ISSUE BRIEF

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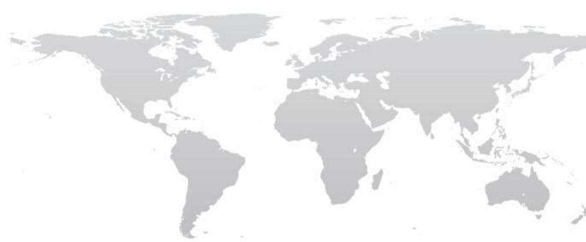

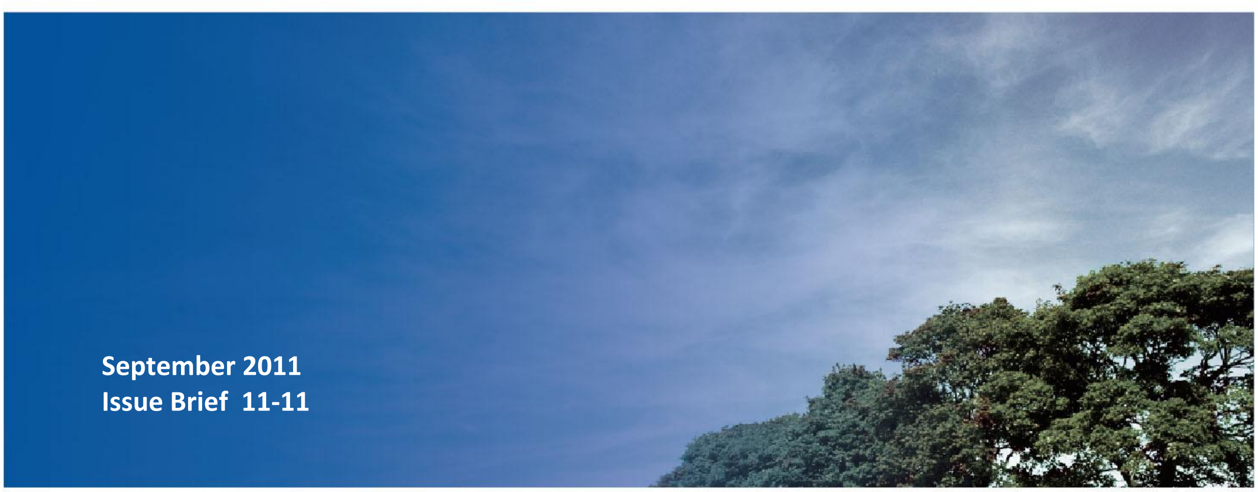

September 2011
Issue Brief 11-11

Resources for the Future

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Daniel F. Morris and Anne Riddle*

Introduction

Tropical forests provide local and global public goods of significant value, including carbon sequestration, water and nutrient cycling, improved air quality, and biodiversity. Despite the social, economic, and environmental significance of forests, currently measurements of their attributes are incomplete and imprecise. The global community lacks systematically collected and verified data with which to catalog forest attributes, construct accurate maps, and track changes in their extent or composition with precision (Macauley et al. 2009). As a result, it tracks human impacts like deforestation of tropical forests with very rough measures, and forest biodiversity and physical attributes are poorly documented. Forested nations use these shaky foundations of forest information to make decisions on further research, conservation, planning, and policy design.

Reducing emissions from deforestation and forest degradation (REDD+[1]) has driven the recent dialogue surrounding improved forest monitoring. Forest monitoring at the local, regional, and international levels will be a key component of any international REDD+ architecture that develops over the next decade. Although REDD+ is advancing slowly within the context of the

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[1] The base definition of reducing emissions from deforestation (*RED*) is frequently expanded to include other methods of reducing greenhouse gas emissions or atmospheric concentrations. The term *REDD* includes degradation of standing forests, while *REDD+* includes degradation as well as sustainable forest management and carbon enhancement. We have referred to REDD+ here to provide the most inclusive definition.

