Forest Carbon Monitoring: A Review of Selected Remote Sensing and Carbon Measurement Tools for REDD+

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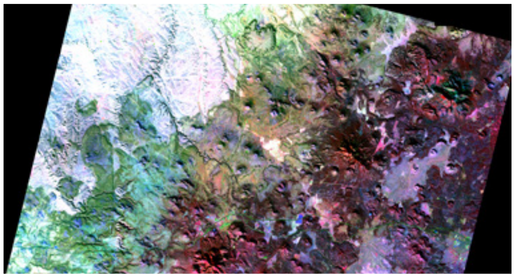

United States Department of Agriculture

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Forest Inventory Analysis

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Executive Summary

The information needed for a robust REDD+ (Reducing Emissions from Deforestation and Forest Degradation) carbon inventory and monitoring program is an integrated system that includes estimates of carbon stock from unbiased estimators and a distribution map of sequestered carbon amounts at repeated intervals across specific forested areas. The appropriate use of remotely sensed data combined with a forest resource inventory provides the only practical means to generate this information and supplies synergistic answers to the important questions of where, how, and by what amount resources are changing over time. Although ground based resource inventories provide critical information, they are costly, do not lend themselves to frequent updates, and do not produce spatially continuous maps. Remote sensing makes the inventory more efficient, typically reduces the standard error of the statistical population estimates, and often provides new information, including map products. Table 1 summarizes selected current methodologies used for REDD+ monitoring. None of these methods are well-integrated systems capable of producing comprehensive forest inventory data. Without an adequate ground-based inventory, these remote sensing methods must approximate values of biomass and/or carbon.

Rationale for This Report

This report was produced in partnership with the U.S. Department of Agriculture, Forest Service International Programs with funding provided by the United States Agency for International Development (USAID). It provides an overview of an integrated approach for inventorying, mapping, and monitoring for REDD+. This integrated approach is important to consider when evaluating current or proposed methodologies for making REDD+ assessments. This report is not intended to be comprehensive; however, it includes references to a forthcoming publication from the SilvaCarbon program that is more inclusive.

How to Use This Report

Despite its considerable size, the heart of this report is a brief (six-page) overview of selected remote sensing and carbon measurement tools for REDD+. It consists of a three-page table (the Summary Matrix of Selected Existing Methodologies), and three pages that explain the table and its limits. The remainder of the report is a series of appendices that provide clarification and offer further information.

Key Words

REDD+, Reducing Emissions from Deforestation and Forest Degradation, biomass, carbon, remote sensing, forest inventory, mapping, monitoring, silvacarbon, satellite sensors, IPCC, Intergovernmental Panel on Climate Change

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Remote Sensing for Inventory and Monitoring

The information needed for a robust REDD+ (Reducing Emissions from Deforestation and Forest Degradation) carbon inventory and monitoring program is an integrated system that includes estimates of carbon stock from unbiased statistical estimators and a distribution map of sequestered carbon amounts at repeated intervals across specific forested areas. Furthermore, the precision of those estimates and the accuracy of the distribution map must be measured. Combining remotely sensed data with a forest resource inventory provides the only practical means to generate this information at the current time. Neither of these techniques supplies all of the desired information alone. However, when properly integrated, remote sensing and forest inventory can provide the geospatial and statistical basis for understanding the impact of carbon distribution and flux on the landscape.

Remote sensing is the study and activity of collecting and interpreting information about features from a distant location. It is the only means to obtain continuous data over large areas at an effective cost. The products derived from remotely sensed data are typically continuous thematic maps (e.g., forest biomass). There are literally hundreds of remote sensing systems used today, ranging from space-borne to airborne to ground-based systems. This variety reflects the multiple uses for Earth observation data; consequently, no single system can satisfy all these needs. Each system has different properties with resulting strengths and weaknesses. The most important properties of an imaging sensor are its spatial resolution (how small a feature can be discerned from the imagery); the number of spectral bands (i.e., the number of distinct colors) it can resolve; its temporal frequency (how often the sensor passes over the same ground location); and the cost of acquiring the imagery. Other important factors are included as column headings in appendix D: Chart of Earth Resource Satellite Sensors. As this appendix demonstrates, there is tremendous diversity in the number and properties of the sensors and imagery available today.

Despite this diversity of sensors, no current remote sensing system directly measures forest biomass and sequestered carbon. The vast majority simply measure and record the energy that is reflected from features on the ground in the spectral bands that the sensor can record.[1] The relative strength of energy[2] that a feature reflects is based on its physical and chemical properties, and is known as its spectral response. Remote sensing is only effective when differences in spectral responses can distinguish specific features. For example, low biomass forests must have a distinct spectral response from moderate biomass forests so that they can be mapped as separate biomass classes.

Because no sensor directly measures biomass, using remote sensing to map it requires measuring one thing (spectral response) and predicting another (biomass). Even when the relationship between the spectral response and the predicted biomass is strong,[3] it is not exact. Error appears in the modeling process and the resulting map.[4] Remote sensing can provide relative, but uncalibrated, indicators of biomass but cannot quantitatively estimate it without substantial ground data to calibrate the spectral response. Thus, remote sensing is effective at indicating where specific features are and how they're distributed but cannot provide an accurate estimate of how much of that feature is in the mapped area without an integrated resource inventory.

A forest resource inventory applies an objective set of sampling criteria to quantify the state and rates of change of forest characteristics, such as biomass, within specified limits of statistical precision (Helms 1998). Typically, an inventory uses ground plots of a particular size, arranged and distributed in a specific sample design, and provides estimates of the statistical population (e.g., 100 tons of biomass/hectare). In addition, the inventory will provide a measure of the standard error (e.g. ± 2 tons of biomass/hectare) of the population estimate, which is equally important to the population estimate. An inventory tells how much of a given feature is there, but—unlike a map derived from remote sensing—it doesn't indicate other locations for the feature of interest or how it's spatially distributed within the inventoried area.

[1] See the definition of spectral resolution in the glossary.

[2] The correct technical term is electromagnetic energy, which is a continuum of energy classified by wavelength that includes ultraviolet, visible, near infrared, and short-wave infrared, among others.

[3] Spectral response and biomass have a strong relationship in less-than-fully developed canopies, but the response becomes saturated once the canopy cover is complete, while the biomass can continue to increase.

[4] Two kinds of error should be distinguished: lack of fit between the model and the data, which produces a biased estimator, and residual uncertainty about the model predictions. There are three reasons for distinguishing between these two kinds of error: (1) different effects on estimates, (2) different methods for detecting and estimating them, and (3) different ways of circumventing them.

A quantitative inventory integrated with remotely sensed data provides robust and synergistic answers to the important questions of how much and where resources are located. A rigorous inventory supplies critical information; however, it is costly, not spatially continuous, and is difficult to update as frequently as international agreements on REDD+ will likely require. Remote sensing increases the efficiency of the inventory, typically reduces the standard error of the statistical population estimate, and often provides new information, including map products. Integrating these two approaches is most effective when 1) the size of an inventory plot is similar in area to the spatial resolution of the remotely sensed imagery, and 2) the inventory covers the full range of variability in the specific feature (e.g., plots should be continuously located from the lowest biomass areas in the imagery to the highest). Integrating the two technologies can provide a much more comprehensive suite of information to address REDD+ monitoring requirements than either one alone. Mapping with remote sensing and conducting a forest inventory have unique complexities that are beyond the scope of this report. Integrating them to assess and monitor resources to support REDD+ adds even more complexity. The SilvaCarbon program, described below, is producing a publication addressing best-practice strategies to accomplish these complex tasks.

Thus far, this report has described the conceptual ideal—a resource inventory combined with a comprehensive remote sensing program. Evaluators of future systems for REDD+ monitoring, should be familiar with the fundamentals of the ideal conceptual system to be able to evaluate how closely a proposed system approaches this conceptual model. The next section provides a summary of a selection of current methodologies used for REDD+ monitoring (table 1). None of these methods are well-integrated systems capable of producing comprehensive forest inventory data. Without a complete ground-based inventory, these remote sensing methodologies must approximate values of biomass and/or carbon to represent the actual values derived by a forest inventory.

SilvaCarbon is a flagship program under United States fast start financing for REDD+ and is a U.S. contribution to the Forest Carbon Tracking task of the intergovernmental Group on Earth Observations (GEO). Working cooperatively, U.S. Federal agencies will draw on their respective strengths to implement SilvaCarbon. Agencies currently involved include: U.S. Agency for International Development (USAID), the U.S. Forest Service within the Department of Agriculture (USFS), the U.S. Geological Survey of the Department of Interior (USGS), the U.S. Environmental Protection Agency (EPA), the U.S. Department of State, the National Aeronautics and Space Administration (NASA), the National Oceanic and Atmospheric Administration within the Department of Commerce (NOAA), and the Smithsonian Institution. SilvaCarbon addresses technical issues including:

- Sampling protocols and design
- Data capture, processing, archiving, and distribution
- Collection and analysis of in situ data, including involvement of local communities and stakeholders
- Integration of remotely sensed and in situ data
- Classification and mapping of forest cover Carbon stock and flow estimation
- Design of monitoring systems for multiple uses
- Land use analysis and planning

Introduction to Table 1: Summary of Selected Existing Methodologies

Caveats of Table 1: the information in table 1 is not comprehensive, uniform, or independently verified, nor does it represent all of the different types of methodologies available. These methodologies were chosen because of their prominence and amount of available information—there are many omissions. The table contains unverified information provided by or inferred from the system vendor or administrator.

Value of Table 1: the table provides a snapshot in time of a selection of methods that have potential use for REDD+ inventorying, mapping, and monitoring. However, these particular and other methods are dynamic, and this snapshot in time will quickly become dated. The real and lasting value of the table is that it provides a conceptual framework to evaluate future systems and methods—or reevaluate these specific methodologies as they change.

