Title: Remote Sensing of REDD+

Name of Author	Nguon Pheakkdey
Name of University	Clark University
Country of Study	United States
Major	Human-Environment Geography
Degree	PhD
Course Title	Advanced Remote Sensing
Type of Document	Final Paper
Year	2011

GEOG39914: Directed Study with John Rogan
Student name: Pheakkdey NGUON

Overview: Remote Sensing of REDD+

Reducing emissions from deforestation and forest degradation and the role of conservation, sustainable management of forests and enhancement of forest carbon stocks in developing countries (REDD+) has significantly changed the landscape of theoretical and practical discussions of complex global environmental problems under the notions of development and climate change. However, the conceptual, technical, and not to mention financial, architecture of the global REDD+ itself is far from universally institutionalized. Therefore, the purpose of this Directed Study is to explore and expand the technical discussion of developing and implementing REDD+ projects with the application of remote sensing because not only has remote sensing been identified as an indispensable tool in providing geospatial data required to validate the establishment of REDD+ projects, it has also been proposed as the principal apparatus for the monitoring, reporting and verification component of the projects.

This report is divided into four segments starting with an in-depth literature review on the various meanings of "forest". The second part is also an in-depth literature review, but the focus is on the principles and capabilities of the different types of remote sensing instruments available currently for the purpose of mapping forest environments. The third segment provides a segue way into the fourth by outlining the proposed applications of remote sensing instruments in the development and implementation of REDD+ projects. Finally, the report integrates the information from the different parts and elaborates on them through the concepts of hierarchy theory and scene model discussed in Phinn, Stow et al. (2003).

Part 1 Defining “Forest”

Defining what constitutes a forest is not easy because forest types differ widely and are determined by such factors as latitude, temperature, rainfall patterns, soil composition and human activity. Different perspectives on tropical forests lead to very different definitions of deforestation. Nevertheless, it has been conventional to distinguish between restricted environmentalist definitions of forest, and more inclusive ‘economistic’ definitions (Barraclough and Ghimire 1995). Environmentalists, ecologists and conservation agencies such as World Wildlife Fund, International Union for Conservation of Nature and the World Conservation Monitoring Center (Sayer, Harcourt et al. 1992) consider the impact of excessive logging, wood gathering, fire and livestock grazing as deforestation, degrading the forest ecosystem through loss of biomass and ecosystem services. By contrast, those defining forests in terms of economic forestry, such as the Food and Agricultural Organization and the World Resources Institute tend to consider such processes as degradation, but not as deforestation unless they result in total conversion of forest to other land uses (Hall 1987).

A recent study of the various definitions of forests (Lund 2011) found that more than 900 different definitions for forests and wooded areas have been in use around the world – with some countries adopting several such definitions simultaneously. For example, in Cambodia "Forest" refers to natural ecosystems, land, water, plants, and micro-organisms, which are dominated by woody plants or bamboo of more than 10% and has a size of 0.5 hectare or more. Forests also include dry-land and wetland forest formations and any non-treed wetlands covering most part of land or open land within a forest that form 10% of that ecosystem. In addition, all stages of natural forest succession and planted trees for forestry purposes with a leaf density smaller than 10% percent or former forest land that were degraded by human action or natural acts but is expected to be repaired/ improved shall be deemed forest (Royal Government of Cambodia 2000)

It should be acknowledged that the information presented in the following tables have been purposely selected to provide the parameters which will be used at a later stage of the report. Having said that, Table 1. summarized the different parameters utilized by different organizations to define forests. Table 2. in addition, provides a sample of forest definition parameters adopted by some tropical countries for participation in the United Nations Framework Convention on Climate Change.

Table 1. Parameters of what constitutes a forest

Concepts	Parameters	Organization	References
Closed or Dense Forests	Area: > 0.5 ha Canopy cover: > 40% Tree height: ≥ 5 m	Food and Agricultural Organization	(Food and Agricultural Organization 1995; Food and Agricultural Organization 2005; Food and Agricultural Organization 2011) (Sasaki and Putz 2009)
Open Forests	Area: > 0.5 ha Canopy cover: 10-30%		
Evergreen Broadleaf Forests	Type: woody vegetation Canopy cover: > 60% Tree height: > 2 m	International Geosphere Biosphere Program	(Loveland, Reed et al. 2000)
Dense Forests	Canopy cover: > 70%	Tropical Ecosystem Environment Observation by Satellites project	(Achard, Eva et al. 2002)
Fragmented (Dense for FAO) Forests	Canopy cover: 40-70%		
Forest thresholds 1. Open Forests 2. Closed Forests 3. Dense Forests	Canopy cover 10-40% 40-70 % > 70%	Various	(Harcourt and Sayer 1996; UNEP 2001; Achard, Eva et al. 2002; Colson, Bogaert et al. 2009)
Forests	Area: > 0.05-1.0 ha Canopy cover: 10-30% Tree height: >2-5 m	United Nations Framework Convention on Climate Change	(UNFCCC 2002)
		Global Observation of Forest and Land Cover Dynamics	(GOFC-GOLD Report version COP16-1 2010)

