Comparison of Remote Sensing Techniques for Measuring Carbon Sequestration

Mark A. Vincent and Sasan S. Saatchi

Jet Propulsion Laboratory, California Institute of Technology

Funded by NASA Earth Science Enterprise

February, 1999

Table of Contents

Figures

Tables

Executive Summary

Different methods of using remote sensing to measure carbon sequestration were compared during this study. The purpose of the study was to find the optimum combination of measurements, and define the technology investments necessary to enable them. The Introduction explains the importance of these measurements in the context of the Kyoto Protocol. Its stipulation that sequestration implies the *managed* storage of carbon was emphasized throughout this study. The Introduction also includes a brief discussion of the common methods of terrestrial sequestration. Next, the measurement requirements were derived. These requirements were then compared to the available capabilities of different measurement techniques. The metrics of resolution, coverage and cost were used for comparison.

The major conclusion was that, in order to monitor/measure sequestration, changes in biomass had to be detected/measured. Only SAR and lidar have the potential to do this, with only SAR having a global capability. However, optical/IR measurements were, in general, indispensable for interpreting SAR data in a practical manner.

The next section discusses several of the complications involved in the application of the various measurement techniques. Two were of particular interest: the saturation limit for SAR systems and the cloud-cover issues facing optical measurements. The impact of the saturation limit on measuring sequestration was found to be less than might be expected. For example, most of the various normal distributions used to represent forest density resulted in an underestimation of biomass of 10% or less. However, applying the methodology to actual forest statistics is a highly recommended follow-on activity. Cloud cover was a definite limiting factor for optical measurements in some regions but not to the extent that SAR images could not be classified through modeling. Thus, the final recommendation was for a P-band (or, to a lesser extent, an L-band) SAR system matched with an optical/IR instrument with the same resolution. Lower resolution radiometer data and lidar altimetry, while providing some supporting information such as calibration, were not satisfactory in providing sequestration measurements by themselves on a global scale. The other complications dealt mainly with analyzing rather than obtaining measurements, but they still supported these general conclusions.

One particular area which may warrant some technology investment is the validation of the use of P-band systems in space. The scope of this work could range from a short theoretical analysis to a space flight demonstration of the entire P-band system using the New Millennium Earth Orbiting program.

Introduction

Purpose and Importance of this Study

For the purpose of this study, carbon sequestration was defined as the carbon sink which occurs from human activity designed to remove carbon dioxide from the atmosphere and store it in other forms. This includes the land-use and forestry activities enumerated in the Kyoto Protocol (see below) that can be used as a credit to offset emission requirements. This study concentrated on the NASA Earth Science Enterprise goal of finding the optimum combination of measurements and modeling to quantify the amount of carbon sequestered. The ability to do this will help formulate the accreditation process and lead to further developments in technology and commercial products.

The United States has a vested interest in being involved in the various aspects of carbon sequestration. Rough calculations (Vincent 1998) indicate that the contribution of sequestration towards the U.S. target of a 6% reduction in net emissions by the 2008-2010 time frame is about 0.6 Gt of carbon. Considering a range of $10 to $100 as the value of each ton saved, this is equivalent to a savings of 6 to 60 billion dollars. Large-scale, ground-based observations of carbon sinks and sources are time-consuming, labor-intensive and is typically constrained by poor accessibility. It is evident that some other means of monitoring and verification is needed in order to assess the world's forests in an accurate, timely and economically feasible manner.

A Working Definition of the Kyoto Protocol

The issues involved with the anthropogenic-induced rise in greenhouse gas concentrations in the atmosphere transcend all political and socio-economic boundaries. Allowing each country to offset their emissions by the amount of carbon they sequester is one of the greatest challenges faced in achieving a meaningful global warming agreement. The sink issue was a contentious one at the recent Kyoto meeting and will continue to be one over the next few years. It is perhaps second only to the debate regarding the role of developed and developing countries. Although there was some dissension, the third section of Article 3 of the Protocol (see UNFCCC, 1997) evolved to become:

The net changes in greenhouse gas emissions by sources and removals by sinks resulting from direct human-induced land-use change and forestry activities, limited to afforestation, reforestation and deforestation since 1990, measured as verifiable changes in carbon stocks in each commitment period, shall be used to meet the commitments under this Article of each Party included in Annex I. The greenhouse gas emissions by sources and removals by sinks associated with those activities shall be reported in a transparent and verifiable manner and reviewed in accordance with Articles 7 and 8.

A determination of the optimal methods that may be used to satisfy the verification aspect of this Article provide the basis for this study. Establishing the requisite accuracy and resolution for measuring carbon sequestration for accreditation is an intricate process which starts from the protocol listed above. Delineating along national boundaries when measuring net changes in emissions is an unfortunate political necessity from a scientific viewpoint. Even if countries were the same size, regional, in particular, latitudinal and related meteorological differences would result in different ecosystems and uneven sequestration characteristics. Resolving how these inequities relate to the Protocol was not pursued in this study, however throughout, related topics such as forest types were considered.