U.N. Framework Convention on Climate Change, it is progressing with more haste in the context of bilateral and multilateral agreements. The United States is increasingly involved in bilateral funding to support REDD+, including the commitment of $1 billion in fast-track financing to create a portfolio of investments in REDD+ readiness activities abroad. Accurate monitoring in recipient countries using the best available information will be essential to ensure the efficient and effective use of funding for protecting forestlands and supporting indigenous communities. The resulting capacity improvements will also be an invaluable tool for a host of other activities of interest to the global community, such as governmental planning, tracking of illegal logging, and endangered species protection.

Although the needs of forest data users will probably impact the kind of data gathered in the future, users must have reasonable expectations of the quality of data they receive. Monitoring for REDD+ in forested countries will require reliable monitoring systems with a sophistication as high as is technically and feasible within the constraints of economic conditions on the ground. Bilateral REDD+ funders will possess a great deal of latitude to define the level of quality that is acceptable for forest information within the confines of existing technology and budgetary concerns. This paper discusses balanced options for moving forward with forest monitoring for REDD+ in this context.

How Carbon Is Measured

Because REDD+ programs are intended to reduce carbon emissions as their primary objective, REDD+ monitoring must capture all attributes of forests relevant to calculating their carbon content. Thus, forest monitoring programs must measure the area and volume of the forests in question; this enables the derivation of biomass and carbon content. Area is easiest to determine directly from remote sensing data, although area censuses have only recently started incorporating such data. Remote sensing platforms easily capture large areas of forest with excellent temporal regularity and fine spatial scales, allowing for regular updating of maps, greater transparency, and easily standardized measurement protocols.

Standing forest volume can also be measured with remote sensing apparatuses, though the most accurate method for measuring volume is to measure the diameter at breast height and the height of each tree. For large stands, sampling methods are used together with complex equations derived from regression models to estimate timber volumes (Schreuder et al. 1993). Biomass estimates derive from volume measurements through complex models, which must take into account the physical geography and species composition of forests to measure this accurately. Carbon can then be derived through its simple and consistent relationship with dry woody biomass. The Intergovernmental Panel on Climate Change (IPCC) has laid out specific guidelines for carbon stock accounting with different levels of rigor called *Tiers* (see Box 1 for a description of the three Tiers).

Box 1. IPCC Carbon Accounting Standards (Tiers)

Tier levels refer to the level of detail in carbon stock information used to calculate carbon inventories and fluxes over time. More detailed information results in more accurate calculations, which are essential to achieving real greenhouse gas reductions. Thus, higher Tier levels are desirable. However, more detailed information is generally more costly to collect and requires greater expertise and resources to manipulate.

The **Tier 1** approach employs the basic, standard methods and equations provided in the IPCC Guidelines and uses default emissions factors provided by the IPCC. Tier 1 methodologies use activity data that are spatially coarse, such as globally available estimates of deforestation rates and biome-level estimates of biomass. At this level, it is impossible to track individual tracts of land over time. It is the least accurate level of monitoring, but also the simplest and least costly. Countries using a Tier 1 approach typically do not produce any data themselves or fail to update data regularly.

Tier 2 can use the same standard method and equations as Tier 1, but applies volume and biomass factors and forest area data that are defined by the country for the most important land uses. Thus, Tier 2 requires some country-specific carbon data, such as those from field inventories or permanent plots, and generally uses higher-quality forest area data. Country-defined emissions factors and activity data are generally more accurate for the climatic regions and land use systems in that country. Countries using a Tier 2 approach generally produce all or some of their own data, but often do not update data regularly.

At **Tier 3**, the highest-order methods are used. Forest area change is tracked by high-quality remote sensing data and is updated regularly. Volume and biomass are calculated by sophisticated models supported by forest inventory measurement systems; these models may deviate from basic IPCC guidelines to reflect nationally specific circumstances. Both remotely sensed and ground measurements are repeated over time and are differentiated by forest type or region. Countries using a Tier 3 approach generally update data at least yearly.