Table 2: Samples of forest definition parameters adopted

Country	Minimum tree crown cover (%)	Minimum area (ha)	Minimum tree height (m)	Forest area in 2005 (‘000 ha)
Brazil	30	1.0	5	477,698
Cambodia	10	0.5	5	10,447
Colombia	30	1.0	5	60,728
Ecuador	30	1.0	5	10,853
Mexico	30	1.0	4	64,238
Peru	30	0.5	5	68,742
Vietnam	30	0.5	3	12,931
Thailand	30	0.16	3	14,520

Source: Food and Agricultural Organization **(2005)**

Part 2: Remote Sensing of Forest Environments: Instruments and Techniques

1. **Ground measurement**

   a. **Tree stems and crowns using lasers**

Laser measurement is termed – LiDAR (Light Detection And Ranging). The instruments developed for ground measurement of trees emit pulses of laser light which shine a spot smaller than 10-15 mm in diameter on an object (the size of the spot increases the further the object is away). This means that the three-dimensional position of objects as small as leaves can be measured. The instruments use the reflection of laser light to construct a three-dimensional image of the trees in a stand. These ground-based, laser measurement instruments are clearly showing potential for detailed measurement of tree characteristics. However, considerable research developments are still needed before they become useful in practice for broad-scale forest inventories, where hundreds or even thousands of plots may need to be measured routinely. The instruments themselves will need to be of a size, weight and durability to allow easy transportation by hand through dense vegetation and over difficult terrain. They will also need to operate much more quickly than at present, perhaps allowing complete measurement of a stand in no more than 30-45 min. Considerable work is also required to develop computer programs capable of analyzing the enormous amounts of raw data obtained from these instruments to derive the required measurements of the individual trees. One further limitation is that they can only determine stem measurements over bark; if under-bark measurements are required, assumptions will need to be made about bark thickness (West 2009).

   b. **Leaf Area Index Using Sunlight**

Leaf area index is an important stand parameter, useful to determine how much sunlight a stand absorbs and, hence, what the photosynthetic production of a stand might be. Instruments which determine leaf area index consider the straight beams of sunlight, coming from any point in the sky above, as 'pointers' which are being projected through the canopy. The path of any beam may be interrupted, by hitting a leaf so that it does not reach the ground below, or it may pass right through the canopy and reach a measuring instrument on the ground. By measuring how many beams of light pass through the canopy, these instruments determine the canopy gap fraction. If the canopy gap fraction is known, together with the angle from the horizontal at which the leaves in the forest hang, the Beer-Lambert law can then be used to calculate the leaf area index of the canopy. Unfortunately, this law requires that the leaves be randomly positioned within the canopy. This is generally not the case; leaves often occur in clumps on individual shoots and shoots are often clumped in different positions within the crown. Also, leaves are not opaque and a small amount of the light which hits them passes through them. In addition, some light beams are interrupted by tree stems or branches, rather than by leaves, and some light beams are scattered by reflection from several leaves. Various methods are used to allow for these complications in measuring leaf area index with these instruments (Fournier, Mailly et al. 2003; Jonckheere, Muys et al. 2005). Perhaps the most reliable way to allow for these complications is to calibrate the instrument specifically for the type of forest in which it is to be used.

c. Roots

Perhaps the measurement of roots is the last frontier of remote sensing of forest characteristics from the ground. The excavation of roots, to measure directly their biomass, length or distribution down the soil profile, is an extremely labor intensive and difficult task. One technique which shows some promise is the use of ground penetrating radar. It involves transmitting radio signals down through the soil and recording the times for reflections to be received back from objects within the soil. The higher the energy of the radio waves used, the deeper within the soil can they penetrate, perhaps to a maximum of about 10 m (West 2009). There are a number of difficulties with using radar in soil. First, the speed of travel of radio waves in air is the same as the speed of light, but soil slows that speed considerably, perhaps by more than one half. The speed is affected particularly by the temperature and amount of water in the soil (Butnor, Doolittle et al. 2003). This means that a ground penetrating radar instrument must be calibrated, before it is used on any day, to determine the speed of travel of radio waves in a particular soil. Also, soils contain many irregularities, such as rocks scattered throughout it or it may have various layers, each with rather different properties. These irregularities can lead to unwanted 'background' reflections of radio waves. These have to be removed from the data collected by the instrument, using complex computer programs, to leave only reflections from the objects it is desired to identify. Research in this field seems rather limited at present; clearly much more will have to be done before ground penetrating radar becomes useful generally for measurement of roots in forests (Wang, Grimley et al. 2008).