The interpretation of the term "direct human-induced" in the above quotation was an important consideration for this study. Although the definitions which are actually implemented will probably be the result of an intense debate for the next few years, the following paragraphs present some ideas which will be useful for this study. In particular, it should clarify the difference of managed and non-managed activities which is relevant to many discussions in the report. The term "getting credit" refers to the general idea of a positive contribution to satisfying the commitments mentioned in the Protocol.

Terrestrial sequestration activities include but are not limited to Preservation, Reforestation, Plantations and Agroforestry (Trexler and Haugen 1994, Butcher *et al* 1998). Getting credit for preserving forests is a prime example where controversy could exist. Since the net change of carbon in mature forests is minimal, the real issue is whether credit should be issued for *not* doing something (deforestation). Independent of this debate however, is the definite need to locate and measure deforestation activities.

Reforestation activities can range from simple abandonment and natural regrowth to the planting and nurturing of trees. The following paragraph gives some examples of how the distinction could be made as to which reforestation scenarios should be credited.

Any annual biomass change resulting from active planting would deserve credit. Natural regrowth would only be credited when it occurs in an area which has previously been penalized as a sink. For example, any slash-and-burn deforestation would be counted as a source in the year that it occurs but after the same land is abandoned, the relatively small annual accumulation of carbon on it will be counted as a sink. Note that this simplification ignores the degradation of the soil which may occur during the period of agricultural use between the burn and abandonment. This and other aspects of the soil content are discussed in the Complications Section.

In a similar manner to reforestation, the credit for carbon sequestrated in (wood) plantations and agroforestry regions should be based on the actual change in carbon content that has resulted from these activities. Plantations would be debited for any removal of biomass including the initial set-up. They would be credited as trees grow back both for the cash crop and after abandonment. There is another argument as to whether the final fate of the wood product is important or not. For example, any expensive hardwood that is used to make furniture will probably remain intact for an extended period of time. Note however, that the IPCC (1996) stresses the importance of the offset to fossil fuel use created by burning biomass for fuel, even though using the latter source has a net zero effect on the atmospheric carbon content.

Agroforestry, though an attractive option from an economic standpoint, can have a wide range in its effect on carbon content. Part of this comes from the various practices which are included in its definition. These range from the sustainable harvest of secondary products such as nuts and fruit to having rows of trees between cultivated fields. In the latter case, it is obvious that the net change in carbon from the new activity depends on whether the area was originally forested or already entirely in agriculture.

Biodiversity is another important consideration when discussing these activities. Generally speaking, any reforestation would have to emulate the natural forest, and plantations and agroforestry would have to minimize their local ecological impacts. Remote sensing can help provide data for analyzing these situations in the form of recognizing tree species and forest fragmentation. However, due to the complicated nature of this subject, it most likely will not be factored into the early accreditation process in a quantitative way.

Finally, although this study focuses on forests, it should be recognized that remote sensing can play a vital role in measuring other greenhouse gas sources and sinks. These include, but are not limited to:

a) observing land transformations such as wetland draining which although generally bad from an ecological point of view, do reduce the amount of emissions of carbon dioxide and methane, both greenhouse gases. Flooding can have the opposite effect.

b) determining any changes in the amount of thawing that occurs in high latitude areas of tundra and peatbogs. Increased thawing produces larger releases of carbon dioxide and methane. This is of particular concern because it could lead to a significant positive feedback mechanism once global warming is initiated.

Requirements

Measurement Types

To develop high level requirements, potential customers were identified. The delegates meeting at Kyoto who formed the Convention of Parties (COP) represent a group who will potentially have the need to validate any international agreements that include credit for carbon sequestration. Another high level requirement comes from the need to validate and monitor joint implementation projects (JIPs). These projects occur when one party gets (possibly tradable) offset credit for sequestration activities which they pay for but which occur at a different location under the stewardship of a second party (Graham, 1995). These transactions will probably occur on a small regional basis of the order of 1000 ha or less. Examples of JIPs that have already occurred are: between an independent U.S. power company and Guatemala (Trexler, 1995); and between the countries of Norway and Costa Rica (Goodman, 1998).

However, in both cases, measurements will have to be of reasonably high resolution. For the country-wide scale, the provision that only managed sequestration will be credited implies that the relative proportions of natural and anthropogenic changes will have to be estimated. This needs to be differentiated at the hectare level of human activity. In the joint implementation case, activity at the few hectare level represents a significant proportion of the area of interest (and equivalently the amount invested). Resolution issues are further addressed in the next section.