Table 1—Summary Matrix of Selected Existing Methodologies

System	Sensor(s)	Spatial Extent	Examples	Strengths	Drawbacks	Operational Readiness [5]	Other Considerations
Videography	Airborne Video Camera to obtain stereo imagery	Applicable to very small areas (e.g., field plots)	Demonstrated on a variety of forest types, analyzing both deforestation and degradation. Ideally, plot-level estimations can be integrated with any other system that uses this data.	Can be used to reduce the cost of obtaining plot reference data, particularly in locations that are difficult to reach on the ground.	Requires some plot-level data collection for calibration; needs a well-trained analyst, which may cost more than ground crews in some locations.	High	Costs for shipment of the sensor could be prohibitive, and the required low-altitude flights may be restricted in some areas.
CLASlite	Landsat TM and ETM+, ASTER, ALI, SPOT, MODIS, EO-1	National coverage	Developed in the Brazilian Amazon and successfully tested in the Peruvian Amazon, as well as other montaine and lowland forest types.	Is cost effective, mitigates cloud problems, can be operated by non-RS/GIS experts, applicable to varying ecosystems at a range of scales.	Does not estimate actual carbon stocks; spatial scale depends on data used.	High	The method may require spectral library updates for ecological types outside of the tropical regions.
CLASlite + LiDAR	Landsat TM and ETM+, ASTER, ALI, SPOT, MODIS, EO-1, LiDAR	Local, maybe subregional coverage	Developed in temperate boreal forests but also successfully tested in the Brazilian Amazon.	Capable of making actual carbon estimates using allometric lidar equations; has potential to address net carbon changes by accessing structure information.	Requires significant planning and cost evaluation before implementing; could be cost prohibitive.	High	Probably not reasonable for estimations at a national scale. Field plots are required to calibrate the LiDAR metrics.
Airborne Taxonomic Mapping System (AToMS)	LiDAR, 2 spectrometers	Regional or local coverage	Used to map the Peruvian Amazon.	Can be used to estimate biomass and carbon, especially in locations inaccessible by ground crews.	Requires extensive spectral library, with the cost of trained biologists to obtain data not already in the library. Expert analyst could be costly.	High	Can also gather information on biodiversity, ecology, and hydrology.

[5] Operational readiness is an estimation based on an evaluation of information provided by the vendor; systems change rapidly.

Note: One-page descriptions of each of these 11 systems appear in appendix C.

Table 1—Summary Matrix of Selected Existing Methodologies (continued)

System	Sensor(s)	Spatial Extent	Examples	Strengths	Drawbacks	Operational Readiness	Other Considerations
Nationwide Forest Resource Assessment in Nepal	Landsat ETM+, MODIS, IKONOS, QuickBird, IRS LISS III, possibly aerial imagery	Entire country of Nepal	Countrywide inventory plan, utilizing remote sensing and plot-level inventory based on similar inventories conducted in Finland.	Comprehensive with wall-to-wall coverage; includes areas not currently forested but targeted for afforestation.	Is very expensive; difficult to collect plot data due to terrain unless remote sensing techniques can be used to supplement.	Low	High resolution or LiDAR data may be used to estimate plot-level biomass for difficult-to-reach locations. Regression analysis can be used to estimate total carbon.
Decision Tree Matrix	MODIS, JERS-1, QuikSCAT, SRTM	National coverage	Developed using the entire Amazon Basin as a study area.	Incorporates existing plot data and provides estimates of carbon stocks across large areas.	Requires extensive ground-plot data; also requires expert analysts to implement.	Low/Moderate	Radar data was integrated with this approach, which can be costly but provided good results.
CATHALAC Tropicarms	Landsat, MODIS, ASTER	National, regional, or local coverage	Developed using information in Panama and has been demonstrated in several locations.	Allows for biomass and carbon estimation without infrastructure investment, permitting countries that collect plot-level data to use them in conjunction with Tropicarms for a REDD Tier 2 or Tier 3 approach.	Highly dependent on Tropicarms; little in-country expertise, development, or control.	Moderate/High	Modules can be used to test hypothetical situations (after licenses for the modules are purchased).
Normalized Difference Fraction Index	Landsat	National, regional, or local coverage	Developed at a site in Mato Grosso, Brazil, which is covered by one Landsat scene.	Estimates biomass using allometric equations; utilizes free satellite imagery.	Requires extensive field data and expert remote sensing knowledge to implement.	Low	The system can integrate historical data and provides a new, useful vegetation index.
Real-time Deforestation Detection System (DETER) in Brazil	MODIS	National coverage	Used in Brazil to detect illegal logging; could be adapted for other countries.	Using MODIS allows coverage of large areas with minimal processing and access to free data; daily coverage improves opportunity to acquire cloud-free data.	Not used for biomass or carbon estimation; spectral resolution limits reliable detection to areas greater than 50 hectares.	Moderate	

Note: One-page descriptions of each of these 11 systems appear in appendix C.

Table 1—Summary Matrix of Selected Existing Methodologies (continued)

System	Sensor(s)	Spatial Extent	Examples	Strengths	Drawbacks	Operational Readiness	Other Considerations
Our Planetary Skin	MODIS	Global, national, regional	Web-based application.	Features free access to data; algorithms have been proven in projects; ability of registered users to share/upload data.	No estimates that relate to carbon are available; project still in development.	Low/Moderate	Current delay in reporting land change is 6 to 8 weeks.
Terrestrial Observation and Prediction Program (TOPS)	MODIS, Landsat TM, AVHRR, AMSR-E, SSM/I, ASTER,	Global, national, regional coverage	Used in California for moisture-gradient forecasting in wine country and in the Columbia River basin to forecast snow dynamics; has also provided net primary productivity estimates for protected areas across the United States.	Free to use and does not require expert analysts; covers the entire globe with net primary productivity estimates as well as leaf-area index measurements.	Does not provide carbon volume data; spatial resolution between 8 kilometers and 0.5 degrees, depending on location.	Low/Moderate	

Note: One-page descriptions of each of these 11 systems appear in appendix C.

Appendix A: REDD+ Tier Levels

Framework of Tier Structure in the IPCC Good Practice Guidance

The **Tier 1** approach employs the basic method provided in the IPCC Guidelines (Workbook) and the default emission factors provided in the IPCC Guidelines (Workbook and Reference Manual) with updates in this chapter of the report. For some land uses and pools that were only mentioned in the IPCC Guidelines (i.e., the default was an assumed zero emissions or removals), updates are included in this report if new scientific information is available. Tier 1 methodologies usually use activity data that are spatially coarse, such as nationally or globally available estimates of deforestation rates, agricultural production statistics, and global land cover maps.

Tier 2 can use the same methodological approach as Tier 1 but applies emission factors and activity data which are defined by the country for the most important land uses/activities. Tier 2 can also apply stock change methodologies based on country-specific data. Country-defined emission factors/activity data are more appropriate for the climatic regions and land use systems in that country. Higher resolution activity data are typically used in Tier 2 to correspond with country-defined coefficients for specific regions and specialised land-use categories.

At **Tier 3**, higher order methods are used including models and inventory measurement systems tailored to address national circumstances, repeated over time, and driven by high-resolution activity data and disaggregated at sub-national to fine grid scales. These higher order methods provide estimates of greater certainty than lower tiers and have a closer link between biomass and soil dynamics. Such systems may be GIS-based combinations of age, class/production data systems with connections to soil modules, integrating several types of monitoring. Pieces of land where a land-use change occurs can be tracked over time. In most cases these systems have a climate dependency, and thus provide source estimates with interannual variability. Models should undergo quality checks, audits, and validations.

From Chapter 3, Box 3.1.1, page 3-17, Intergovernmental Panel on Climate Change (IPCC), Good Practice Guidance for Land Use, Land-Use Change and Forestry.

Appendix B: Benefits and Limitations of Available Methods to Estimate National-Level Forest Carbon Stocks

Method	Description	Benefits	Limitations	Uncertainty
Biome averages	• Estimates of average forest carbon stocks for broad forest categories based on a variety of input data sources	• Immediately available at no cost • Data refinements could increase accuracy • Globally consistent	• Fairly generalized • Data sources not properly sampled to describe large areas	High
Forest inventory	• Relates ground-based measurements of tree diameters or volume to forest carbon stocks using allometric relationships	• Generic relationships readily available • Low-tech method widely understood • Can be relatively inexpensive as field-labor is largest cost	• Generic relationships not appropriate for all regions • Can be expensive and slow • Challenging to produce globally consistent results	Low
Optical remote sensors	• Uses visible and infrared wavelengths to measure spectral indices and correlate to ground-based forest carbon measurements • Ex: Landsat, MODIS	• Satellite data routinely collected and freely available at global scale • Globally consistent	• Limited ability to develop good models for tropical forests • Spectral indices saturate at relatively low C stocks • Can be technically demanding	High
Very high-res. airborne optical remote sensors	• Uses very high resolution (10–20 cm) images to measure tree height and crown area and allometry to estimate carbon stocks • Ex: Aerial photos, 3D digital aerial imagery	• Reduces time and cost of collecting forest inventory data • Reasonable accuracy • Excellent ground verification for deforestation baseline	• Only covers small areas (10 000s ha) • Can be expensive and technically demanding • No allometric relations based on crown area are available	Low to medium
Radar remote sensors	• Uses microwave or radar signal to measure forest vertical structure • Ex: ALOS PALSAR, ERS-1, JERS-1, Envisat)	• Satellite data are generally free • New systems launched in 2005 expected to provide improved data • Can be accurate for young or sparse forest	• Less accurate in complex canopies of mature forests because signal saturates • Mountainous terrain also increases errors • Can be expensive and technically demanding	Medium
Laser remote sensors	• LiDAR uses laser light to estimate forest height/vertical structure • Ex: Carbon 3-D satellite system combines Vegetation Canopy LiDAR (VCL) with horizontal imager	• Accurately estimates full spatial variability of forest carbon stocks • Potential for satellite-based system to estimate global forest carbon stocks	• Airplane-mounted sensors only option • Satellite system not yet funded • Requires extensive field data for calibration • Can be expensive and technically demanding	Low to medium

From H.K. Gibbs and others (2007) "Monitoring and Estimating Tropical Forest Carbon Stocks: Making REDD a Reality," table 1, page 3.