2. Airborne measurement

If broad-scale measurements are to be undertaken over hundreds or thousands of hectares of forests, it is practical to do so only using instruments carried aloft in aircraft or satellites. These can provide information useful for various purposes, including identifying and mapping different forest types, assessing their site productive capacity, stratifying the forest or providing covariate variables for inventory. A principal limitation to forest measurements taken from aircraft or satellites is that the forest canopy conceals the tree stems. This prevents direct measurement of the stem sizes and, hence, the wood volumes they contain. Perhaps an exception to this is the possibility of measuring deciduous forests during winter, when they have lost their leaves and their stems can be seen directly (Tarp-Johansen 2002).

a. Aerial Photography

Photographs taken from the air have been used extensively for forest management purposes for many years. Not only can aerial photographs provide measurements of some tree and stand characteristics, they can also be used for general mapping and for vegetation studies, perhaps identifying where different vegetation types occur across the landscape or where insect attack or disease has damaged the forest (West 2009). Aerial photography is also an essential tool to overcome the difficulty of varying terrains in the study areas as demonstrated in Harcombe at al. (2004).

b. Laser Scanning

This form of remote sensing uses laser light, transmitted from an aircraft or a satellite, some of which is reflected back when it strikes a solid object on the ground below. This is another application of LiDAR. For this form of remote sensing, a laser is used which emits light in pulses only some nanoseconds long and which reaches the ground as a spot. The size of the spot and the distance along the ground of successive pulses varies with the speed over the ground and altitude of the aircraft or satellite and the quality of the laser equipment. At best, very fine-grained information may be obtained with spot sizes and intervals between spots of only a few centimeters (West 2009). An example of the type of image of forest canopy which can be obtained using aerial borne LiDAR method is discussed in Lovell et al. (2005). As with aerial photographs, this often requires development of functions which relate those characteristics to the variables which are measured directly by the laser scanner.

c. **Spectrometry**

A spectrometer is an instrument which records the amount of each of a very wide range of wavelengths across the radiation spectrum. Typically, it might record the light received from as many as 300 separate, narrow, wavelength bands in the visible or infra-red light regions. In this context, a spectrometer is similar to a camera, except that a camera produces an image which combines the light received at many wavelengths, whereas a spectrometer records separately the light received at each wavelength. Spectrometers can be used on the ground, from the air or can be carried in satellites. However, for forestry purposes, there are some good examples of their use when carried in aircraft. Just as with aerial photographs, the properties of the instrument and the altitude at which the aircraft flies will determine the scale on the ground of the spectrometer recordings. At sufficiently a large scale, they can certainly record the radiation reflected from the crowns of individual trees on the ground below (West 2009).

3. **Satellites**

With their world-wide coverage at all times of the year, satellites offer one of the most comprehensive forms of remotely sensed information from forests. Some satellites are passive, that is, they sense radiation reflected from the surface of the earth. Others are active, that is, they emit radio or laser radiation which is reflected from the surface below back to the satellite (Eastman 2009). Satellite imagery has been used to map different forest types, to determine the density of forest canopies to determine the age structure of forests, to identify forest suffering decline, as an aid in predicting forest growth over large regions and as an aid in forest inventory. Satellite imagery has been used to map different forest types, to determine the density of forest canopies to determine the age structure of forests, to identify forest suffering decline, as an aid in predicting forest growth over large regions and as an aid in forest inventory (West 2009). Table 3. provides an overview of existing satellites.

Table 3. Summary of existing satellites

Satellite	**Description**
Landsat (U.S. Geological Survey) **Launch and Retirement Dates** Landsat 1 – July 23, 1972 to January 6, 1978 Landsat 2 – January 22, 1975 to July 27, 1983 Landsat 3 – March 5, 1978 to September 7, 1983 Landsat 4 – July 16, 1982 Landsat 5 – March 1, 1984 Landsat 6 - October 5, 1984 – DID NOT ACHIEVE ORBIT Landsat 7 – April 15, 1999	Launched from time to time between 1972 and 1999, they provide over 35 years of data, offering the possibility of studying changes that have occurred over that time in the vegetation at any point on earth. The most recent, **Landsat 7ETM+** provides images (**30 x 30 meter resolution**) of a variety of wavelength in the **visible and infra-red** light spectrum. These resolutions are inadequate to identify or measure individual trees in a forest, but are certainly adequate to identify quite fine scale variation in vegetation across the landscape. Unfortunately, there are some technical problems with the images obtained from Landsat 7, but similar images are still available from Landsat 5.
Others: I. Advanced Land Observing Satellite (ALOS, Japan),	

II. IKONOS (American), III. Indian Remote Sensing Satellite (IRS, Indian), IV. National Oceanic and Atmospheric Administration-Advanced Very High Resolution Radiometer (NOAA-AVHRR, American), V. Quickbird (American), VI. Systeme Probatoire d'Observation de la Terra (SPOT, French)	All these satellites produce images at each of several light wavelengths and, as their technology improves, at finer and finer resolution; some are attaining a resolution which allows individual tree crowns to be identified.