The measurement types involved in carbon sequestration can be grouped by the three colors shown in Table 1. First detection and measurement were grouped together for both changes in Land Use (LU) and Land Cover (LC). The first pairing is because any change of a discrete land use or cover is inherently detected when the areal extent of each classification is measured. Next, although the concepts of LU and LC are distinct (see the Analysis Section), the similarity in the physical quantities needed for their measurements dictate that they should be joined together to determine the instrument requirements used in that section (see Figure 6).

Table 1
Measurement Types

	Δ LU	Δ LC	Δ BioM	Abs BioM
Detection				
Measurement				

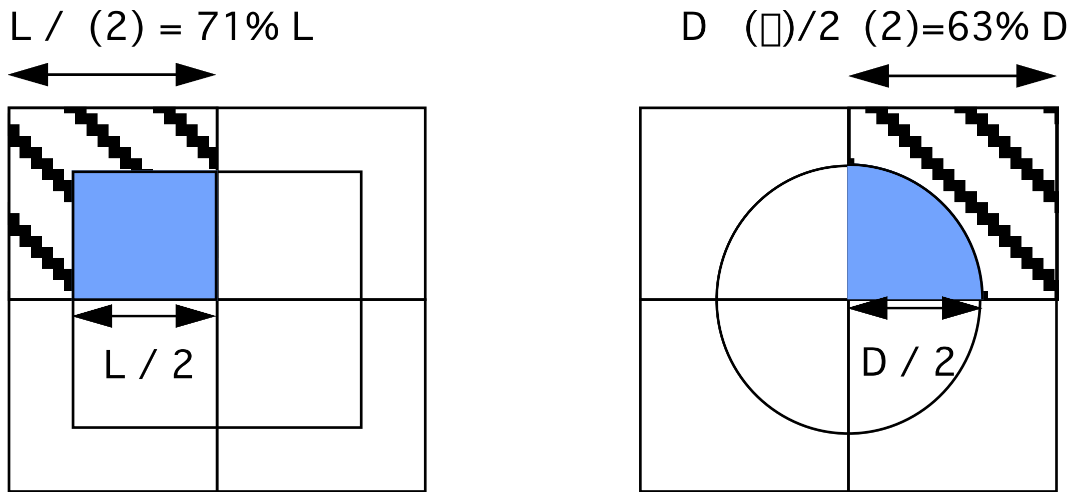
The only distinction between detection and measurement of Δ BioM (change of Biomass) is one of measurement precision. However due to the vast difference in the precision required, they were considered as different types. However detection and measurement of Abs BioM (Absolute Biomass) were lumped together because they both require the same high level of accuracy (calibration) and precision. Further, repeated Absolute Biomass values must be differenced to give equivalently accurate Δ BioM measurements. Thus, the latter was combined with the absolute measurements.

Resolution Requirements

The resolution specifically needed for sequestration measurements is the topic of this and future studies. However, the needs for land coverage change and biomass estimates have already been extensively studied. Townsend and Justice (1988) present a thorough investigation one of these studies of the resolution required for determining land transformations. Their overall conclusion was that at least 500m resolution was needed but 250 or less was better (though marginally in some cases). Their principle objection to stipulating that 250m or less should be the requirement was the computational burdens this would place on computers either on-board or on the ground. Although, they assumed a reasonable development schedule for computer capabilities however, they were targeting the early nineties (when MODIS was originally supposed to fly) as the period of interest. There have been dramatic improvements in data processing since then. In particular, the 100m resolution required to recognize activity at the one hectare level mentioned in the previous section does not create undue data management burdens. In conclusion, a 100 to 200m resolution appears to be needed for both sequestration and land transformation measurements.

The previous discussions assumed that the resolution had to be of the same size as the hectare activity. The following is the next to simplest argument which indicates that the requirements are significantly more stringent. The basic rule used is that a pixel must contain at least 50% of an object type to recognize the existence of that object. Hence, the shaded areas in the figures below were chosen to be 50% of the pixel (quadrant) area.

As the left-hand figure illustrates, a square object of side L can only be recognized in the worst case geometry when the resolution is $1/\sqrt{(2)} = 71\%$ of L. The right-hand figure shows that a round object (not uncommon in agricultural cases) needs an even higher resolution of $\sqrt{(\pi)}/2\sqrt{(2)} = 63\%$ of its diameter, D. As explained by Townsend and Justice (*ibid*), resolution is just one aspect which contributes to change detection. Another spatial property is geometric registration and there are also radiometric/spectral and temporal properties. Thus recognizing one hectare activity might require even finer resolution (50m or less).



Minimum Resolution needed to Recognize an Object
Figure 1

However, Woodcock and Strahler (1987) discuss cases when too fine a resolution can degrade the classification process. They present analyses which show that the highest local variance in the measurements occurs when the resolution is 50 to 75% of the size of the objects (a similar result to above) but go on further to explain that high variance is optimal for only certain types of classifiers. Combining all these ideas suggests a 100m or slightly better requirement for sequestration measurements.