Appendix C: One-Page Descriptions of Selected Existing Methodologies

Corresponds to table 1—Summary Matrix of Selected Existing Methodologies.

The following summary descriptions are based on unverified information provided or inferred from the system vendor or administrator. The information provided is not comprehensive, uniform, or independently verified. The selected methodologies were chosen because of prominence and availability of information—there are many omissions.

The following systems are included:

- Videography: Plot-level Biomass Estimation
- CLASlite: Approach to Monitoring Deforestation and Forest Degradation
- CLASlite + LiDAR: Mapping Carbon Stocks Directly
- Airborne Taxonomic Mapping System (AToMS)
- Nationwide Forest Resource Assessment (FRA) in Nepal
- Decision Tree Matrix: Biomass Estimations in the Amazon Basin using Remotely Sensed Data and Ground Plot Data
- CATHALAC Tropicarms
- Normalized Difference Fraction Index: Combining spectral and spatial data to map canopy damage
- DETER: Brazil's Rapid Deforestation Assessment Tool
- Our Planetary Skin
- Terrestrial Observation and Prediction Program (TOPS)

These systems likely have a number of non-carbon benefits, including information on the extent and distribution of forest cover as well as other forest characteristics. Some also possess the potential to map forest degradation and locate forest-canopy changes associated with silvicultural activities and detect illegal logging as it occurs. The result is improved reduction of leakage, an important element within an overall REDD+ program.

Videography: Plot-Level Biomass Estimation

Background: Winrock International is a nonprofit organization that has been involved in REDD efforts, particularly in developing measuring, monitoring, and verification guidelines. One of its programs captures forest biomass data using airborne videography. Data from a video system, coupled with navigational information such as location, altitude, and heading, is used to create fine-scale imagery. Using special hardware and software, this imagery can be viewed in stereo on a computer and above-ground biomass measurements can be estimated (assuming some type of reference data or relationship to biomass is defined). This system has been developed using three distinct forest types: a closed tropical forest and a tropical savanna with open grasslands (both in Belize), and a homogeneous temperate forest in Mississippi.

Sensors used: Airborne videography system tied in with GPS and IMU data for positional information.

Spatial extent: Useful for plot-level or areas of only a few square kilometers.

Examples: This videography system has been demonstrated in a closed tropical forest and a tropical pine savannah in Belize, and a bottomland hardwood forest in the United States. It has also been used to analyze deforestation and forest degradation within the Congo.

Strengths: While this methodology has not been used for forest-wide or nationwide carbon estimation, it could be useful as part of a ground inventory effort to reduce the costs of obtaining reference data. Since this system is airborne-based, there is very little environmental restriction on where or when it can be used. It has proven effective over a variety of forest types and could reduce costs of obtaining plot data in locations that are challenging to reach on the ground.

Drawbacks: The system requires some ground data collection to calibrate results. It cannot directly estimate below-ground biomass, although well-calibrated allometric relationships may be used. The system requires a well-trained analyst, which may cost more than field personnel in some locations.

Other considerations: Unless a videography system is present locally, there could be an added cost to ship the sensor. Low-altitude flights may also be restricted in some locations.

CLASlite: Approach to Monitoring Deforestation and Forest Degradation

Background: CLASlite was created by Greg Asner, and others (2009) as an extension to the Carnegie Landsat Analysis System (CLAS), which was developed for large-scale mapping of tropical forest degradation by remote sensing experts. CLAS was updated to include deforestation data and redeveloped to allow automation, which makes it suitable for non-experts. The CLASlite method is simplified by using an automated cloud mask, shadow mask, and atmospheric aerosol thickness estimation. These steps are usually performed manually by an analyst, and automating them in preprocessing allows a non-expert user to complete the process. The core of CLASlite is a subpixel classification. Each pixel is broken into percentages of photosynthetic vegetation (live), non-photosynthetic vegetation (dead or senescent), and bare substrate. The system has a fully automated approach, which applies robust classification techniques without the need for expert analysts.

Sensors used: Landsat TM and Landsat ETM+, ASTER, EO-1 ALI, SPOT, and MODIS.

Spatial extent: The site used for development in the Peruvian Amazon was 900 square kilometers of lowland tropical forest.

Examples: While it was being developed, CLASlite was used to map selective logging in the Brazilian Amazon, then updated to include deforestation data and successfully tested in the Peruvian Amazon. The system has been used successfully in highly diverse ecosystems with varying topography. It has since been tested on other ecological types as well, including sites in Borneo, Madagascar, Mozambique, and the Hawaiian Islands. The spectral library may need to be updated for land cover types that significantly depart from the mid-latitude types.

Strengths: CLASlite is a fully automated land cover mapping tool that is accessible to non-experts. It is capable of running a countrywide analysis on a typical desktop computer. To help mitigate cloud problems, CLASlite can use data from multiple sensors. The system creates a spatially explicit error estimate output image. This allows the user to evaluate areas of uncertainty and determine if they are part of a class that is not well represented in the spectral library, as well as estimate a lower level of uncertainty.

Drawbacks: This system does not directly estimate carbon stocks. However, the resulting land cover change maps can be further evaluated and used to estimate carbon-stock losses on an annual or biannual basis.

Other considerations: This method requires an extensive spectral library, which has been established for savannas, woodlands, shrublands, and broadleaf tropical forests. It is unlikely that more spectral signatures would need to be obtained unless land cover types are significantly different. The system offers a complex classification system while avoiding the need to train expert users.

CLASlite + LiDAR: Mapping Carbon Stocks Directly

Background: CLASlite alone is a useful tool for REDD, but it has limited ability without extensive field data. The inventors—Asner and his group—developed a cost-effective way to achieve a more comprehensive data set using LiDAR (light detection and ranging). LiDAR augments the CLASlite system to create a product that inventories carbon stock among different land cover types. LiDAR-to-biomass models replace field-plot-measurements-to-biomass ones. However, some field-plot measurements are required to establish LiDAR-to-biomass relationships.

Sensors used: Landsat TM and ETM+, ASTER, EO-1 ALI, SPOT, MODIS and airborne LiDAR.

Spatial extent: The site used to analyze this technique was an 8,000 km^2 sample area in the Brazilian Amazon.

Examples: LiDAR-to-biomass estimates have shown to be as accurate as ground measurements-to-biomass equations.

Strengths: Adding LiDAR data to the CLASlite system provides the ability to make carbon-stock estimates, rather than only calculating canopy cover loss or gain. The combination reduces the number of field plots needed to complete an inventory.

Drawbacks: This method requires a great deal of planning to be executed in a method that is as accurate as possible. An up-to-date, detailed land cover map of the entire study area is needed. A large land mass with significant variation in biomes would require flying a large amount of LiDAR data.

Other considerations: According to Asner (2009), the Carnegie Airborne Observatory can operate its LiDAR at a cost of $0.20 per hectare. This does not include ferrying the aircraft and sensors to the site, which is usually the most expensive part. In remote, developing nations, LiDAR may be cost prohibitive. Using the CLASlite land cover mapping system and free satellite imagery helps keep the cost low for producing a high-level product. The other major cost is the field validation plot data needed to adjust and evaluate the LiDAR-to-biomass equation.

Airborne Taxonomic Mapping System

Background: An advancement of Asner's previous airborne LiDAR sensor package (see the CLASlite + LiDAR summary), the Airborne Taxonomic Mapping System (AToMS) adds two spectrometers to the LiDAR sensor. By combining the information from the three sensors, as well as a large (and expanding) library of spectral signatures, the Carnegie Institute is able to map the physical structure of a forest in three dimensions, including its chemical and optical properties. By recording the spectral information in several specific wavelengths, they are able to map species within the forest, the health of the trees, and locations where the forest is growing the fastest.

Sensors used: LiDAR, a custom designed VSWIR spectrometer, and a spectrometer with zoom lens in an integrated package mounted in the Carnegie Airborne Observatory (CAO) aircraft.

Spatial extent: Forest, regional.

Examples: The system has been used in Madagascar and the Peruvian Amazon, with trips to Columbia and Panama also planned.

Strengths: AToMS can obtain biomass and carbon estimates across large areas, or can be used in smaller areas in conjunction with satellite imagery to provide broader coverage. It could be particularly valuable for gathering biomass estimates in inaccessible areas. The ability to obtain biomass and species ground reference could result in cost savings from not having to send ground crews into difficult terrain.

Drawbacks: AToMS could require a large extent of work by well trained biologists to obtain ground reference for any species not already in the system's library. System requires expert analysis, and could be very expensive.

Other considerations: Information is also useful for biodiversity, ecological, and hydrologic studies.

Nationwide Forest Resource Assessment (FRA) in Nepal

Background: Nepal—with the financial and technical assistance of Finland—is carrying out a national forest inventory. As a REDD+ pilot country, Nepal plans to perform a complete forest inventory. This includes incorporating all five carbon pools identified by the Intergovernmental Panel on Climate Change (IPCC): above-ground biomass, below-ground biomass, dead wood, litter, and soil. The FRA inventory will include 5,000 permanent, stratified plots where they will collect a wide array of reference data. This data will be combined with several remote sensing data sets, primarily from Landsat, to complete a national carbon inventory.

Sensors used: Landsat ETM+, IKONOS, MODIS, QuickBird, and the Indian Remote Sensing (IRS) LISS III sensor. Alternatives to field inventory collection in remote and inaccessible areas include the use of high-resolution satellite data, airborne imagery, or LiDAR to estimate field-plot parameters for biomass calculations.

Spatial extent: The entire country of Nepal.

Examples: The plan developed by Nepal can be used as a guideline to develop a national inventory for any country. The plan is comprehensive, utilizing ground inventory, remote sensing techniques, and statistical analysis.