Source: *Remote Sensing of the Environment: An Earth Resource Perspective* (Jensen 2007)

Different research projects that have applied the abovementioned remote sensing instruments and techniques are summarized in Appendix 1.

Part 3: Applications of remote sensing instruments and techniques in REDD+

At the national level, the Intergovernmental Panel on Climate Change has produced a set of guidelines for estimating greenhouse gas inventories at different tiers of quality, ranging from Tier 1 (simplest to use; globally available data) up to Tier 3 (higher solution methods specific for each country and repeated through time) (Penman, Gytarsky et al. 2003; Eggleston, Buendia et al. 2006). Appendix 2. reviews and summarizes a range of approaches that could be adapted to estimate forest carbon stocks across tropical countries at different tiers of detail and accuracy. Biome averages and new geographically explicit datasets, for instance, provide rough approximations that can be immediately used to estimate a nation's carbon stocks (Tier 1). Ground-based measurements of tree diameters and height can be combined with predictive relationships to estimate forest carbon stocks (Tiers 2 and 3). Remote-sensing instruments mounted on satellites or airplanes can estimate tree volume and other proxies that can also be converted using statistical relationships with ground-based forest carbon measurements (Tiers 2 and 3). These approaches have varying benefits and limitations.

Part 4: Compliance matrix for comparing scene model and Landsat-5 TM data

Thus far, this report has reviewed literature on forest definitions, instruments and techniques for remote sensing of forest environments and comparison of proposed applications of remote sensing methods in REDD+ projects. In this last segment, the paper will attempt to explore the feasibility of employing remote sensing technology to assess and better address deforestation in Seima Biodiversity Conservation Area (BCA), a site selected for the implementation of REDD+ project in Mondulkiri province, Cambodia. This is because, at its core, REDD+ is a proposal to provide financial incentives to assist developing countries to voluntarily reduce national deforestation rates and associated carbon emissions below a baseline (based either on a historical reference case or future projection). Countries that demonstrate emissions reductions may be able to sell those carbon credits on the international carbon market or elsewhere. These emissions reductions could simultaneously combat climate change, conserve biodiversity and protect other ecosystem goods and services (Angelsen 2009). In short, the purpose of this study is to utilize the concepts and tools in remote sensing to determine whether current remotely sensed data source is appropriate to map deforestation in the study area. The two most important benefits of this analysis are (1) facilitating the feasibility of achieving the objectives of REDD+, and (2) recommending the most appropriate remotely sensed data source for the study area, should the current one is deemed unsuitable.

To accomplish this aim, relevant parameters and characteristics related to deforestation in Seima BCA are drawn to the literature reviews in previous sections, as well as the characteristics of available sources of remotely sensed data to understand deforestation rate in the area. In particular, a scene model and a compliance matrix are constructed to assist in this suitability comparison of the parameters specified in the scene model and the available remote sensing data. A scene model is comprised of spatial, spectral, radiometric, and temporal dimensions and represents the ideal data dimensions to address a particular question (Phinn, Stow et al. 2003). Once a scene model has been specified, a compliance matrix can assist in understanding how well available data matches this scene model (Phinn, Menges et al. 2000). The scene model was originally defined by Strahler, Woodcock et al. (1986) to generalize and parameterize the critical qualities of a scene. The object of interest is the landscape in the study site and the interest is on its composition (forested or non-forested). The scene model to determine deforestation in Seima BCA is presented in Table 4.

As of April 2011, there are five REDD+ projects in Cambodia, two of which are being implemented. The first REDD+ project in Cambodia, the Oddar Meanchey REDD+ project, is developed and currently being implemented under the community forest management option. The second REDD+ project, the Seima BCA REDD+ project, has been proposed to be implemented through protected areas combined with integrated community development programs. Seima BCA covers 298,250 hectares in Mondulkiri Province in eastern

Cambodia (Forestry Administration 2011). Wildlife Conservation Society in association with the Forestry Administration amongst other institutions including Clark Labs is developing the project. to map the various geospatial aspects (land use types, slope, distance to infrastructure…etc) of the study area, Landsat-5 TM data is used. In terms of mapping land use change from forest to other land use type, there are three Landsat-5 TM images of the area taken in 1998, 2002 and 2008. Table 5 provides a comparison of the scene model to the three Landsat-5 TM images of land use types in Seima BCA.