<u>*Accuracy Requirements*</u>

The accuracy requirement depends on the context in which the measurements are used. In some cases, changes may need to be just detected rather than measured. A major application of this will be when credit is given for preserving an intact forest. Then, obviously any detectable change due to logging or intentional burns will void the credit for the preservation. Natural fires (see below) may or may not void the preservation, but this is more of a legal and perhaps insurance issue.

Getting credit for reforestation will require measurements of biomass change. The accuracy needed is difficult to know at this time, however some observations can be made in order to speculate on the approximate needs. There will always be some uncertainty in the extent of managed and natural regrowth even if the definitions get resolved. If the measurement error in biomass change is significantly below this uncertainty level, remote sensing should be considered valid, though the overall uncertainty may still make accreditation difficult. Expectations are that acceptable accuracy values could range from 10 to 30% depending on the degree to which the biomass changes have to be measured rather than detected. Again, it should be kept in mind that first-order credit will be given to *doing something* over a certain area while the actual amount of sequestration could be at a higher level of abstraction. For example, a reasonable credit for reforestation could be given even if there was a 20% error in 10 t/ha yearly growth. Conversely, assessing the proper penalty for chopping or burning down a 200 t/ha forest might benefit from accurate *a priori* biomass knowledge but the actual event would be easy to recognize.

Coverage Requirements

Coverage requirements can be generated by considering a list of questions:

a) Where (what regions) does data need to measured?
b) in these regions, what proportion of the area needs to be directly measured?
c) and how often do the measurements need to be taken?

When all countries and their forests are included, the answer to the first question is: all land areas except the polar regions. However most candidate mission platforms have orbits with high enough inclinations so this is not a problem.

The second question can be restated as asking whether sampling will provide the needed end products (discussed in the Measurement Types section above). Sampling could possibly give a rough indication of country-wide carbon stocks but any extrapolation of the proportion of carbon content change activities which are managed would result in huge uncertainties. There is also the somewhat far-fetched but not impossible idea that deforestation and reforestation would purposely occur in the unmeasured and measured swaths respectively. Further, the need to monitor specific areas such as joint implementation projects would produce an unreasonable restriction on the location of the projects if they had to be along prescribed ground tracks. Thus the conclusion is that there must be a capability to measure carbon sequestration over 100% of forested areas.

Answering the question of how often the measurements have to be taken can be separated into ecological factors and external properties which affect the signals. The former includes annual variations in leaf and foliage content. Using deciduous trees as an example indicates that at a bare minimum two measurements have to be taken per year with a strong preference for one each season. Compounding the problem are external factors such as soil moisture which affects radar backscatter, and leaf pigment which affects optical measurements. Getting monthly measurements would improve the capability of measuring sequestration even further but seasonally seems like a reasonable compromise for practical purposes. How the potential coverage is limited by factors such as cloud cover and darkness are discussed in the Coverage Capabilities section.

Remote Sensing Techniques

Instrument Descriptions

While the Measurement Types and Analysis sections of this report concentrate on the end products that could be used for determining sequestration, the following is a description of all the various instruments which might potentially provide the raw data which could be transformed into these products.

The two major instrument types are passive optical/infrared (IR) sensors and active radar devices. The radar systems are usually designed to use a signal combination technique to synthesize a longer antenna, hence the name Synthetic Aperture Radar. Variations of the two main categories are active laser ranging and interferometric SAR images. There is also stereoscopic optical imaging but they were not considered due to the difficulty (expense) in obtaining their images. Most of the information (SAR-related being the exception) comes from the respective instrument web-sites. Thus some of the claimed capabilities might not completely agree with the rest of this report.

ASTER: ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer) is an imaging instrument that will fly on EOS AM-1, a satellite planned for launch in 1998 as part of NASA's Earth Observing System (EOS). ASTER will be used to obtain detailed maps of surface temperature, emissivity, reflectance and elevation. The EOS platforms are part of NASA's Mission to Planet Earth program, whose goal is to obtain a better understanding of the interactions between the biosphere, hydrosphere and atmosphere. ASTER is the only high spatial resolution instrument on the EOS-AM1 platform. It will be used with MODIS, MISR and CERES which monitor the Earth at moderate to coarse spatial resolutions. ASTER's ability to serve as a 'zoom' lens for the other instruments will be particularly important for change detection, and calibration/validation studies.