Strengths: The methodology is a comprehensive inventory effort, utilizing multiple remote sensing tools in combination with extensive fieldwork. The data will produce a wall-to-wall estimate of carbon, including areas that are currently not forested. Labor for completing the groundwork in this region is very inexpensive.

Drawbacks: Obtaining Tier 3 REDD+ status requires annual assessment of ground plots, which will be a challenge given the large areas of steep terrain and lack of access within the Himalayan region that accounts for a large part of Nepal. The inventory is very expensive; the estimated total cost for all elements is budgeted at €5.5 million (c. $7.6 million).

Other considerations: The data will be mapped according to forest resources and cover types with regression models used to calculate biomass/carbon amounts based on data from the ground plots. High-resolution IKONOS satellite data, or potentially LiDAR data, will be used to estimate plot-level statistics for biomass calculations. This is particularly important due to the inaccessibility of many parts of the country.

Decision Tree Matrix: Biomass Estimations in the Amazon Basin Using Remotely Sensed and Ground-Plot Data

Background: This method results from a study that estimated live biomass volumes by integrating remotely sensed data with on-the-ground plot information for the entire Amazon Basin (Saatchi and others 2007). The remotely sensed data is used to represent structural canopy features and environmental variables, and provided study-area-wide coverage. The ground-plot data supplied the biomass measurements needed to correlate the remotely sensed data and also provided an assessment of accuracy.

Sensors used: MODIS 32-day composite NDVI and LAI, QuikSCAT (radar) mean and standard deviation backscatter, JERS-1 radar, and SRTM.

Spatial extent: This methodology was implemented over the entire Amazon Basin.

Examples: This study succeeded in mapping biomass volumes across a large area with an overall accuracy of 78 percent. This is very high considering the spatial variability and extent of the study. This technique would be suitable anywhere as long as the data were similar to this study. This method can also be applied to any reasonable remotely sensed data set for classification. Note: Since the ground-plot data did not constitute an actual inventory, it is impossible to compare inventory estimates to remote sensing ones.

Strengths: This system incorporates a unique kind of remotely sensed data (radar) that is not typically used but has great value since radar can penetrate clouds. When combined with extensive ground and spectral data, radar information can help provide accurate biomass volumes.

Drawbacks: A large amount of ground biomass measurements are required. This technique is complicated to implement, and trained remote sensing or GIS professionals are needed to run this analysis. The spectral data came from free sources, but radar data can be expensive. The classification took advantage of existing ground-plot data, which kept some costs down, but plot data collection can be expensive if it has to be done as part of this method.

Other considerations: None identified.

CATHALAC Tropicarms

Background: CATHALAC is an international organization based in Panama involved in research and development, education, and technology transfer for sustainable development in Latin America and the Caribbean. It has developed methods to evaluate forest change and estimate biomass throughout the region, working on many pilot projects with NASA, USAID, the UN, and other partners. To assist countries in REDD+ readiness, CATHALAC has developed a Web-based tool called Tropicarms.

Sensors used: Utilizing multiple sensors—including Landsat, ASTER, and MODIS—Tropicarms can download data at a variety of spatial resolutions and time frames for maximum flexibility.

Spatial Extent: Tropicarms is scalable and can be used at a national, regional, or local level.

Examples: Tropicarms was developed primarily to monitor forest carbon in the tropical regions of the Americas and the Caribbean, but is suitable for any carbon monitoring project across a variety of land cover types and land uses. It has also been demonstrated in African, Asian, and Oceanic forests.

Strengths: The major benefit of Tropicarms is that it allows a country to estimate forest biomass and carbon stocks without investing in infrastructure or expertise. Clients do not need to employ their own experts to develop algorithms and analyze the data. Instead, Tropicarms has developed the modules. The system is an Internet-based software-as-a-service that runs on servers, rather than the user's computer. This liberates the user from having to purchase high-end workstations and imagery processing software to complete an analysis. The system contains a series of processing modules where the user selects the data to use as an input and receives the desired results, such as carbon amounts or biomass change. For example, if a user desires up-to-the-moment carbon amounts, this typically requires MODIS data (which can be collected daily) but results in lower-resolution, national-level information.

There remain cases where the user must collect data. For example, data is required to develop country-specific information and emissions factors relating to biomass for a Tier 2 or Tier 3 approach (this data can be obtained from ground-based inventories or published data). If this information is not available, Tier1 level estimates of carbon stocks can still be obtained, as well as historical estimations of carbon back to 1990, allowing for baseline estimation.

Drawbacks: Clients are very dependent on Tropicarms—there is little in-country infrastructure or expertise development.

Other Considerations: The modules can be used to test hypothetical situations once they have been purchased.

Normalized Difference Fraction Index: Combining Spectral and Spatial Data to Map Canopy Damage

Background: This study (Souza and others 2005) used spatial anthropogenic features, specifically roads and log landings, to indicate the type of disturbance occurring. This technique employs both a contextual classification algorithm and a new spectral Normalized-Difference Fraction Index (NDFI). The NDFI classification and the proximity of pixels to log landings (spatial distance) can determine if the pixel is "forest disturbed." This technique assumes that the degradation is caused by logging that uses landings. However, as an index, the NDFI reveals areas with values associated with degradation, regardless of their proximity to a log landing. This method can be adapted for different types of forest cover in various locations and can reasonably be applied over large areas.

Sensors used: Landsat TM.

Spatial extent: The area evaluated in this study fits within one Landsat scene (185 kilometers square), but can be used for any sized area.

Examples: The location for this study was the state of Mato Grosso in Brazil. Ground data was collected in 19 forest areas of 0.5 hectares (10-by-500 meter transects). The data collected included the Diameter at Breast Height (DBH) for all trees greater than 10 centimeters. Every 50 meters along the 500 meter transect, a 10-by-10 meter subparcel plot was added. In the subplots, ground cover and canopy cover fractions were estimated and tree locations were mapped. Above-ground biomass measurements were completed using published allometric equations. Forest disturbance history data were also used to help test the threshold of the index value of the NDFI.

Strengths: This method uses free satellite data and can detect forest degradation.

Drawbacks: The analysis requires trained GIS/Remote Sensing professionals to implement, which can be costly.

Other considerations: None identified.

DETER—Brazil's Rapid Deforestation Assessment Tool

Background: DETER (Sistema de Detecção de Desmatamento em Tempo Real, or Real-Time Deforestation Detection System) was developed by the Brazilian National Institute for Space Research (INPE). The country already had a system to estimate annual countrywide biomass loss (PRODES). The concern with the PRODES system was the inability to detect locations of illegal logging in near real time using Landsat imagery (Landsat only revisits a location every 16 days). Instead, the DETER system uses daily MODIS data for its analysis. The increased temporal coverage of INPE improves the opportunity to obtain cloud-free information.

Sensors used: MODIS; an improved system called INDICAR will utilize the Japanese Space Agency's PALSAR radar sensor on the ALOS satellite to supplement the MODIS imagery. With the loss of the ALOS satellite in May 2011, the INDICAR program will need to rely on a different active sensor.

Spatial extent: The entire country of Brazil.

Examples: Currently, the system is only used in Brazil. The techniques used by DETER are well established within the remote sensing community and can be readily adapted in other parts of the world where detecting illegal logging is a major challenge.

Strengths: With the wide coverage of the MODIS sensor, INPE can map the entire Amazon Basin without needing to process the several hundred individual scenes required for fine- or medium-resolution data. The daily overpass of the satellite increases the chances of obtaining cloud-free data over the two-week analysis period. Data from several days can be merged to create a single image, and any pixels covered by clouds are removed and replaced by those with non-cloud data. Use of this system should be fairly cost effective as the data from MODIS is available for free. The main cost is a trained analyst to process the data since the spectral mixing process requires some expert knowledge, but a worker familiar with image processing can also be trained by a knowledgeable expert.

Drawbacks: This methodology is not used for biomass or carbon estimation. The biggest drawback to using MODIS for detection of forest change is its spatial resolution—harvest or disturbance areas must be at least 50 hectares for reliable detection.

Other considerations: None identified.

Our Planetary Skin

Background: Planetary Skin (www.planetaryskin.org) is a nonprofit collaboration between NASA and Cisco to address the need to "harness the power of information technology and networks to help decision-makers manage scarce resources and risks more effectively in a changing world," according to its Web site. One of the first live skins is the Forestry Skin. Using proven algorithms developed by project partners INPE (see the information on the DETER program) and the University of Minnesota, Forestry Skin incorporates land use data from various sources with a change detection system that leverages time-series data from the MODIS sensors. The algorithm provides a historical spatial record of deforestation and near-real-time change detection. The Web-based service is free and includes additional data such as United Nations Environmental Programme Protected Area boundaries, NASA-CASA carbon stock and carbon flow maps, and forecast maps.

Sensors used: MODIS.

Spatial extent: Global coverage.

Examples: The Web application can be accessed at http://www.ourplanetaryskin.org.

Strengths: Access to the data is free. Eventually, registered users will be able to add datasets relating to land use/land cover change, and other moderate-resolution sensors may be added to the system later to improve the change detection algorithm. Additionally, disturbance data downloads are planned to be available. The underlying application (called ALERTS) can ingest other data such as economic figures, migration policies, historic land use maps, and soil fertility statistics to assess risks.

Drawbacks: The system does not provide a measurement of change in biomass or carbon. The algorithm primarily uses the 1km MODIS product and may not capture smaller disturbances. The Web site is still in the developmental stage, and many parts are still not functional.

Other considerations: Currently, the delay in reporting land change events is approximately 6 to 8 weeks, although this could eventually improve.

Terrestrial Observation and Prediction Program (TOPS)

Background: Terrestrial Observation and Prediction Program (TOPS) is a software system developed to integrate remotely sensed and ground data with climate models to predict ecological function changes—at this time, TOPS does not provide estimates of forest carbon stocks. It does have ecological forecasting for biogeochemical processes, including carbon, water, and nutrient cycling. Analyzing these processes along with ground ecosystem characteristics and up-to-date climate and weather data creates an ecosystem prediction. These forecasts can then be translated into drought threats, crop yields, Net Primary Productivity, and water yield estimates.