For more in-depth descriptions of the specific methodologies for each Tier, see Penman et al. (2003).

Measurement, Reporting, and Verification Programs in the Developing World

A discussion of forest monitoring in the developing world must account not only for existing and projected technologies, but the ability of developing countries to use those technologies. Although remote sensing technology and ground-based protocols are available, using them requires a processing architecture with sufficient human and material resources, expertise, access, and time. Natural resources managers and governments in the developing world are typically more constrained by these attributes than are those in the developed world. Some developing countries successfully harnessed forest monitoring techniques and developed substantial monitoring programs. Examining those successes can potentially reveal patterns and realistic expectations for developing country performance in setting measurement, reporting, and verification (MRV) standards.

Brazil's PRODES (Programa de Cálculo do Desflorestamento da Amazônia) deforestation monitoring program, which operates through their space agency, INPE (Instituto Nacional de Pesquisas Espaciais), is the most advanced in the developing world. PRODES uses Landsat data from the United States to create yearly deforestation maps at a 60-m by 60-m resolution. Landsat, the longest-running program for acquiring satellite imagery of Earth, produces a full set of Earth images every 16 days in resolutions ranging between 15 and 60 meters. INPE also uses the DETER (Detecção de Desmatamento em Tempo Real) system, a rapid, coarse inventory produced on a monthly basis to track illegal deforestation, using MODIS (Moderate Resolution Imaging Spectroradiometer) from the United States and the China–Brazil Earth Resource Satellite Wide-Field Imager, a joint China–Brazil satellite (INPE n.d.). MODIS uses data compiled from two different satellites to produce a full set of Earth images every one to two days, in resolutions between 250 meters and 1 kilometer.

Brazil has planned a stratified ground sampling network of permanent sample plots distributed across the country (de Freitas et al. 2006). These plots, which will be used to ground-truth satellite data and to collect data that cannot be obtained remotely, will ensure a full suite of forest information sources. Coupled with PRODES, this network makes Brazil's forest monitoring system the most advanced and comprehensive such system in the humid tropics and one that is on par with those employed in the developed world. Similarly, China has its own remote sensing system using three satellites that encompass all resolution types (Fagan and DeFries 2009). China's ground inventory system is carried out by individual provinces throughout the country at five-year intervals, based on fixed ground sample plots and regular measuring (Food and Agriculture Organization 2007). Both of China's forest monitoring systems are similar in sophistication to those used in the developed world.

Other developing countries have developed less comprehensive forest monitoring programs that may serve as a platform for improved measures. Frequently, these programs omit remote sensing or ground sampling, conduct one or both less frequently, or use less comprehensive data. For example, Guyana recently completed its first systematic attempt at tracking deforestation and creating a baseline forest map in anticipation of a REDD+ mechanism (Det Norske Veritas 2010). Guyana used at least nine medium- and high-resolution sensors for its initial attempt at monitoring deforestation, including at least two sensors based in the United States. The results were highly accurate and independently verified; however, the program does not include ground sampling and is not yet conducted on a regular basis. In contrast, India creates its forest inventories from one remote sensor and a series of systematic ground sample plots covering 80 percent of the country (Forest Survey of India 2007). Although its remote sensing outputs are unlikely to be robust, its ground sampling capabilities allow for forest inventories of at least a modest level of sophistication.

The international community recognizes some value in tracking forest resources, and therefore has contributed to international capacity-building efforts to monitor forests and forest change. The United Nations and other international organizations have spearheaded initiatives dedicated to compiling forest information and increasing in-country capacity for forest monitoring, some created in direct response to deforestation. For example, the U.N.-REDD+ Programme conducts significant work in capacity building, including in-country pilot programs on remote sensing and inventory. Older programs such as the Forest Resource Assessment (FRA), conducted by the Food and Agriculture Organization, also work to complete global forest inventories, but the accuracy of the FRA's data is limited (Fagan and DeFries 2009). Although these efforts contribute to a wide range of tasks related to forest monitoring, their strongest functions are providing technical assistance and capacity building for forest countries to develop internal forest-monitoring systems.