AVHRR: The AVHRR instrument onboard the NOAA-series satellites (TIROS-N/NOAA 6-12) provides daily coverage of the Earth in 4 or 5 spectral bands at a nominal resolution of 1 km. Because the 1 km resolution data are too voluminous to be captured daily, the data are subsampled and averaged onboard and then transmitted to central receiving stations as Global Area Coverage (GAC) data with a nominal resolution of 4 km providing full global coverage. Pathfinder input data commence with NOAA-7 which was launched in June 1981. This was the first AVHRR instrument with five channels, and it is the five channel AVHRR instruments which are used in producing the Pathfinder data sets. The additional channel provides better cloud discrimination and is useful for determining Sea Surface Temperature which will be produced in a separate Pathfinder effort. The AVHRR instrument's 110.8° cross-track scan equates to a swath of about 2700 km. The orbital period is about 102 minutes and there are 14 orbits per day with a repeat cycle of approximately 14 days.

IfSAR: Combining two SAR (Synthetic Aperture Radar) images using interferometric methods produces stereoscopic measurements. These IfSAR data can be used to measure topography and of particular interest for sequestration, tree heights. Although the radar penetrates somewhat below the top canopy this can be calibrated as a function of the frequency used. The two images can come from two antennas on one platform (as in the SIR-C mission), two co-flying platforms (the proposed TOPSAT mission) or repeated pass of a single satellite (ERS and the proposed ECHO mission). Note in the latter cases there has to be short revisit time when measuring trees so that the backscattering properties do not change too much in the interim.

Landsat: In 1992, the US Congress authorized the procurement, launch and operation of a new Landsat satellite. This new system, Landsat 7, is now under construction and is scheduled for launch in April, 1999. It will be the latest in a series of earth observation satellites dating back to 1972. The twenty-two year record of data acquired by the Landsat satellites constitutes the longest continuous record of the earth's continental surfaces. Preservation of the existing record and continuation of the Landsat capability were identified in the law as critical to land surface monitoring and global change research. Landsat 7 will have a unique and essential role in the realm of earth observing satellites in orbit by the end of this decade. No other system will match Landsat's combination of synoptic coverage, high spatial resolution, spectral range and radiometric calibration. In addition, the Landsat Program is committed to provide Landsat digital data to the user community in greater quantities, more quickly and at lower cost than at any previous time in the history of the program. The earth observing instrument on Landsat 7, the Enhanced Thematic Mapper Plus (ETM+), replicates the capabilities of the highly successful Thematic Mapper instruments on Landsats 4 and 5*. The ETM+ also includes new features that make it a more versatile and efficient instrument for global change studies, land cover monitoring and assessment, and large area mapping than its design forebears. The primary new features on Landsat 7 are: a panchromatic band with 15m spatial resolution, on board, full aperture, 5% absolute radiometric calibration and a thermal IR channel with 60m spatial resolution

MISR: the Multi-angle Imaging SpectroRadiometer is a satellite instrument designed to measure sunlight reflected by the Earth into space, measurements that will contribute to studies of the planet's ecology and climate. MISR is being built for NASA by the Jet Propulsion Laboratory in Pasadena, California. It is scheduled for launch into polar orbit aboard NASA's first Earth Observing System spacecraft (EOS AM-1) in mid 1999. In addition to improving our understanding of the fate of sunlight in the Earth environment, MISR data can also distinguish different types of clouds, particles and surfaces. Specifically, MISR will monitor the monthly, seasonal, and long-term trends in the amount and type of atmospheric particles (aerosols), including those formed by natural sources and by human activities, the amounts, types, and heights of clouds and the distribution of land surface cover, including vegetation canopy structure