Sensors used: Landsat TM, several products from MODIS, AVHRR, AMSR-E, SSM/I, ASTER, SRTM.

Spatial extent: Global prediction coverage at 0.5-degree resolution, continental U.S at 8 km and at 1 km over California.

Examples: NASA performed a study in the Napa Valley to help manage crops more efficiently for the production of quality wine. The study found that inter-annual climate variability has a strong impact on wine quality.

Strengths: Every 8 days, TOPS assembles the latest MODIS data on land cover, other spectral indices, climate data, and more. It then re-grids the data to 0.5-degree resolution and expresses the output as weekly/monthly anomalies from long-term normals. When a persistent anomaly is detected, TOPS can be tasked to perform a higher-resolution model run for that region using the best possible data sets. This system provides tools to predict future resource conditions, resulting in improved resource management strategies and more efficient management practices.

Drawbacks: The low spatial resolution makes this system less practical for resource managers. However, it offers a way to evaluate the global impacts of climate variability on a local scale. The system does not directly estimate forest biomass or carbon stock.

Other considerations: More information about TOPS can be found at http://ecocast.arc.nasa.gov/ or downloaded at http://builds.worldwind.arc.nasa.gov/

Appendix D: Chart of Earth Resource Satellite Sensors

How to Use This Chart

This chart should be used to compare different Earth resource satellite sensors. Each of the sensors on the chart also appears in a subsequent section on data types, appendix E, which includes links to more information. The sensors are grouped into categories based on spatial and spectral resolution. Reviewing the introduction to each section in appendix E will help to interpret the table. Generally, the important factors separating the sensors are: revisit time (temporal resolution), coverage (swath width), finest spatial representation (spatial resolution), and the bands of data the sensor provides (spectral data). These characteristics should help managers determine appropriate sensor types for their area. The cost column indicates the relative expense of purchasing data. This is only the cost for obtaining imagery from the particular sensors archives, and requesting an acquisition will add to the cost. Occasionally, cost of data can only be obtained when placing an order for imagery, so costs for some sensors are not provided.

	Sensor Name	Satellite Name	Temporal Resolution (days)	Coverage (swath width)	Sensor Type	Spatial Resolution	Spectral Resolution	Appropriate Map Level	Cost
Coarse Optical	AATSR	Envisat-1	3	500 km	Multispectral	1 km	G, R, NIR, SWIR, MIR, TIR		Low
	ATSR	ERS-1, ERS-2	2–35	500 km	Multi/microwave	1 km to 20 km	G, R, NIR, SWIR, TIR/23.8 and 36.5 GHz		Low
	AVHRR	NOAA-#	Daily	2400 km	Multispectral	1.1 km	R, NIR, SWIR, 3 TIR		Free
	MERIS	Envisat-1	3	1,150 km	Multispectral	300 m land, 1,200 m ocean	B, G, R, NIR (15 programmable bands 390–1,040 nm)		Low
	MISR	Terra	2–9	360 km	Multispectral	4 at 250 to 275 m	B, G, R, NIR		Free
	MODIS	Terra, Aqua	Daily	2,330 km	Multispectral	2 at 250 m, 5 at 500 m, 29 at 1,000 m	B, G, R, NIR, MIR, Far IR, TIR	Mid, broad, national	Free
	SeaWiFS	OrbView-2	Less than 3	2,800 km	Multispectral	1km	V, V–B, B, G1, G2, R, NIR1, NIR2	National	Low
	VMI	SPOT-4, SPOT-5	1	2,250 km	Multispectral	1 km	B, R, NIR, MIR		Low
	HRCCD	CBERS-2	3p	113 km	Multispectral	1km	Pan, R, G, B, NIR		Low
	WFI	CBERS-2	3 to 5	890 km	Multispectral	260 m	R, NIR	Base, mid	Free**
Medium Optical	AWFI/WFI-2	CBERS-3*	5	866 km	Multispectral	64 m	B, G, R, NIR	Base, mid	Free
	ASTER	Terra	4–16	60 km	Multispectral	3 at 15 m, 6 at 30 m, 5 at 90 m	VNIR, SWIR, TIR		Low
	AWiFS	IRS-P6, RESOURCESAT-1	5p	370 km	Multispectral	56 m	G, R, NIR, SWIR		Low
	DMC	ALSat-1, UK-DMC2, NigeriaSat-X, Beijing-1, DEIMOS-1	Daily for the constellation	600 km	Multispectral	22 m to 32 m	G,R, NIR	Base, mid	Medium
	ETM+	Landsat 7	16	185 km	Multi/Pan	6 at 30 m, 1 at 60 m 1 at 15m	B, G, R, NIR, SWIR,TIR, Pan	Mid, broad, national	Free
	HRG	SPOT 5	2–3p	60 km	Multi/Pan	3 at 10 m, 1 at 20 m 2 at 5m	G, R, NIR, SWIR, Pan	Base, mid	Medium
	HRV	SPOT 2	2–3p	60 km	Multi/Pan	3 at 20 m, 1 at 10m	G, R, NIR, Pan	Mid, broad	Low
	HRVIR	SPOT 4	2–3p	60 km	Multi/Pan	4 at 20 m, 1 at 10m	G, R, NIR, SWIR, Pan	Mid, broad	Low
	IRMSS	CBERS-2, -3*	26	120 km	Multispectral	3 at 40 m, 1 at 80 m	Pan, 2 SWIR, TIR		Free**
	LDCM	Landsat Data Continuity Mission (LDCM)*	16	185 km	Multi/Pan	7 at 30 m, 1 at 100 m, 1 at 15m	B1, B2, G, R, NIR, 2 SWIR, TIR, Pan		Free

** Data are free to Latin American and African customers.

	Sensor Name	Satellite Name	Temporal Resolution (days)	Coverage (swath width)	Sensor Type	Spatial Resolution	Spectral Resolution	Appropriate Map Level	Cost
Medium Optical	LISS-III	IRS-P6, RESOURCESAT-1	24	70 km	Multispectral	23.5 m	G, R, NIR, SWIR		Low
	MSS	Landsat 1-5	16		Multispectral	57 m by 79 m	2 visible, 2 NIR		Free
	TM	Landsat 4-5	16	185 km	Multi/Pan	6 at 30 m, 1 at 120 m	B, G, R, 2 NIR, SWIR, TIR	Mid, broad, some national	Free
Fine Optical	LISS IV	IRS-P6, RESOURCESAT-1	5p	23.9 km	Multispectral	5.8 m	G, R, NIR	Base, mid, broad	High
	Cartosat-1	IRS-P5	5	29.41 km fore, 26.24 km aft	Panchromatic	2.452 m fore across track, 2.187 m aft across track, 2.54 m along track	0.5–0.85 µm	Mapping	Medium
	IKONOS	IKONOS	1–3	11 km	Multi/Pan	4 at 4 m, 1 at 1 m	B, G, R, NIR, Pan	Base, mid	High
	PANMUX	CBERS-3*	TBD	60 km	Multispectral	1 at 5 m, 4 at 10 m	Pan, R, G, B, NIR		TBD
	QuickBird	QuickBird	2–3p	16.5 km	Multi/Pan	4 at 2.4 m, 1 at 0.61m	B, G, R, NIR, Pan	Base, mid	High
	WorldView-2	WorldView-2	3.7 days for full res.	16.4 km	Multispectral	2.0 m	B1, B2, G, Y, R, R-edge, 2 NIR	Base, mid	High
				16.4 km	Panchromatic	0.5 m	Pan		Low
	Pléiades-1	Pleiades-1*	Daily	20 km	Multi/Pan	4 at 2 m, 1 at 0.5m	B, G, R, NIR, Pan	Base	TBD
	Pléiades-2	Pleiades-2*	Daily	20 km	Multi/Pan	4 at 2 m, 1 at 0.5m	B, G, R, NIR, Pan	Base	TBD
	AVNIR-2	ALOS (DAICHI)***	2	70 km	Multispectral	10 m	B, G, R, NIR		Low
Radar	AMSR-E	Aqua	24	1,445 km	Radar	6 km to 74 km	6.9–89 GHz (12 channels)		Medium
	PALSAR	ALOS (DAICHI)***	2	40–70km	Radar	7 m to 100 m	L (1.3 GHz)		Medium
	SAR	RADARSAT-1	1–6 @ max swath, 24 @ nadir	45 km–500 km	Radar/SAR	8 m to 100 m	C (5.3 GHz) HH only	Mid, broad, national	Medium
	SAR	RADARSAT-2	16	20 km–500 km	Radar/SAR	3 m to 100 m	C (5.3 GHz) quad-pol enabled		Medium
	SAR	ERS-2	3	100 km	Radar	30 m	C (5.3 GHz microwave)	Broad, national	Medium

* Satellite to be launched by the end of 2013.

** Data are free to Latin American and African customers.

*** The ALOS satellite ceased operations in May, 2011. Data from its sensors are still available in archives.

p Satellite can be tilted in orbit to improve revisit time.

Pan=Panchromatic, V= violet, B=blue, G=green, Y= yellow, R=red, NIR=near infrared, MIR=mid infrared, TIR=thermal infrared, SWIR=shortwave infrared, VNIR=very near infrared.

Appendix E: Remote Sensing Data Types

Coarse-Resolution Optical Data

These types of data are suitable only for broad-level mapping unless coupled with other data that has better spatial resolution. When integrated with higher-resolution imagery or field data sets, course-resolution imagery can effectively map land cover. The main advantage of coarse-resolution data sets is the short revisit time. The same scene may be available daily to once every 10 days, depending on the sensor. When a specific area of interest has long periods obscured by clouds, it is important to have a multitude of available imagery dates to create a viable data set. Often these data are free or inexpensive compared to higher-resolution imagery. Also these data cover large areas in one scene, as opposed to higher-resolution data which requires multiple scenes.