Other international groups have recently arisen to address the data gaps that plague developing countries. The Group on Earth Observations (GEO), an international pan-governmental organization focused on remote sensing, has recently developed comprehensive programs related to monitoring forests (GEO 2011). The Forest Carbon Tracking task combines the efforts of a large number of contributor countries, including the United States, to provide both data and technical assistance in all aspects of forest monitoring related to carbon. This task will focus on national demonstrator countries in the developing world, which will act as laboratories for developing and demonstrating methods in situ.

Member countries of GEO's Committee on Earth Observation Satellites have committed to providing systematic optical and radar satellite data for demonstrator countries, and teams are assigned to help each country develop classification and forest change products. Validation procedures and accuracy assessments are also being standardized to the extent possible. GEO hopes to use this process as a proof of concept and transition into a more operational phase that can be applied to other countries attempting to monitor their forests; the local capacity for MRV built into pilot locations may be a fortunate co-benefit.

Forest monitoring systems have existed for decades in the developed world, where both private and public entities have tracked forest area, volume, and composition for a variety of purposes. In the past, many of these systems have relied on ground-based sampling protocols or aerial photography. More recently, public and private entities have made use of available satellite-based remote sensing data to map forest extent and find areas of rapid change for further assessment. The advantages offered by satellite remote sensing in this regard are so profound that they have driven recent recommendations by independent bodies for creating forest monitoring systems. For example, Global Observation of Forest and Land Cover Dynamics (GOFC-GOLD) incorporates all categories of satellite remote sensing in its forest monitoring recommendations (Global Observation of Forest and Land Cover Dynamics 2010). Although GOFC-GOLD prefers medium-resolution sensors as a primary tool to track forest area and changes in area, they recommend coarse-resolution data to identify “hotspots” and high-resolution data for validation or ground-truthing of results. This targeted sampling of change reduces the overall resources typically required in assessing change over large areas, an ideal attribute of a monitoring protocol for developing countries.

Existing Capacity from the United States

Forest metrics are of interest for activities unrelated to climate change, so many pieces of the measuring puzzle already exist in tested and usable forms. Although satellite imagery suitable for measuring forest area is currently available from many sources, the United States provides the lion’s share of forest remote sensing capability at known availability and cost for outside parties (Fagan and DeFries 2009). Worldwide, 15 medium-resolution optical sensors currently provide data relevant to forests, either for free or for varying costs; of these, 5 were launched by the United States alone or in partnership with other countries. Four coarse-resolution optical sensors also provide data, all for free and all originating in the United States.

Higher-resolution remote sensing data from three different satellites is also available, though the costs are higher than those of any other sensor type. One of these is based in the United States. Although worldwide remote sensing capacity is projected to increase substantially in the near term through planned satellite launches and data releases, the United States remains the largest provider of free remote sensing data. Particularly important are the extensive archives of past images from the U.S. Landsat sensors, which are critical to generating historical baselines for REDD+. The extensive historical record from Landsat has made this family of sensors the standard for long-term monitoring of tropical forests (Trigg et al. 2006).

Although satellite remote sensing like Landsat is by far the most efficient method for tracking forest area and area change, these kinds of satellite images show only land cover. They cannot be used to measure other attributes of forests, like tree volume and biomass, which are necessary to determine the carbon content of forest stands. Calculating these attributes requires additional specialized imagery or physical measurements. The United States also provides significant expertise and technical tools for these additional tasks.

Measuring volume involves both sampling trees in a given space to provide a one-time measurement, and developing descriptive allometric equations for use over time and space. The United States provides a wide variety of technical tools for measuring volume remotely. Optical high-resolution data have provided 40 to 90 percent accuracy (Fagan and DeFries 2009), and radar instruments, including synthetic aperture radar (SAR) and interferometric SAR (inSAR) can provide higher accuracies of 50 to 95 percent. Light detection and ranging (LIDAR), the most promising technology for accurate estimates of forest volume, can estimate area with a range of 45 to 97 percent accuracy, with greater than 80 percent accuracy commonly achievable (Fagan and DeFries 2009). Seven active sensors provide coarse- to medium-resolution data of this type, largely at no cost; two inSAR sensors and the world's only LIDAR sensor originate in the United States.