Table 4: Scene model to determine deforestation in Seima BCA

Information required	Extent of forest and non-forest land in Seima BCA
Environment type	Forests and other land uses
Spatial scale	Grain = individual forest stand (71 m)
	Extent = Seima BCA (2982.5 km^2)
Temporal scale	1 annual image at the close of monsoonal season (compare successive November images)
Components and hierarchy	Constraint: Forest/ non-forest stand matrix
	Focus: crown cover (> 10%)
	Mechanism: individual forest stand (>0.5 ha)
Spatial dimensions	H-resolution
	grain: 35.5 to 47 m
	extent: 2982.5 km^2
	Image comparison: match pixel sizes and ensure accurate geometric registration
Temporal dimensions	Optimal date: November
	Selected date: November 31 (years image taken)
	Solar conditions: 0°- 20° zenith angles
	Acquisition time: between 9:30 a.m. and 2:30 pm
	Image comparison: similar acquisition times
Spectral dimensions	Blue (400-500 nm), Red (600-700 nm)

	NIR (700 - 1100 nm), SWIR (1300-1800 nm)
	Image comparison: match spectral band centers and widths
Radiometric dimensions	Grain (quantization): 0.01
	Extent (dynamic range): green (0.04), red (0.07), and NIR (0.14)
	Image comparison: match quantization and dynamic range
Error tolerance levels	>85% accuracy in distinguishing forested areas from non-forested areas

Table 5. A compliance matrix for the comparison of Landsat-5 data to the scene model

Parameter	Scene Model	Landsat-5 Data	Level of match
Spatial			
Pixel size	35.5 - 47 m	30 m	Suitable
Scene extent	2982.5 km^2 (total area)	185 km^2	Suitable
H/L resolution	H-resolution	L-resolution	Suitable
Spectral			
No. of bands	5	4	Suitable
Position of bands	blue (400-500 nm),	blue (450-520 nm),	Suitable
	red (600-700 nm),	red (630 - 690 nm),	
	NIR (700-1100 nm),	NIR (760-900 nm)	
	SWIR (1300-1800 nm)		
Radiometric			
Quantization levels	0.004	0.004	Suitable
Dynamic range	N/A	N/A	N/A
Temporal			
Date	November 31	15 Nov '98, 10 Nov '02, 20 Nov '08	Suitable
Solar time	0°-20° zenith angles	Unknown	Suitable
Interval between	12 months	4 to 6 years	Non-preferable

images			
Error levels			
Types	forest delineation, forest labeling	N/A	N/A
Magnitude	>85% accuracy in distinguishing forest from non-forest	N/A	N/A
Time + cost	not specified	cost: $0	N/A

Discussion and Conclusion

Given the many different definitions of what constitutes a forest, the parameters used to construct the scene model are those that are adopted by the Cambodian government for participation in the United Nations Framework Convention on Climate Change. To reiterate, Cambodia defines forest as an area that is dominated by woody plants or bamboo of with at least 10% crown cover, and has a size of at least 0.5 hectare (Royal Government of Cambodia 2000). The resolution at which forest stand can be detected depends predominately on the size of the object of interest and the pixel size of the remotely sensed data. According to Woodcock and Strahler (1987), local variance peaks at a pixel size slightly smaller than the object (1/2 to 3/4 the size of the object in the scene). Based on this logic, if the object of interest is a forest stand (> 0.5 ha), then the ideal pixel size would be 35.5 m to 47 m. Based on this logic, Landsat-5 TM data (30 m pixel) should provide an accurate and precise extent of forest stands in Seima BCA. Overall, the construction of a scene model can be a very effective tool to assist in the selection of an appropriate remotely sensed data source to answer a complex global environmental question such as REDD+.

The main benefit of the scene model is that it allows users to be explicit about the assumptions and goals of the analysis. A compliance matrix, in turn, allows a clear comparison of data sources and how well a particular data source matches the scene model. Given the large extent of the study area, Landsat-5 data would provide a less data management intensive and much more cost-effective approach. If Landsat-5 is selected, the object of interest should be identifying forest stands, not an individual tree, because of the coarseness of Landsat-5 data (30 m resolution). In addition, the scale of the management unit must also be considered. Landsat-5 data are closely corresponded with the scale of the management unit compared to other finer data sources such as Quickbird or IKONOS. Plus, Landsat-5 data is currently available free of cost. Therefore, based on these reasons, Landsat-5 data seem to be the most appropriate to map the extent of forested and non-forested lands in Seima BCA for the development and implementation of REDD+ project. Once this initial data is collected, a case can be made for the feasibility of REDD+ project establishment within selected project areas. The next step for the project would be to move the project through the matrix of methods to estimate carbon stock with more advanced remote sensing techniques and instruments as specified in Appendix 2. As of 2011, for the more than 40 countries that are developing their national architecture for implementing REDD+, mapping the extent of forest and non-forest areas is still the main socio-political and technical discussion.

