.epa.gov/climatechange/emissions/downloads09/LULUCF.pdf	Government data collection project	Policymakers, scientists	In 2007, 910.1 Tg CO ₂ equivalent fluxed from forest lands in the United States with an uncertainty range of ± 19%.
Chicago Climate Exchange Project Guidelines: Forestry (p. 31) http://www.chicagoclimatex.com/docs/offsets/CCX_Forestry_Sequestration_Protocol_Final.pdf	Voluntary GHG offset reporting protocol	Offset suppliers, offset purchasers	Accurate inventory data is ± 10% of the mean estimated CO ₂ sequestration at 90% confidence level.
General and Technical Guidelines for the Voluntary GHG Reporting (1605(b)): Forestry Appendix (p. 3) http://www.usda.gov/oce/global_change/Forestryappendix.pdf	Government-sponsored voluntary GHG offset reporting protocol	Policymakers, scientists, offset suppliers, offset purchasers	Best accuracy: ±10% of true value of forest carbon. Adequate accuracy: ±20% of true value of forest carbon. Marginal accuracy: ±30% of true value of forest carbon. Inadequate accuracy: higher than ± 30% of true value.
GOFC–GOLD Sourcebook (pp. 75, 102) http://www.gofc-gold.uni-jena.de/redd/sourcebook/Sourcebook_Version_July_2009_cop14-2.pdf	Ad hoc REDD working group methodological descriptions	Policymakers, scientists, offset suppliers, offset purchasers	Research data: uncertainty level of 20% or less (95% confidence equal to 20% of the mean or less). Conservativeness: to avoid overestimation of emissions reduction, measurements are multiplied by a category-specific conservativeness factor.
IPCC National GHG Inventory for AFOLU (pp. 4–19) http://www.ipcc-nggip.iges.or.jp/public/2006gl/index.html	Reporting standards for national GHG inventories	Policymakers, scientists, offset suppliers, offset purchasers.	Uncertainty estimates (percentage of mean) for forest carbon factors: wood density, 10–40%; natural losses for industrialized countries, 15%; industrialized country growing stock, nonindustrialized growing stock, 30%; annual increment in managed forests (industrialized countries), 6%; wood removals for industrialized countries, 20%.
American Carbon Registry Forest Carbon Project Standard (p. 26) http://www.americancarbonregistry.org/carbon-accounting/ACR%20Forest%20Carbon%20Project%20Standard%20v1%20March%202009%20FINAL.pdf	Voluntary GHG offset reporting protocol	Offset suppliers, offset purchasers	± 10% mean estimated CO ₂ sequestration at 90% confidence level.
EPA Climate Leaders Reforestation/Afforestation Methodology (p. 12) http://www.epa.gov/climateleaders/resources/optional-module.html	Government-sponsored voluntary GHG offset reporting protocol	Policymakers, scientists, offset suppliers, offset purchasers	± 10% precision of estimated CO ₂ sequestration at 95% confidence level.

Box 4. Measuring Forest Carbon

Forest carbon cannot be measured directly from remote sensing but is derived from allometric relationships in combination with on-the-ground sampling. The allometric equations are based on harvesting, drying, and weighing trees in forest plots and can be site- and species-specific if enough sampling is done (Fagan and DeFries 2009 and references therein). Individual carbon sequestration projects can sometimes use remote-sensing data that have already been generated by large-scale studies, but the resolution of the data is often too low to apply to small-scale projects.

Third-party verification adds an important layer of confirmation that can further establish the credibility of forest offsets. The use of independent verifiers has not yet fully saturated voluntary carbon activities, however. In one survey, only one-third of carbon retailers indicated that they verified their offsets with a third party, whereas other vendors provided no verification information (GAO 2008). Third-party verification is particularly important for investors because they will want an idea of the risk that offset projects may not be able to deliver their promised carbon benefits and some understanding of the uncertainty of the actual sequestration potential of forest offsets.

Because the uncertainty of final forest carbon measures is an aggregate of the uncertainties of each component of the measures, it is critically important that inputs be accurate and precise. For a far more complete discussion of current monitoring and satellite technologies, see Fagan and DeFries (2009).

Although improved technology is a more long-term solution to more accurate and precise carbon measures, it is not the only way to reduce uncertainty. *Conservativeness* offers another, less technical option for reducing uncertainty in measures. Within the context of forest carbon, conservativeness means that when the completeness or accuracy of measures cannot be established, the risk of overestimating emissions reductions should be reduced as much as possible. Typically, this consists of multiplying a carbon measure by a conservativeness factor determined by a third-party expert of reporting the lowest end of the error bars for the whole measure. For example, reporting the lower bound of the 50 percent confidence interval (CI) of a carbon measure will result in a 25 percent chance of overestimating the amount of CO₂ sequestration in a forest. Reporting the lower bound of the 95 percent CI, however, will result in a 2.5 percent chance of overestimation (Global Observation of Forest and Land Cover Dynamics [GOFC-GOLD] 2008). Conservativeness may be useful and desirable when accuracy is incomplete or not well-known, but it is a temporary and imperfect substitute for accurate and precise data.