Biomass is the most difficult characteristic to determine, as it is a derivation of both volume and area estimates. Smith and colleagues (2003) recently developed a comprehensive model for calculating forest biomass using data from the U.S. Forest Inventory and Analysis program, the national ground-based forest monitoring program. Their model includes whole-tree biomass, accounts for differences in species composition, and easily scales to cover large areas with only minimal error. This approach is promising for REDD+, which will probably incorporate large areas with extremely diverse forests (Macauley et al. 2009).

The U.S. government contains a wealth of forest monitoring and modeling information and expertise that could be made available to developing countries. In particular, the U.S. Department of Agriculture Forest Service conducts ground-based inventories of forest volume and develops allometric equations for volume and biomass, and the National Aeronautics and Space Administration possesses considerable expertise in remote sensing technologies and possesses extensive remote sensing data reserves. The United States is attempting to harness these varying areas of expertise through several cross-agency programs, most of which will also support GEO's Forest Carbon task. Silvacarbon, a cross-agency program developed by the U.S. federal government, is designed to demonstrate and compare forest and terrestrial carbon measurement and monitoring methodologies for the developing world (U.S. Agency for International Development [USAID] 2010). Silvacarbon supports the assessment and integration function for methodologies currently being deployed in the national demonstrator sites, by developing methods for carbon and biomass inventories and coordinating data collection and dissemination.

The United States also supports SERVIR, a system of data hubs providing both remote sensing data from medium- and coarse-resolution data sets and some technical assistance in interpreting these data (USAID 2010). SERVIR's role in the forest monitoring world is properly seen as an access point for remote sensing data for countries with little or no remote sensing capability of their own. SERVIR acts as a complement to Silvacarbon, which is intended to build data interpretation and analysis skills and complete the necessary suite of forest monitoring activities.

Setting the Bar for Success

The international community will have to move forward with MRV systems that have embedded limitations and inaccuracies. The imprecision in forest measurement is a consequence of the wide variety of techniques used worldwide. Although most nations report forest data, they differ widely in their interest in collecting it accurately and in their ability to do so, particularly in the developing world. In many nations, forest data are collected infrequently, extrapolated from past trends rather than measured directly, or include the estimation of only selected forest attributes while excluding other significant components; in some cases, forest data are affected by a combination of these types of limitations (Macauley et al. 2009). The aggregation of data for broad measurement provides further challenges. Inaccuracies in area or volume measurements are multiplied in conversions to biomass and carbon, adding uncertainty to already inexact measures. Furthermore, these imperfections in forest data mean that combining country-level data sets propagates errors and inaccuracies, further reducing the reliability of data on large scales.

Policymakers and on-the-ground implementers must consider these constraints as they design effective MRV systems. Although the technology and methods necessary to improve forest information have been developed, barriers to their adoption remain. Remote sensing techniques involving LIDAR and other focused measurements hold promise for significantly improving monitoring, but they are not yet operational for large areas. Similarly, widespread volume measures are expensive to obtain and interpret through ground sampling, and administering a national system will probably be cost-prohibitive without regular financing from REDD+ markets.

Technical accuracy forms only part of the discussion about the quality of monitoring. Equally important are the technical and financial feasibility of conducting monitoring and the willingness to pay for improved information in each area. Improved quality and timeliness of information requires additional resources in human, time, and financial resources; forest countries must weigh the value of improved information on forests against using these resources elsewhere. Demanding major improvements in forest information above existing free or low-cost data has tradeoffs with other kinds of capacity building. Valuing forest services through mechanisms like REDD+, however, will concurrently generate more value for improvements in forest data.