Appendix 1: Remote sensing of forest environments: instruments and techniques

Type	Instrument	Objective	Method	Discussion	References
Ground-based	**LIDAR** 2,000 laser pulses per second 10 mm spaced for light spots 3-dimensional scanning	Measure trees in 0.12 ha square in each of a mature red pine forest and a complex, uneven-aged, deciduous hardwood forest, dominated by sugar maple in Ontario, Canada	6 views of each plot, taken from points positioned outside the plots, to ensure each tree in a plot could be 'seen' clearly by the instrument It required about 6 hours to get these views. It accumulated data for the positions of over 30 million separate points within their two plots	Data were used to determine DBH of each tree in their stands and its total height. They found that the instrument gave unbiased estimates of tree stem diameters, with an accuracy quite adequate for normal forest measurement purposes. However, tree heights were under-estimated, by about 1.5 m on average.	**(Hopkinson, Chasmer et al. 2004)**
		Measure trees in 20-year-old plantation of loblolly pine in Virginia, USA	**Same as (Hopkinson, Chasmer et al. 2004)**	They were able to measure successfully how the diameter changed along individual tree stems to a height well within the tree crown. They were also able to determine the position of branches in the lower part of the crown. However, a small degree of bias was evident in their results.	**(Henning and Radtke 2006)**
	Leaf Area Index-2000 plant canopy analyzer	Develop a reliable leaf area index estimation function for plantations,	The instrument directs sunlight passing through the canopy to one of five light detectors, depending on the angle above the horizon from which the light beam was	They found that the canopy characteristics of flooded gum plantations changed sufficiently, even between 2-and 3-year-old plantations,	**(Dovey and du Toit 2006)**

		South Africa	directed. It detects light only in the ultra-violet to blue wavelengths.	that separate functions were required for both ages. This emphasizes how important it is to undertake the calibration process for any particular forest type in which the instrument is to be used.	
	Wide-angle photography	Estimate leaf area index in plantation stands of jarrah in Western Australia	Taking a photograph of the canopy, usually with a wide-angle lens, looking vertically upwards from the ground below	Found that digital photography, with or without a wide-angle lens, or the LAI-2000 plant canopy analyzer all gave very satisfactory estimates.	**(Macfarlane, Hoffman et al. 2007)**
	Ground penetrating RADAR	estimate the biomass of the root system, to a depth of 30 cm below the ground, in a 34-year-old experimental plantation of loblolly pine in Georgia, USA	Tested their system in different parts of the experiment, where the growth of the trees, hence their root biomasses, had been affected substantially by the experimental treatments.	They were able to identify roots only with diameters greater than about 5 mm. This would exclude fine roots. They also found that the ground surface over which the instrument was used had to be quite smooth and free of debris; this would pose a problem to the use of the instrument in native forests where under-storey plants and various sorts of ground debris are common	**(Butnor, Doolittle et al. 2003)**
Airborne	**Aerial photography**	Estimate the above-ground biomasses of individual trees in 40-year-old plantations of	They had available medium-scale (1:13,000) aerial photographs of the plantations. Photo interpretation using stereo pairs of photographs and special equipment which allowed measurement of the three-	They found negligible differences between the ground measurements and the measurements obtained from the aerial photographs. They dealt with this problem by developing a new	**(Massada, Carmel et al. 2006)**

		Aleppo pine in Israel	dimensional coordinates of the tip of each tree and the ground below.	biomass function for their species, from ground measurements of biomasses, crown diameters and heights of a set of sample trees.	
	Spectrometry	Predict the site productive capacity of pine plantation forests across wide areas of Queensland, Australia	Airborne spectrometry to measure the concentrations of three elements, potassium, thorium and uranium in the top 35-40 cm of the soil on the ground below. It does so by measuring the emission of y-rays (radiation of a rather short wavelength) emitted during radioactive decay of these elements.	They used the information to infer various properties of the soil including its depth, texture and its degree of weathering.	**(Wang, Preda et al. 2007)**
Satellites	**Landsat 7**	Monitore young Sitka spruce plantations in Britain, to determine if they have developed adequately	The average height and stand basal area of a number of plots, located in 2-17-year-old Sitka spruce plantations, were measured on the ground. It was found that their average height correlated well with infra-red light intensity, as measured for the plots from a satellite, whilst stand basal area correlated reasonably well with light intensity measured in green wavelengths.	The results were similar using data collected by Landsat 7 satellite. It was concluded that the satellite information was sufficient to allow assessment of the viability or otherwise of individual plantations.	**(Donoghue, Watt et al. 2004)**
	Japanese Earth Resources Satellite (JERS)	Detect and measure fresh plant biomass in open eucalypt forest in southern New South Wales, Australia	It was found that the level of radar reflection correlated reasonably well with both the stand above-ground live tree biomass and the biomass of coarse woody debris measured on the ground in a set of plots in open eucalypt forest in, Australia.	It was concluded that this form of remote sensing had some potential for the estimation of forest stand biomass.	**(Austin, Mackey et al. 2003)**