Land cover maps created from coarse data sets contain far less detail than those created with higher-resolution imagery. Coarse-resolution imagery also reduces the ability to identify small changes in land cover. These data are called optical because of their location on the electromagnetic (EM) spectrum. The sensors that acquire them are defined as passive. Passive sensors receive energy emitted by the target or surface being viewed.

AATSR (Advanced Along-Track Scanning Radiometer) is a sensor onboard the Envisat satellite owned by the European Space Agency. Its primary purpose is to measure the temperature of the sea surface. The sensor revisits a scene every 3 days and records seven bands of data, ranging from visible to thermal. The spatial resolution is 1 km and the swath width is 500 km.

http://envisat.esa.int/earth/www/object/index.cfm?fobjectid=3773

ATSR is a combination of data from two sensors on the ERS-1 and ERS-2 satellites, one infrared radiometer that records visible bands, and one sounder that measures emitted microwave radiation. The European Space Agency administers these satellites and uses them for monitoring oceans, natural resources, and atmospheric phenomena. The imagery has 1-km spatial resolution for visible and infrared data and 20 km spatial resolution for the microwave sensor. The two satellites are in orbit exactly one day apart so that ERS-1 covers the same area that ERS-2 covered the day before. The total revisit time is variable and can extend to 35 days. The swath width is 500 km.

http://earth.esa.int/object/index.cfm?fobjectid=4006

AVHRR (Advanced Very High Resolution Radiometer) is an optical multispectral scanner flown aboard National Oceanic and Atmospheric Administration (NOAA) orbiting satellites. The instrument measures reflected sunlight and emitted radiation (heat) from Earth daily in 4-6 bands in the visible, near-infrared, and thermal infrared regions of the electromagnetic spectrum at 1.1 km resolution. The instruments have been in use since the late 1970's, offering a large amount of historical data available.

http://eros.usgs.gov/#/Find_Data/Products_and_Data_Available/AVHRR

MERIS (Medium spectral Resolution Imaging Spectrometer) is a fully programmable instrument on the Envisat satellite owned by the European Space Agency. Data are collected in 15 bands in the visible and infrared regions of the EM spectrum. The sensor can collect data on any of the bands starting at 300 m pixel resolution. The swath width is 1,150 km and the revisit time is 3 days.

http://envisat.esa.int/instruments/meris/

MISR (Multi-angle Imaging Spectro-Radiometer) is one of the instruments on the Terra satellite owned by NASA. It contains cameras pointed at the Earth from nine different angles. The primary purpose of this sensor is to understand what happens to sunlight as it interacts with the atmosphere. Data are recorded in visible and near-infrared bands. The spatial resolution ranges from 250 to 275 m. The revisit time is between 2 and 9 days, and the swath width is 360 km.

http://www-misr.jpl.nasa.gov/

MODIS (Moderate-Resolution Imaging Spectroradiometer) is on the Terra and Aqua satellites, both operated by NASA. It provides 36 bands of data in the visible to thermal range of the EM spectrum. The imagery has a spatial resolution of 250 to 1,000 m, depending on the band. A unique feature of MODIS is that it has daily coverage of the entire Earth with a swath width of 2,330 km.

http://modis.gsfc.nasa.gov/

SeaWiFS (sometimes called SeaStar) was developed by Orbital Sciences Corporation to deliver daily images of the oceans, but it has proven useful in studying land phenomena. It has multispectral image datasets with a spatial resolution of 1 km. It rides on NASA's OrbView-2 satellite with a revisit time of less than 3 days and a swath width of 2,800 km.

http://oceancolor.gsfc.nasa.gov/SeaWiFS/SEASTAR/SPACECRAFT.html

VMI (Vegetation Monitoring Instrument, also simply called VEGETATION) is on the SPOT-4 and SPOT- 5 (Système pour l'Observation de la Terre) satellites, which were designed and developed by the French Space Agency with the participation of Sweden and Belgium. The VMI was developed for vegetation monitoring; the imagery has a spatial resolution of 1 km and a swath width of 2,250 km. Four bands of imagery from blue to midinfrared are recorded by the VMI. The revisit time for the VMI is 1 day.

http://uregina.ca/piwowarj/Satellites/SPOT.html

HRCCD (High-Resolution Charged Coupled Device) is a pointable sensor on CBERS-2 (China Brazil Earth Resources Satellite). The CBERS series of satellites were developed as a joint effort between China and Brazil. It has a spatial resolution of 1 km and a swath width of 113 km. Spectral data in the visible to very-near-infrared range are recorded every 3 days. The primary goal of CBERS is providing data to Brazil and China for land monitoring.

http://www.satimagingcorp.com/satellite-sensors/cbers-2.html

WFI (wide-field imager) is mounted on the CBERS-2 (China Brazil Earth Resources Satellite). This satellite was developed as a joint effort between China and Brazil and was launched in 2003. The WFI operates in the very-near-infrared region of the EM spectrum. The spatial resolution is 260 kilometers. This imagery is suitable for forestry evaluations over large areas. The revisit time is every 3 to 5 days, and the swath width is 890 kilometers.

http://www.satimagingcorp.com/satellite-sensors/other-satellite-sensors/cbers-2/

Medium-Resolution Optical Data

These data types are generally higher spatial resolution than the coarse optical systems and can map land-cover change more accurately. They have a revisit time ranging from 5 to 26 days. Moderate-resolution imagery is usually free or less expensive than high-resolution data, while also providing more detail than coarse-resolution sensors. However, fewer scenes for a given location due to less-frequent revisit times can be a drawback if an area is frequently cloud covered. These data must still be combined with ground or higher- spatial resolution data to create detailed mapping products.

AWFI (Advanced Wide-Field Imager, also referred to as WFI-2) is an instrument aboard the CBERS -3 satellite scheduled to launch in late 2011. Four bands of imagery from blue to near-infrared are recorded with 46 m spatial resolution. Scenes are revisited every 5 days, and the swath width is 866 km.

http://www.cbers.inpe.br/ingles/satellites/cameras_cbers3_4.php

ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer) is a sensor riding on the Terra satellite. ASTER is cooperative effort between NASA, Japan's Ministry of Economy, Trade and Industry, and Japan's Earth Remote Sensing Data Analysis Center. Data are collected in the very-near-infrared, shortwave-infrared, and thermal-infrared portions of the EM spectrum. The data sets range from 15 to 90 m in spatial resolution. The sensor's primary purpose is to support the study of change in the Earth's systems. The revisit time is 4 to 16 days, and the swath width is 60 km.

http://asterweb.jpl.nasa.gov/obtaining_data.asp

AWiFS (Advanced Wide-Field Sensor) rides on the IRS-P6, also known as the ResourceSat-1, which is operated by the ISRO (Indian Space Research Organization). The sensor records four spectral bands with a pointable spatial resolution of 56m. Its applications include forestry, agriculture, topography, water, and tectonics. The swath width is 370 km and the revisit time is 5 days.

http://www.euromap.de/products/prod_033.html

DMC (Disaster Monitoring Constellation) is designed to provide data comparable to Landsat to leverage the expertise of those familiar with that system. The sensors are housed in a series of satellites operated by several countries, including Algeria, Nigeria, and Turkey. Multiple sensors in orbit give the constellation a better opportunity to capture imagery over areas affected by natural disasters, which is the primary mission of the DMC. Any other time available is focused on capturing data for sale. The DMC collects data in only the green, red, and near-infrared wavelengths at a resolution of 22 or 32 m.

http://www.dmcii.com

ETM+ (Enhanced Thematic Mapper+) is aboard the Landsat 7 satellite operated by NASA, and the data can be downloaded from the USGS. Eight bands of data are recorded from the blue to the thermal zones of the EM spectrum. The visible and near-infrared imagery is available in 30-m spatial resolution. The panchromatic band has a 15-m and the thermal band a 60-m spatial resolution. The swath width is 185 km and the revisit time is 16 days. Landsat 7 is currently plagued by a scanner malfunction that results in a banding effect that may render resulting imagery unusable.

http://landsathandbook.gsfc.nasa.gov/

HRG (High-Resolution Geometric) is an instrument on board the SPOT-5 (Système Pour l'Observation de la Terre) satellite, which was designed and developed by the French Space Agency with the participation of Sweden and Belgium. The spatial resolution is between 5 and 20 m, depending on the band of data. Information is collected in the visible, near-infrared, shortwave infrared, and panchromatic ranges. The revisit time is 2-3 days; this is a pointable satellite, so data requests can easily be filled for a specific location. This sensor has a high degree of geometric fidelity. It can create a paired set of images that can be viewed in stereo and used to create for DEMs (digital elevation models). The swath width is 60 km.

http://www.spot.com/?countryCode=US&languageCode=en

HRV (High-Resolution Visible) is mounted on the SPOT-2 satellite, and collects visible and near-infrared data with a spatial resolution of 20 m and panchromatic data with a 10-m resolution. This sensor also has a pointable design, a revisit time of 2-3 days, and a swath width of 60 km.

http://www.spot.com/?countryCode=US&languageCode=en

HRVIR (High-Resolution Visible Infrared) rides on the SPOT-4 (Système pour l'Observation de la Terre) satellite. Data are recorded in the visible, near-infrared, shortwave-infrared, and panchromatic ranges. Spatial resolution for these data is 20 m except for the panchromatic band, where it is 10 m. This pointable sensor was developed with vegetation monitoring in mind. It has a revisit time of 2-3 days and a swath width of 60 km.

http://www.spot.com/?countryCode=US&languageCode=en

IRMSS (Infrared Multispectral Scanner) is on CBERS-2 (China Brazil Earth Resources Satellite) and collects three bands of infrared and a band of panchromatic data. The spatial resolution is 40 m except for the thermal band, where the resolution is 80 m. Its revisit time is 26 days, and the swath width is 120 km.