Luckily, MRV systems do not have to be perfect from the outset of REDD+ program implementation. They must simply be good enough to provide a solid foundation upon which improved techniques can be built. Existing technologies, data, and monitoring programs, though far from comprehensive, provide a good starting point for developing minimum standards for in-country MRV programs. Additionally, early movers on national MRV programs and in the voluntary offset market are already establishing benchmarks that can provide guidance for others. Specifically, the few national measurement systems that are in operation in developing forested countries (Guyana and Brazil) appear to be settling on IPCC Tier 2 standards for country-level assessments. Guyana has gone further in requiring Tier 3 standards for pilot REDD+ projects with plans to extend them to the entire country in 2012. See Table 1 for a detailed breakdown of selected national approaches.

Project-level measurement standards are understandably more stringent. Many of the leading forest carbon offset developers set the desirable level of uncertainty at within 10 percent of the actual carbon content of the forest with a 90 to 95 percent confidence interval (Macauley et al. 2009). This level of accuracy is generally at least as stringent as the standards of Tier 3 reporting. Table 2 reviews various requirements of voluntary offset protocols.

These two approaches, though different in scale and stringency, may be combined to provide a realistic path forward for MRV. Bilateral REDD+ funders can recommend to recipient countries that they first conduct initial nationwide forest measurements generally in line with the standards set by IPCC Tier 2 accounting. Presumably, both funder and recipient countries will have some idea of specific areas of interest that are at significant risk of deforestation and/or degradation or that have highly valuable carbon stores. These areas can then be targeted in the second phase of measurement with the more rigorous requirements of either IPCC Tier 3 standards or something akin to voluntary carbon offset standards. This approach will provide flexibility, allowing policymakers and implementers to focus on the key areas in the forest while maintaining a basic level of MRV in other areas with less risk (Herold and Skutsch 2011). It can set the bar high enough to force countries engaging in REDD+ activities to develop MRV systems that are as reliable as is currently feasible, but low enough that they may clear it while working with limited resources.

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Tables *(see following pages)*

Table 1. Attributes of Different National-Level Forest Carbon Monitoring Systems

	Type	Type/spatial resolution of data	Tier level	Accuracy/uncertainty
United States	National level	The United States uses Landsat (medium resolution) and MODIS (coarse resolution) in the first steps of the forest inventory process to stratify inventory data. It is unclear how forest area data are collected and interpreted.	U.S. monitoring is at Tier 3. Carbon inventory data are gathered from a detailed national inventory system (the Forest Inventory and Analysis program of the USDA Forest Service), which is stratified by region; measurements are repeated through time and converted to GHG data through complex modeling (FORCARB 2). Data are collected on most or all key categories. (United States Department of Agriculture 2008).	The uncertainty analysis for the USDA 2005 GHG inventory was performed using the IPCC-recommended Tier 2 uncertainty estimation methodology and provided carbon stock change estimates based on a 95% confidence interval. No accuracy assessment was available for remote sensing data. (United States Department of Agriculture 2008).
Guyana (ad hoc)	National level	Guyana used Landsat (medium resolution) and many other medium- and high-resolution sources for its baseline forest mapping. The data were interpreted visually on-screen.	Guyana does not currently conduct carbon and GHG accounting. However, Guyana's REDD+ readiness plan includes instituting Tier 2 monitoring nationwide, and Tier 3 on pilot sites, in 2011–2012, with scaling up to Tier 3 nationwide after 2012. (Guyana Forestry Commission 2009).	For baseline forest/nonforest mapping and year one deforestation mapping, Guyana reached accuracies of 95.8% and 92.81%, respectively, which were independently assessed. Because Guyana does not regularly conduct carbon and GHG accounting, no accuracy assessment was available.
Brazil (ad hoc)	National level	Brazil's yearly inventory uses Landsat (medium resolution) and the China–Brazil Earth Resource Satellite (medium resolution). Brazil probably interprets these data digitally, but this is not known.	Brazil may achieve Tiers 2 or 3 for carbon accounting. It is unclear whether Brazil's national sampling scheme samples the categories necessary to achieve Tier 3. (de Freitas 2006)	No analyses of uncertainty for carbon or GHG accounting, or of accuracy for remote sensing, have been conducted because the Brazilian forest inventory system is still under development.