Appendix 2. Methods to estimate national-level forest carbon stock (After Gibbs, Brown et al.(2007))

Method	Description	Benefits	Limitations	Uncertainty
Biome average	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 described 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,	- Satellite data are generally free - New systems launched in 2005 expected to provide improved data	- Less accurate in complex canopies of mature forests because signal saturates - Mountainous terrain also increases errors	

	Envisat	- Can be accurate for young or sparse forest	- Can be expensive and technically demanding	Medium
Laser remote sensors	- LiDAR uses laser light to estimates 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

References:

Achard, F., H. Eva, et al. (2002). "Determination of deforestation rates of the world's humid tropical forests." Science **297**: 999-1002.

Angelsen, A., Ed. (2009). Realizing REDD+: National strategy and policy options. Denmark, Center for International Forestry Research.

Austin, J. M., B. G. Mackey, et al. (2003). "Estimating forest biomass using satellite radar: an exploratory study in a temperate Australian Eucalptus forest." Forest Ecology and Management **176**: 575-583.

Barraclough, S. L. and K. Ghimire (1995). Forests and Livelihhods: The Social Dynamics of Deforestation in Developing Countries Geneva, UNRISD and Macmillan.

Butnor, J. R., J. A. Doolittle, et al. (2003). "Utility of ground-penetrating radar as a root biomass survey tool in forest systems." Soil Science Society of America Journal **67**: 1607-1615.

Colson, F., J. Bogaert, et al. (2009). "The influence of forest definition on landscape fragmentation assessment in Rondonia, Brazil." Ecological Indicators **9**: 1163-1168.

Donoghue, D. N. M., P. J. Watt, et al. (2004). "An evaluation of the use of satellite data for monitoring early development of young Sitka spruce plantation forest growth." Forestry **77**: 383-396.

Dovey, S. B. and B. du Toit (2006). "Calibration of the LAI-2000 canopy analyzer with leaf area index in a young eucalypt stand." Trees **20**: 273-277.

Eastman, J. R. (2009). Idrisi Taiga Guide to GIS and Image Processing. Worcester, Massachusetts, Clark Labs.

Eggleston, H. S., L. Buendia, et al., Eds. (2006). IPCC Guidelines for National Greenhouse Gas Inventories. Japan, Prepared by the National Greenhouse Gas Inventories Programme, Institute For Global Environmental Strategies.

Food and Agricultural Organization (1995). State of the World's Forests. Rome, Food and Agricultural Organization of the United Nations.

Food and Agricultural Organization (2005). "Global forest resources assessment 2005. Progress towards sustainable forest management." FAO Forestry Paper **147**: Rome.

Food and Agricultural Organization (2011). State of the World's Forests. Rome, Food and Agricultural Organization of the United Nations.

Forestry Administration (2011). "Cambodia Readiness Plan Proposal on REDD+ (Cambodia REDD+ Roadmap)." Version 3.3 **January 10, 2011, Royal Government of Cambodia**.

Fournier, R. A., D. Mailly, et al. (2003). Indirect measurement of forestry canopy structure from *in situ* optical sensors. Remote sensing of forest environments: concepts and case studies. M. A. Wulder and S. E. Franklin, Kluwer, Dordrecht**:** 77-113.

Gibbs, H., S. Brown, et al. (2007). "Monitoring and estimating tropical forest carbon stocks: making REDD a reality." Environmental Research Letters **2**: 1-13.

GOFC-GOLD Report version COP16-1 (2010). A sourcebook of methods and procedures for monitoring and reporting anthropogenic greenhouse gas emissions and removals caused by deforestation, gains and losses of carbon stocks in forests remaining forests, and forestation. Alberta: Canada, Global Observation of Forest and Land Cover Dynamics.

Hall, J. B. (1987). "Conservation of forest in Ghana." Universitas **8**: 33-42. University of Ghana at Legon.