http://www.cbers.inpe.br/ingles/satellites/cameras_cbers3_4.php

LDCM (Landsat Data Continuity Mission) is a sensor and platform that are still under development. The purpose is to continue the global coverage and historical record of imagery offered by previous Landsat systems. The sensor is planned to have nine bands, including visible, aerosol, near-infrared, two mid-infrared, thermal, panchromatic, and cirrus. The sensor and its platform is scheduled to be launched in December 2012.

http://ldcm.nasa.gov/

LISS-III (Linear Imaging and Self-Scanning sensor) is on the IRS-P6 satellite, also known as the ResourceSat-1, operated by the ISRO (Indian Space Research Organization). Data are recorded in four bands: green, red, near-infrared, and shortwave-infrared. The spatial resolution is 23.5 m with a revisit time of 24 days. The swath width is 70 km.

http://www.isro.org/satellites/irs-p6resourcesat-1.aspx

MSS (Multispectral Scanner) rides on board the Landsat 5 satellite operated by NASA. This sensor records two bands of visible data and two bands of infrared data with a spatial resolution of 57 by 79 m. The revisit time is 16 days. The properties of this MSS sensor are consistent with those aboard previous Landsat satellites.

http://landsat.gsfc.nasa.gov/

TM (Thematic Mapper) is also on the Landsat 5 satellite operated by NASA. This instrument records six bands of data, from blue to shortwave infrared, with a 30-m spatial resolution. The seventh band is the thermal band which has a spatial resolution of 120 m. Revisit time for this data set is 16 days with swath width of 185 km. The TM sensor was developed as a more advanced Earth-resources sensor than the MSS.

http://landsat.gsfc.nasa.gov/

Fine-Resolution Optical Data

Fine-resolution sensors have a spatial resolution of 10 meters or less. These data are more expensive but provide the highest amount of detail possible for space-borne optical sensors. One drawback to fine-resolution data is the greatly increased processing volume. The amount of imagery needed for complete coverage of a given area is greater than for a moderate-resolution sensor. The amount of data and the cost associated with their fine resolution make them impractical for most countries to use for wall-to-wall coverage.

LISS-IV (Linear-Imaging and Self-Scanning sensor) is mounted on the IRS-P6 (ResourceSat-1) satellite owned by ISRO (Indian Space Research Organization). Data are recorded in the green, red, and near-infrared locations of the spectrum. These three bands are useful for land cover mapping. The spatial resolution of the data is 5.8 m. The sensor is pointable, so the revisit time is as little as 5 days with a swath width of 23.9 km.

http://www.isro.org/satellites/irs-p6resourcesat-1.aspx

CARTOSAT-1 is aboard the IRS-P5 satellite, built and operated by the ISRO (Indian Space Research Organization). The sensor on this satellite records panchromatic data in stereo pairs in 0.5-0.85micrometer wavelengths. The revisit time for this sensor is 5 days. The primary use for this data is creating DEMs, based on the 3-D data from stereo pairs.

http://www.isro.org/satellites/cartosat-1.aspx

IKONOS is a commercial satellite owned and operated by DigitalGlobe (formerly by GeoEye). The data are collected in the multispectral range with a 4-meter resolution and panchromatic with a 1-m resolution. The sensor is pointable, and therefore the revisit time is 1-3 days; it can create stereoscopic images. The swath width for this sensor is 11 km.

http://www.digitalglobe.com/about-us/content-collection#ikonos

PANMUX is currently in development and will be mounted on the CBERS-3 satellite. The data collected will be in the visible and near-infrared range at 10-m spatial resolution and panchromatic with a resolution of 5 m. With a swath width of 60 km, these data can be used for land cover mapping.

http://database.eohandbook.com/database/instrumentsummary.aspx?instrumentID=700

QuickBird is a commercial satellite owned by DigitalGlobe. Visible and near-infrared data are collected with a spatial resolution of 2.4 m. Panchromatic data have a spatial resolution of 0.61 m. This sensor is also pointable with a revisit time of 2-3 days and a swath width of 16.5 km.

http://www.digitalglobe.com/about-us/content-collection#satellites&quickbird

WorldView-2 is a commercial system owned by DigitalGlobe. The data collected by this sensor include coastal (narrow band in the low blue wavelength), visible, edge-red, near-infrared, and panchromatic bands. The spatial resolution is 2 m, except for the panchromatic band, which has a 0.5 m resolution. Revisit time for this sensor is 3.7 days, and the swath width is 16.4 km.

http://www.digitalglobe.com/

Pléiades-1 and **Pléiades-2** are owned by the Spot Image Company. The two satellites are planned to be launched as a constellation by the middle of 2012. Together they will provide visible and infrared data with 2 m resolution and a daily revisit time. The satellites will also collect a panchromatic band with a resolution of 0.5 m. This constellation will offer excellent locational accuracy of 3 m before orthorectification. The swath width for these sensors is 20 km.

http://www.spot.com/?countryCode=US&languageCode=en

AVNIR-2 (Advanced-Visible and Near-Infrared Radiometer type 2) was on the ALOS (Advanced Land Observing Satellite) developed by the Japan Aerospace Exploration Agency (JAXA). This sensor provided data in the visible and near-infrared zones of the EM spectrum for land and coastal observation. The spatial resolution of the data was 10 m with a revisit time of 2 days. The swath width for this sensor was 70 km. The ALOS satellite ceased operations in May 2011, and only archived data is available from the AVNIR sensor.

http://www.eorc.jaxa.jp/ALOS/en/about/avnir2.htm

Active Sensor Data

Active sensor systems produce the energy they are recording. All of the sensors discussed in the optical sections are passive; they record energy that was created by the sun and has interacted with the Earth in some way. Active systems transmit energy to a surface and record the energy that is reflected back to the sensor. Radar systems provide information about the target's moisture content and structure. The major benefit of active sensors is the ability of the wavelengths of the energy produced to penetrate clouds, allowing them to be used at any time. Since the sensors do not depend on the sun's energy, they work at night as well as during the day. Also, depending on the wavelength of the radar system, problems with the presence of aerosols in the atmosphere can be eliminated.

Coarse-Resolution Passive Microwave Data

AMSR-E (Advanced Microwave Scanning Radiometer for EOS) was developed by the National Space Development Agency of Japan (NASDA) and is mounted on the Aqua satellite developed by NASA. It is a passive microwave radiometer that records data that are emitted from the Earth in six locations of the EM spectrum. It has a spatial resolution ranging from 6 to 74 km depending on the data band. Its primary objective is to provide information about precipitation, water vapor, sea-surface temperatures, soil moisture, and snow cover. Possibilities for land cover mapping with this data is marginal, although research continues to investigate how moisture information relates to vegetation health and amount.

http://aqua.nasa.gov/about/instrument_amsr.php

Multi-Resolution Active Microwave Data

PALSAR (Phased-Array L-band Synthetic Aperture Radar) was on the ALOS satellite, which was launched by Japan. PALSAR collected data in single-, dual-, or quadrature-polarization. The polarization allows for greater interpretability of the data. The spatial resolution varies accordingly from 10 to 100 m. In the quadrature-polarization mode, this sensor produced data suitable for global or regional scale land use classifications. These data have a spatial resolution of 7-100 m, and were collected in the L-band at 1.3 GHz. The ALOS satellite ceased operations in May 2011, and only archived data is available from the PALSAR sensor.

http://www.eorc.jaxa.jp/ALOS/en/obs/palsar_strat.htm

Medium-Resolution Radar Data

SAR (Synthetic Aperture Radar) is available from the RADARSAT-1 satellite developed by the Canadian Space Agency (CSA). The sensor was developed to monitor land resource changes. The sensor's beam can be steered to different incident angles, creating swath widths of 45 to 500 km. The spatial resolution, therefore, varies between 8 and 100 m. The revisit time is dependent on the swath width, with the standard 100 m width covering the Earth every 24 days, and its steerable mechanism allowing for a fewer number of days between acquisitions of a single place on Earth. The EM data recorded are at 5.3 GHz, also referred to as the C band. The system is HH polarized, which means energy emitted from and recorded by the sensor is polarized in the horizontal direction. The type of polarization has an effect on the interpretability of the data. SAR on the RADARSAT-2 works in a similar way. The spatial resolution ranges from 3 to 100 m and it also records C-band data. The data are quadrature-polarized, rather than HH polarized, which means they are polarized in HH, HV, VV, and VH directions. This difference in polarization allows for greater object discrimination.

http://gs.mdacorporation.com/

SAR from ERS-2 (European Remote Sensing Satellite) is mainly used to observe the arctic regions. Data are collected in the C band at 5.3 GHz, with a spatial resolution of 30 m. The swath width is 100 km and the revisit time is 3 days. This system is VV polarized, meaning both the energy emitted and recorded by the sensor is vertically polarized. Data are only collected in image form when the vehicle is within line-of-sight communication with an ERS ground location. Therefore, this system's range of usability is limited to those ground locations.

http://southport.jpl.nasa.gov/polar/ers1.html

Other Data Sources

IfSAR (Interferometric Synthetic Aperture Radar), also called InSAR

IfSAR is a specialized radar technique that uses two or more synthetic aperture radar (SAR) images to generate digital surface models (DSMs) and digital terrain models (DTMs). The two SAR images are often collected simultaneously aboard the same platform; however, they can be collected at different times. A number of different radar bands with different characteristics are utilized, including X-band, P-band, and L-band. The bands affect the accuracy of the resulting products and their ability to penetrate the tree canopy. The generated DSM is a topographic model of the Earth's surface and includes vegetation, buildings, and other cultural features. The DTM is a topographic model of the bare earth, where the vegetation, buildings and other features have been removed. Both are typically provided as off-the-shelf products. Subtracting the DTM from the DSM provides vegetation height information—useful for vegetation and biomass mapping. The unit cost of IfSAR is much less than LiDAR, but the minimum project size is much larger. In some areas in Europe, the United States, and Asia, large inventories of IfSAR data are available to purchase.