GOFC-GOLD	National level	GOFC-GOLD recommends a minimum of Landsat-type (medium-resolution) remote sensing data with on-screen visual interpretation.	GOFC-GOLD recommends a minimum of Tier 2 carbon accounting, with Tier 3 being ideal. Tier 3 is recommended for key categories even if Tier 2 is primarily used.	GOFC-GOLD recommends 80%–95% forest mapping accuracy, which is achievable with mid-resolution data, and recommends independent assessment. GOFC-GOLD presumes uncertainty analyses to a 95% confidence interval, as required by the UNFCCC.
Voluntary Carbon Standard	National or regional level	VCS permits high- to medium-resolution data of any kind and makes no distinction among interpretation methods.	VCS does not use tier recommendations, though their requirements probably fall under Tier 2. VCS excludes some categories that may be necessary for a Tier 3 approach, such as soil organic carbon. VCS allows a variety of in situ sampling techniques for carbon accounting, which probably fall under Tier 3.	For deforestation mapping, VCS requires a minimum accuracy of 70%, with discounting factors applied for accuracies under 85%. Accuracies of 70%–75% are discounted by 0.7; those of 75%–80% are discounted by 0.75; and those of 80%–85% are discounted by 0.8. If only four images are used to create the historical reference period, these factors must be multiplied by 0.9. Historical reference periods using fewer than four images are ineligible. VCS requires a 95% confidence interval for uncertainty analyses. (Voluntary Carbon Standard 2010)

Notes: GHG, greenhouse gas; GOFC-GOLD, Global Observation of Forest and Land Cover Dynamics; MODIS, Moderate Resolution Imaging Spectroradiometer; REDD+, reducing emissions from deforestation and forest degradation; UNFCCC; U.N. Framework Convention on Climate Change; USDA, U.S. Department of Agriculture; VCS, Voluntary Carbon Standard.

Table 2. Attributes for Project-Level Forest Carbon Measurements from Voluntary Markets Standards

Project-Level Approaches	Included categories	Estimating drivers and rates of conversion	Buffer pool	Reporting and verification	Inventory	Stratification
Climate Action Reserve (CAR)	Standing carbon, carbon in in-use wood products, site preparation and leakage emissions, and emissions from decomposition are required. Belowground, understory, duff, lying dead, soil, and products in landfills are optional in most circumstances.	CAR requires a real estate appraisal to determine the most likely cause of conversion. Rates can be either defaults following the conversion cause, or planning documents with identifiable conversion time frames.	Buffer pool contributions are variable and based on a risk assessment. Contributions to the buffer pool are waived with proof of valid insurance.	CAR projects undergo on-site verification every six years and are reported every year.	The project inventory must consist of permanent plots sampled every 12 years. Biomass is determined using allometric equations developed by the USDA Forest Service or those of demonstrably equal or better quality. CAR will deduct a percentage from final awarded credits if sampling error is greater than 5%.	Not required
Voluntary Carbon Standard (VCS)	Standing carbon, belowground carbon, fossil fuel use, and nitrogen emissions are required. Nontree, dead wood, soil, and wood products are optional.	Drivers are found in planning documents or most likely agents of deforestation determined through stratification. Deforestation rates may be determined from planning documents or proxy areas, which can be determined using either remote sensing data or legal documents.	Variable, based on risk assessment.	VCS projects undergo on-site verification every five years and are reported every year.	Inventory may follow either a fixed system of permanent sample plots or a point-sampling system combined with specific allometric equations provided by VCS and measured every five years. VCS takes no deduction based on sampling error.	Stratification is required for determining the deforesting agent to create the baseline.

Notes: CAR, Climate Action Reserve; USDA, U.S. Department of Agriculture; VCS, Voluntary Carbon Standard.