Conclusions

We have discussed improved measures and monitoring of forest area, volume, biomass, and carbon. We have largely focused on the requirements and preferences of groups such as industry, researchers, forest certifiers, and policymakers for better data, but we also emphasize the fundamental usefulness of simply having an accurate map of global forests and how they change over time to inform public understanding of forests as a valued natural resource.

In a perfect world, the needs of all interested parties could be met with frequently updated wall-to-wall coverage with satellite data at various spatial, temporal, and spectral resolutions and appropriate ground-truthing. Such a system, if possible, is a long way off—it would require new

satellites, funding from government and other agencies, or financing from forest carbon offset markets, as well as coordination between agencies responsible for existing satellites. Some of the newest and most capable satellites are privately owned and operated. Using these satellite data in a global forest inventory also requires a means of payment.

At present, much of our understanding of forests rests on the long-standing Landsat program. These data are the basis of FAO's new effort to integrate satellite data into that organization's global forest inventories. Estimates of volume, biomass, and carbon require the use of other remote-sensing technology, including radar and LIDAR, as well as ground-truthing and higher spatial resolution optical imagery. Table 3 summarizes the current and expected remote-sensing capabilities.

Perhaps the most worrisome problem is that, at present, no satellite system is optimized to observe forests. Satellite systems are designed for a variety of purposes to observe many Earth processes (for example, to observe land uses in general, to measure air quality, or to assess freshwater supplies or ocean health), to carry out scientific research rather than routine monitoring and measurement, and often, to demonstrate national technical prowess. As a result, forest measurement and monitoring is not a priority but, at best, an ancillary opportunity. Moving toward a census to characterize the world's forests will require a change in priority, funding, and institutional coordination.

Table 3. Expected Improvements in Accuracy in Remote Sensing of Forests (Fagan and DeFries 2009)

		<u>Current (2009)</u>		<u>Expected (2009–2015)</u>	
<u>Forest attribute</u>	<u>Sensors</u>	<u>Capability</u>	<u>Limitations</u>	<u>Capability</u>	<u>Limitations</u>
Area	Optical and radar, moderate-resolution	>80% accuracy for forest/nonforest maps at moderate resolution (~30- to 50-meter pixels).	Lack of detailed global forest types. Current coarse-resolution maps have more detail, but ~65% accuracy. ¹	>80% accuracy for global maps of nonforest and several forest types, at moderate resolution (30 meters).	Availability of free, moderate-resolution imagery depends on continuation of some government satellite programs (e.g., continuing the Landsat program).
	Optical, high-resolution	>90% accuracy for forest/nonforest maps. ²	Many images are needed to map large areas ³ and images are difficult to standardize for analysis.	A global set of high-resolution images will be gathered by 2015.	Difficulties in standardization are likely to persist, limiting use for global mapping.
Volume	Optical, high-resolution	40–90% accuracy for forest volume estimates.	See above. Accuracy is low in closed forests with tree canopy overlap.	See above. Regional equations correcting for canopy overlap may be developed.	See above.
	SAR (Radar)	50–95% accuracy; >80% is common for forest volume.	Limited to low-biomass forests; higher biomass decreases accuracy.	>80% accuracy in dense, high-biomass forests. ⁴	Accurate volume estimates will depend on several new satellite programs. ⁵
	inSAR (Radar-derived height)	30–80% accuracy for forest volume estimates (from forest height).	Lack of ground elevation data prevents global forest height/volume estimation.	The amount/diversity of inSAR data will increase. ⁴ Processing innovations may create ground elevation maps.	A global ground elevation map may be difficult to develop.
	LIDAR (Laser-derived height)	45–97% accuracy; >80% accuracy is common for forest volume.	LIDAR sampling is spatially limited, data-intensive, and expensive.	Global sampling of forest and ground height will come from new satellite sensors. ⁷	Satellite sensors will be spatially limited; global LIDAR coverage requires expensive aerial platforms.
Biomass	Same sensors and accuracy as volume; estimated through correlation with ground-truth points. ⁶				
Carbon	Same as biomass; estimated through a standard conversion from biomass, with minor inaccuracy (±8% max.)				

Notes. See text for definition of *accuracy*.

¹ Forest types are general (e.g., deciduous forest) in global, coarse-resolution maps (>200-meter pixels). Their forest/nonforest accuracy is 70–80%.

² Currently, forest type mapping accuracy for high-resolution imagery is similar to that of moderate-resolution imagery.

³ A very large number of expensive images are needed to create a global map (see Fagan and DeFries 2009). Global image coverage does not currently exist.

⁴ Advances in satellite technology and image processing will allow fusing of inSAR and SAR for synergy in volume/biomass estimation.

⁵ These include plans by the United States for a satellite known as DESDynI and by Europe for a satellite known as BIOMASS. Innovations in processing SAR imagery from multiple satellites may also improve volume estimates.

⁶ Accurate ground-truth points from forest inventory data are critical to any effort to measure forests using remote sensing (see text).

⁷ Global LIDAR sampling of forest volume will allow synergy with forest type maps for regional forest volume estimation.

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