LiDAR (Light Detection and Ranging)

LiDAR is an active remote sensing technique which sends a light beam to the target, and measures the time it takes to return to the sensor and how much intensity is lost. This system requires a specific type of aircraft and equipment. The laser scanner, an onboard Global Navigation Satellite System (GNSS, the US version is known as GPS), an inertial measurement unit (IMU), and a very accurate clock are necessary to collect LiDAR data. Post-spacing (i.e., how far apart each light pulse is) and flying height determine the spatial resolution of the data collected. LiDAR usually provides better than 1-m accuracy. Several returns can be recorded per pulse, which provides information about forest structure. The first return is assumed to be from the canopy top, the last return from the ground, and any other returns indicate some part of the canopy structure. LiDAR offers a lot of detail but at a fairly high cost. Transporting the aircraft and needed instruments to a study area can be very expensive. However, actual data collection costs are not significant considering the amount of detail provided, so a LiDAR system and aircraft that are located near a study site can be more cost effective. LiDAR does require specific image-processing methods and knowledge to extract information from the data, which can substitute for ground data by applying calibrated conversion factors. These conversions must be created through ground data validations, and for now LiDAR remains cost prohibitive compared to ground data acquisition and cannot replace an actual forest inventory.

Aerial Photography

Historically, aerial photography was used heavily for remote sensing. This type of data is still collected for many regions of the world. It provides an excellent source of map validation data due to the fine spatial resolution (typically less than half a meter.) Data collection of this type can be very expensive, so one must determine if the project justifies the expense. A significant number of photographs are usually needed to achieve adequate area coverage, which can create data management issues. Until recently, aerial photography was limited to the acquisition of frame images (similar to those from a hand-held film camera) and three bands of information, typically red, green, and blue. To be used in resource management, a technician needed to scan the film-based images into the computer and go through a lengthy process of geocorrecting them. Newer collections can take advantage of Global Navigation Satellite Systems (GNSS) and Inertial Measurement Unit (IMU) data to help automate the geocorrection process. In addition, modern sensors allow direct to digital collection of several bands concurrently, including hyperspectral imagers, which can collect hundreds of bands simultaneously.

Aerial Videography

Videography is the collection of full motion video from an airborne vehicle. This is an expensive method, but it provides high-resolution data, even less than 1 m. It is common practice to use videography in place of ground data to validate coarser map products, particularly in systems that utilize cameras pointed both forward and aft. This set up allows for the viewing of the data in stereo. An advantage of this type of system over aerial photography is that recording the data continuously makes it possible to match the location where ground data have been collected more accurately. In addition, videography is also useful for forest cover mapping.

Appendix F: Glossary

Afforestation—The conversion of land that has not been forested for a period of at least 50 years to forested land through planting, seeding and/or human-induced promotion of natural seed sources.

Atmospheric correction—Corrections to the radiometric properties of satellite data to remove the effects of the atmosphere so the pixel values more accurately represent values on the ground.

Baseline—The reference scenario or state against which change is measured. The Intergovernmental Panel on Climate Change (IPCC) uses this term interchangeably with business-as-usual.

Biomass—The total mass or volume of living organisms in a given area; dead plant material can be included as dead biomass.

Business-as-usual (BAU)—The pre-intervention land use and emissions profile for a forest carbon project area, also called the baseline.

Carbon pools—The five ecosystem components that contain terrestrial carbon as defined by the Intergovernmental Panel on Climate Change (IPCC): above-ground biomass, below-ground biomass, dead wood, litter, and soil.

Carbon stocks—The quantity of carbon in a carbon pool.

Cloud masking—A remote sensing technique used to remove pixels containing either clouds or their shadows from an analysis. These pixels are typically left blank or can sometimes replaced by pixels of the identical location containing non-cloud data from images acquired near the same date.

Deforestation—Conversion of land use from forest to non-forest, defined by a maximum threshold of crown cover typically between 10 to 30 percent of the original amount. Some definitions require a human-induced component.

Digital Elevation Model (DEM)—A raster grid of elevation values.

Electromagnetic spectrum—For remote sensing, the characteristic distribution of electromagnetic radiation emitted, reflected, or absorbed by a particular object, typically identified by its wavelength.

Endmember—The pure reference spectral signature of a particular material, typically used to construct classification algorithms.

Forest—An area where forest is the predominant use, defined by trees having a minimum cover of 10 percent, a height of at least 5 meters, and an area of coverage of more than 0.5 hectare or the ability to reach these values *in situ*. This does not include areas that are under agricultural or urban use (Food and Agriculture Organization of the United Nations 2005).

Forest degradation—The removal of trees to a level below the natural capacity but above what would be defined as deforestation. The exact definition in the REDD+ context is still being formulated by working committees.

Geocorrection—The process of assigning an image or images geospatial information so that they accurately represent locations on the Earth.

Hyperspectral remote sensing– the collection of electromagnetic energy from an object or area, using hundreds of narrow bands of the spectrum.

Incident angle—The angle between the most direct ray from an illumination source and that of the sensor.

Indices—In remote sensing, typically a ratio of individual bands used to extract information not readily seen by directly displaying the bands on a monitor.

Inertial Measurement Unit (IMU)—An electronic device which measures the angular orientation or attitude of the aircraft, and is collected with navigational (GPS) information during image acquisition. Used to aid in imagery geocorrection.

Infrared radiation—A portion of the electromagnetic spectrum from about 700 to 3,000 nanometers (0.7 to 3 micrometers).

Leaf Area Index (LAI)—A biophysical measurement of the total vegetation coverage of an area, typically computed as the ratio of all leaf surface areas divided by the total surface area of the land on which the vegetation grows. Values range from 0 for bare ground to 6 for dense forest.

Landsat—An Earth-observation program operated by NASA that has produced a series of seven satellites (one of which did not attain orbit) with sensors designed for systematic, repetitive, multispectral acquisition of data about resources.

Leakage—The unexpected loss of carbon benefits in an area caused by moving biomass removal activities to other locations outside the project, resulting in carbon emissions.

LiDAR (Light Detection and Ranging)—A remote sensing system that uses active laser scanning to measure height or elevation as well as certain canopy characteristics.

Methodology—For this project, methodology refers to the system of tools and procedures used to measure various characteristics of forest biomass and/or carbon.

Monitoring—An organized effort to track forest change using either remote sensing tools or evaluation of measured ground plots.

Multispectral remote sensing—Collection of electromagnetic energy from an object or area in multiple wide bands (more than 1 but less than 50) of the spectrum.

Normalized Difference Fraction Index (NDFI)—A ratio of the green vegetation, non-green vegetation, and soil endmembers used to estimate the amount of canopy cover depicted in a pixel.

Normalized Difference Vegetation Index (NDVI)—A ratio of several bands of satellite imagery (typically bands 3, 4, and 5 of Landsat data) used to estimate vegetation quantity and health.

Orthorectification—The process of geometrically correcting imagery to remove displacements caused by camera tilt and relief of terrain.

Panchromatic remote sensing—Collection of a region of the electromagnetic spectrum in a single band.

Permanence—A measure of how resistant a carbon stock or project is to potential changes that could reverse the carbon benefits of the project at a future date.

Pixel—A two-dimensional element representing a location on the surface of the Earth; the smallest non-divisible element of a digital image.

Pointable—The ability to rotate a satellite within its orbit to obtain data from a specific angle.

Radar (RAdio Detection and Ranging)—A system that uses short pulses of microwave energy and records the signal's strength and time of arrival to create a representation of the Earth's surface, with or without the natural and man-made objects.

Raster—A regularly spaced grid that stores values representing physical features within the computer's memory.

REDD (Reducing Emissions from Deforestation and Forest Degradation)—A program that rewards countries for the reduction in the conversion of native forests to non-forest land, includes activities that reduce degradation and enhance carbon stocks in degraded or secondary forests.

REDD+—An advanced version of REDD that awards credit for forest conservation and sustainable management of forests, and carbon stock enhancement. The program is the result of the Copenhagen Accord reached at COP-15 (2009 United Nations Climate Change Conference).

Reforestation—The re-establishment of forest on land that has not been tree covered for at least 10 years.

Remote sensing—Using sensors (typically aboard aircraft or satellites) to obtain data for analysis from objects, areas, or phenomena on the ground.

Scale—An indication of the relationship between the distances on a map or photo and the corresponding ground distances.

Sequestration—The process of increasing the carbon content of a carbon pool other than the atmosphere; for REDD it refers specifically to the pools of trees and soils.

Side-Looking Airborne Radar (SLAR)—A type of radar that sends the signal at an angle down to the side, rather than directly below the sensor.

Spatial resolution—For remote sensing, the ground distance (width) of a single pixel in a digital image. Traditionally defined (and still applicable for non-digital imagery) as how small an object in an image can be and still be "seen" by a sensor or human as being separate from its surroundings.

Spectral Mixture Analysis (SMA)—An algorithm that assumes that each pixel contains a mixture of several pure components (called endmembers) and analyzes the pixels to estimate the percentage of each endmember they contain.

Spectral resolution—A description of the bands of a sensor and their associated wavelengths.

Synthetic Aperture Radar (SAR)—Radar technology that uses the relative motion between an antenna and its target to artificially improve the spatial resolution of the sensor (hence its designation as synthetic). SAR sensors are located on both aircraft and spacecraft.

Temporal Resolution—The amount of time between two successive images of a particular area.

Validation—A process by which an independent third-party organization that has been certified to evaluate a project thoroughly reviews its design, methodologies, calculations, and strategies to ensure the project conforms to specific standards.

Verification—The periodic, independent review of the monitored reductions in greenhouse-gas emissions or increases in carbon stocks that have occurred as a result of project activity during a specific period.

Videography—A remote sensing technique where electronic imagery composed of analog or digital video signals is recorded on magnetic tape or magnetic or optical discs; the individual frames can be substituted for traditional aerial photography.

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