Harcombe, P. A., S. E. Greene, et al. (2004). "The influence of fire and windthrow dynamics on a coastal spruce-hemlock forest in Oregan, USA, based on aerial photographs spanning 40 years." Forest Ecology and Management **194**: 71-82.

Harcourt, C. S. and J. A. Sayer, Eds. (1996). The Conservation Atlas of Tropical Forests: The Americas. Compiled by World Conservation Monitoring Centre and IUCN. New York, Macmillan.

Henning, J. G. and P. J. Radtke (2006). "Detailed stem measurement of standing trees from ground-based scaning lidar." Forest Science **52**: 67-80.

Hopkinson, C., L. Chasmer, et al. (2004). "Assessing forest metrics with a ground-based scanning lidar." Canadian Journal of Forest Research **34**: 575-583.

Jensen, J. (2007). Remote Sensing of the Environment: An Earth Resource Perspective. New Jersey, Pearson Education, Inc.

Jonckheere, I., B. Muys, et al. (2005). "Allometry and evaluation of *in situ* optical LAI determination in Scots pine: a case study in Belgium." Tree Physiology **25**: 723-732.

Loveland, T., B. Reed, et al. (2000). "Development of a global land cover characteristics database and IGBP DISCover from 1-km AVHRR data." International Journal of Remote Sensing **21**: 1303-1330.

Lovell, J. L., D. L. B. Jupp, et al. (2005). "Simulation study for finding optimal lidar acquisition parameters for forest height retrieval." Forest Ecology and Management **214**: 398-412.

Lund, H. G. (2011). Definitions of Forest, Deforestation, Afforestation, and Reforestation - Note, this paper has been continuously update since 1998. Gainesville, VA, http://home.comcast.net/~gyde/DEFpaper.htm.

Macfarlane, C., M. Hoffman, et al. (2007). "Estimation of leaf area index in eucalypt forest using digital photography." Agricultural and Forest Meteorology **143**: 176-188.

Massada, A. B., Y. Carmel, et al. (2006). "Assessment of temporal changes in aboveground forest tree biomass using aerial photographs and allometric equations." Canadian Journal of Forest Research **36**: 2585-2594.

Penman, J., M. Gytarsky, et al. (2003). "Good practice guidance for land use, land-use change and forestry." IPCC National Greenhouse Gas Inventories Programme and Institute for Global Environmental Strategies, Kanagawa, Japan **available at: http://www.ipcc-nggip.iges.or.jp/public/gpglulucf/gpglulucf.htm**.

Phinn, S. R., C. Menges, et al. (2000). "Optimizing remotely sensed solutions for monitoring, modeling, and managing coastal environments." Remote Sensing of Environment **73**: 117-132.

Phinn, S. R., D. A. Stow, et al. (2003). "Remotely Sensed Data for Ecosystem Analyses: Combining Hierarchy Theory and Scene Models." Environmental Management **31**(3): 0429-0441.

Royal Government of Cambodia (2000). ANUKRET on Forest Concessions Management. Phnom Penh, Ministry of Land Management, Urban Planning and Construction.

Sasaki, N. and F. E. Putz (2009). "Critical need for new definitions of “forest” and “forest degradation” in global climate change agreements." Conservation Letters **xx**: 1-7.

Sayer, J., C. S. Harcourt, et al. (1992). Conservation Atlas of Tropical Forests: Africa. London, Macmillan.

Strahler, A. H., C. E. Woodcock, et al. (1986). "On the nature of models in remote sensing." Remote Sensing of Environment **20**: 121-139.

Tarp-Johansen, M. J. (2002). "Stem diameter estimation from aerial photographs." Scandinavian Journal of Forest Research **17**: 369-376.

UNEP (2001). "An assessment of the status of the world’s remaining closed forests." Technical Report **TR 01-2**: United Nations Environment Program.

UNFCCC (2002) Report of the Conference of the Parties on its seventh session, held at Marrakesh from 29 October to 10 November 2001 (FCCC/CP/2001/13/Add.1, UNFCCC, Marrakesh, Morocco, 2001).

Wang, J. S., D. A. Grimley, et al. (2008). "Soil magnetic susceptibility reflects soil moisture regimes and the adaptability of tree species to these regimes." Forest Ecology and Management **255**: 1664-1673.

Wang, Q., M. Preda, et al. (2007). "Spatial model of site index based on y-raynspectrometry and a digital elevation model for two *Pinus* species in Tuan Toolara State Forest, Queensland, Australia." Canadian Journal of Forest Research **37**: 2299-2312.

West, P. W. (2009). Tree and Forest Measurement. New South Wales: Australia, Springer.

Woodcock, C. E. and A. H. Strahler. (1987). "The factor of scale in remote sensing." Remote Sensing of Environment **21**: 311-333.