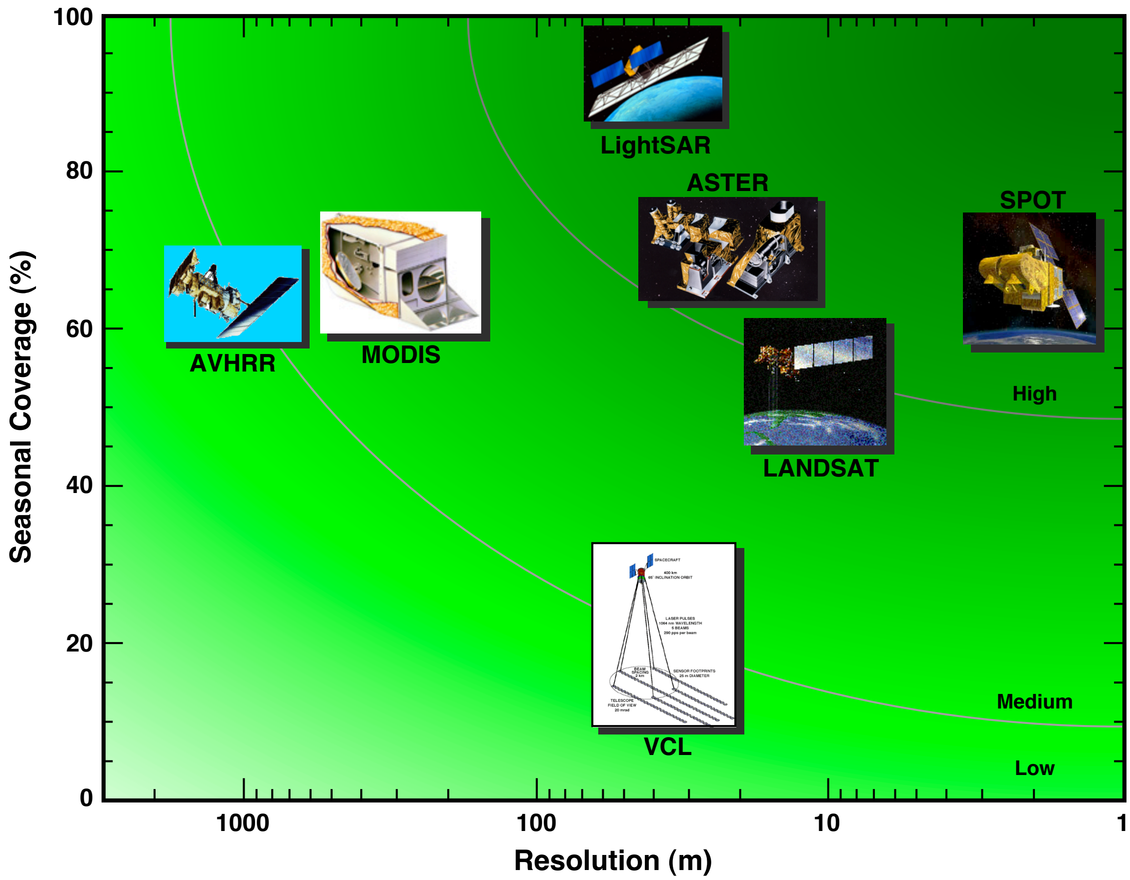
MODIS: MODIS is the key instrument aboard the EOS AM-1 satellite. These data will improve our understanding of global dynamics and processes occurring on the surface of the Earth, in the oceans, and in the lower atmosphere. MODIS will play a vital role in the development of validated, global, interactive Earth system models able to predict global change accurately enough to assist policy makers in making sound decisions concerning the protection of our environment. The MODIS instrument provides high radiometric sensitivity (12 bit) in 36 spectral bands ranging in wavelength from 0.4 μm to 14.4 μm. The responses are custom tailored to the individual needs of the user community and provide exceptionally low out-of-band response. Two bands are imaged at a nominal resolution of 250 m at nadir, with five bands at 500 m and the remaining 29 bands at 1,000 m. A ±55-degree scanning pattern at the EOS orbit of 705 km achieves a 2,330-km swath and provides global coverage every one to two days.

SAR: Existing or past Synthetic Aperture Radar missions include ERS-1, ERS-2, JERS-1, Radarsat and SIR-C/X-SAR. The first two European missions and the Canadian Radarsat use C-band, the Japanese JERS used L-band and the shuttle based SIR had L, C and X band. Future proposed missions include L-band LightSAR and ECHO, another shuttle misssion (SRTM), this time with interferometic C- and X-band and follow-ons to Radarsat and JERS. SAR imaging can gather data pertinent to this study both from the intensity of the backscatter and its fine spatial variability or texture.

VCL: The Vegetation Canopy Lidar mission seeks to provide the first global inventory of the vertical structure of forests across Earth using a multibeam laser-ranging device. VCL will enable direct measurement of tree heights, forest canopy structure, and derived parameters such as global biomass with at least ten times better accuracy than existing assessments. It was selected as an ESSP (Earth Science System Pathfinder) mission to be launched in 2000. Science Objectives: The principal goal of the VCL mission is the characterization of the three-dimensional structure of the Earth. The two main science objectives are: a) Landcover characterization for terrestrial ecosystem modeling, monitoring and prediction and climate modeling and prediction. b) Global reference data set of topographic spot heights and transects

Resolution Capabilities

The range of resolutions available for each instrument type for reasonable configurations is well established though the actual value is a function of antenna or aperture size, transmitting power and orbital altitude. The horizontal values assigned to various missions in Figure 2 represent typical values. Note that there are often several resolutions available for pictures, digital data and the various modes of radar operation The general trend is that optical instruments have better resolution than radar instruments which have higher resolutions than radiometers. However, this has to be put into the context of what resolution is required for measuring carbon sequestration, which was discussed earlier.



Coverage vs. Resolution
Figure 2

Coverage Capabilities

Assigning a value to coverage capability is not as straightforward as doing it for resolution. There are two separate issues. The geometrical issue involves the choice of orbit and the field of view of the instrument. It can be further divided into a spatial and temporal coverages. The two spatial quantities of interest are the latitudinal coverage which is a function of the orbit inclination and instrument pointing and the longitudinal coverage which is a combination of the repeatability of the groundtrack and the instrument pointing capabilities. The temporal coverage has the same functionality as the longitudinal coverage though in an inverse manner, such that repeat time and groundtrack spacing is a common trade off. Of course, the size of the footprint or groundtrack width is usually also inversely related to the resolution.

The second coverage issue, is the availability of a signal. Passive optical systems need the reflected sunlight during the day, infrared signals can theoretically be obtained at any time, though the diurnal heating and cooling dictate that dawn and dusk are the best time to obtain the signatures of interest. Clouds are the other issue because they can cause reflection during the day and not permit optical measurements. Active radar can be obtained at any time. Laser ranging can also be done during any cloud-free time except over the subsolar point however the footprint is of limited size and thus the longitudinal coverage is limited.

Coming up with a coverage value that incorporates all the above issues is further complicated by the choice of which time period to average over. In order to produce the values represented in Figure 2, the seasonal (3 month) coverage over the tropics was picked. The repeat times given in Table 2 can be used to determine how many viewing opportunities there will be per season. With the exception for VCL and IfSAR (discussed below) the major remaining factor is the probability of cloud cover. This issue is discussed in the Complications Section. As explained there, obtaining specific values was not done, though this is a potentially interesting follow-on study.

However as Figure 8 attests representative values are easy to estimate. The tropical forests can vary from often to always cloud-covered. Consider a region that is cloudy 90% of the time. In three months, or six passes, there is about a 50% ($=0.9^6$) chance of being cloudy every time. This is used for the vertical placing of the Landsat icon in Figure 2.

Missions with limited footprints, such as the VCL mission, deserve further discussion. As explained above, only the transects corresponding to the repeat ground track will be measured. Thus on a global or even regional scale there will be very limited coverage. However as demonstrated by Rodriguez *et al* (1996 and 1998) there is good agreement between IfSAR tree height measurements and those from VCL-type instruments. Thus the accuracy of the VCL could be extended to larger areas by the wider SAR swaths. It should be noted that IfSAR measurements have additional coverage issues if repeat-pass interferometry is being used (as opposed to having two antennas on a single platform or two satellites taking simultaneous measurements). In particular, the repeat orbits have to be navigated accurately, measured even more accurately and occur frequently enough so the radar scattering characteristics of the targets do not change substantially (for example leaves falling from trees).

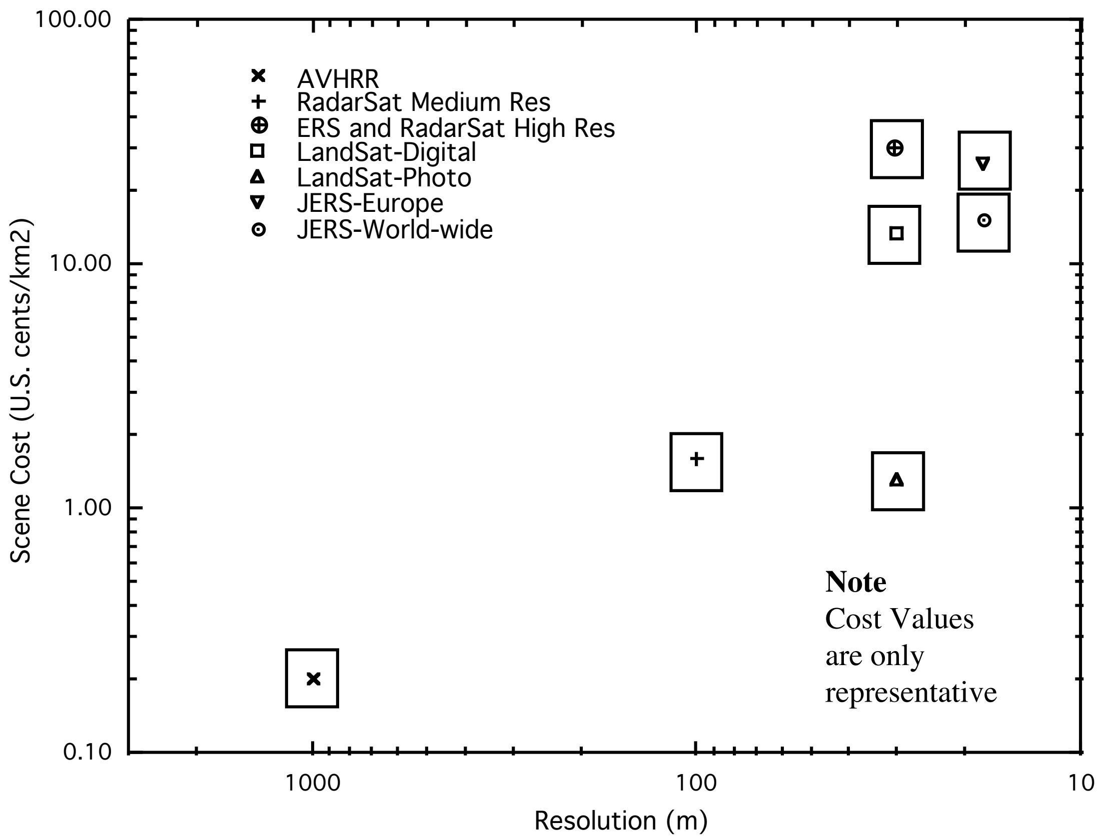
Table 2
Instrument Characteristics

Name	Type	Spatial Res (m)	Revisit T (d)	Restrictions
AVHRR	Radiometer	1100	1	No Clouds
MODIS	Radiometer	250 - 1000	16	No Clouds
ASTER	Radiometer	15-90	16	No Clouds
Landsat	MSS/TM	30	17	No Clouds
Other Optical	Optical	1 - 30	Varied	No Clouds
VCL	Lidar	25	Transect	No Global
BIOMASS*	P-band SAR	100	60	Proposed
SIR-C	MP (Int) L,C,X	25	N/A	Limited Site, Time
SRTM	Interferom C,X	20	N/A	11 day mission C,X
LightSAR	MP SAR	25	8-10	Proposed
ECHO	L,C-band SAR		35	Proposed (change detect)
Topsat	Interferom	30	73	Not Planned
ERS-1,2	C-band SAR	30	35	C-band only
JERS-1	L-band SAR	18	44	Low Sat, 1-polar, Noisy
RadarSat	C-band SAR	10 - 100	2 - 10	C-band only

* note that the proposed BIOMES mission is essentially the same as BIOMASS

Cost

Comparing the costs of various products has some inherent difficulties. It was decided to compare the commercial prices that were available rather than the costs of the instruments and missions, though hopefully the former is a true (unsubsidized) proxy for the latter costs. Nevertheless there were still several layers of processing that could be chosen. A refined product of comparable scene size was chosen to get a cost in U.S. cents per kilometer (currency conversions were another small factor). The results shown in Figure 3 were good enough to draw some broad conclusions. AVHRR data is almost free since it is available for the price of a disc. The RADARSAT data has a price related to the resolution but its price along with the JERS data is about the same as the Landsat digital data at the same resolution. However, the Landsat photos are significantly less expensive. The fact that scenes with similar format and resolution were close in price could be by design or accident. In either case, it appears that cost is not a distinguishing factor at this time. It is fair to say that a future SAR mission dedicated to biomass measurements could substantially lower the cost of obtaining the data of interest.



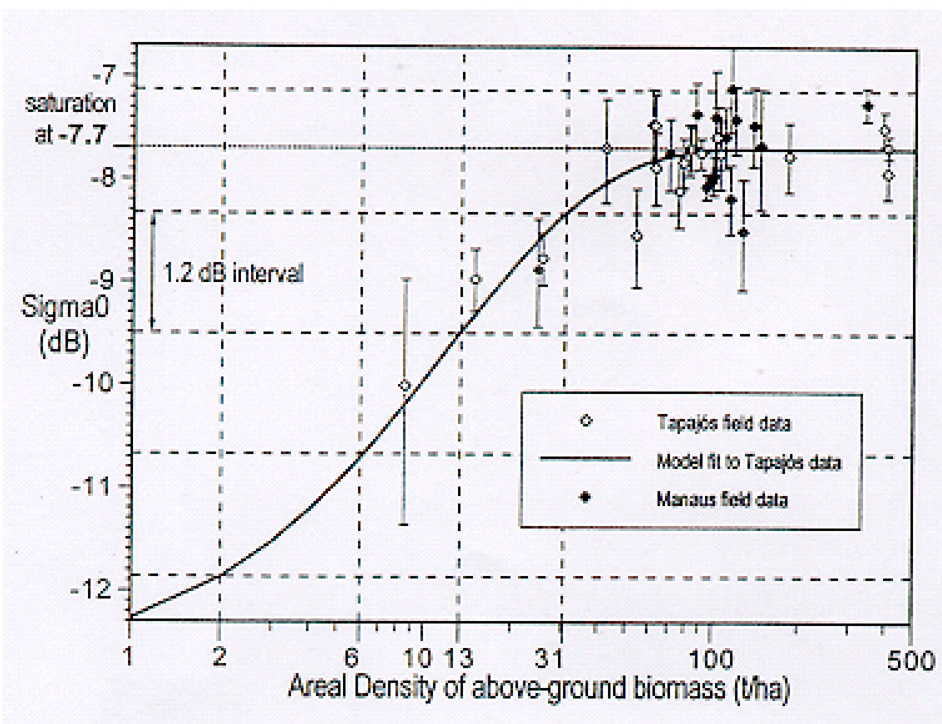
Cost vs. Resolution
Figure 3

Some Complications in Measuring Carbon Sequestration

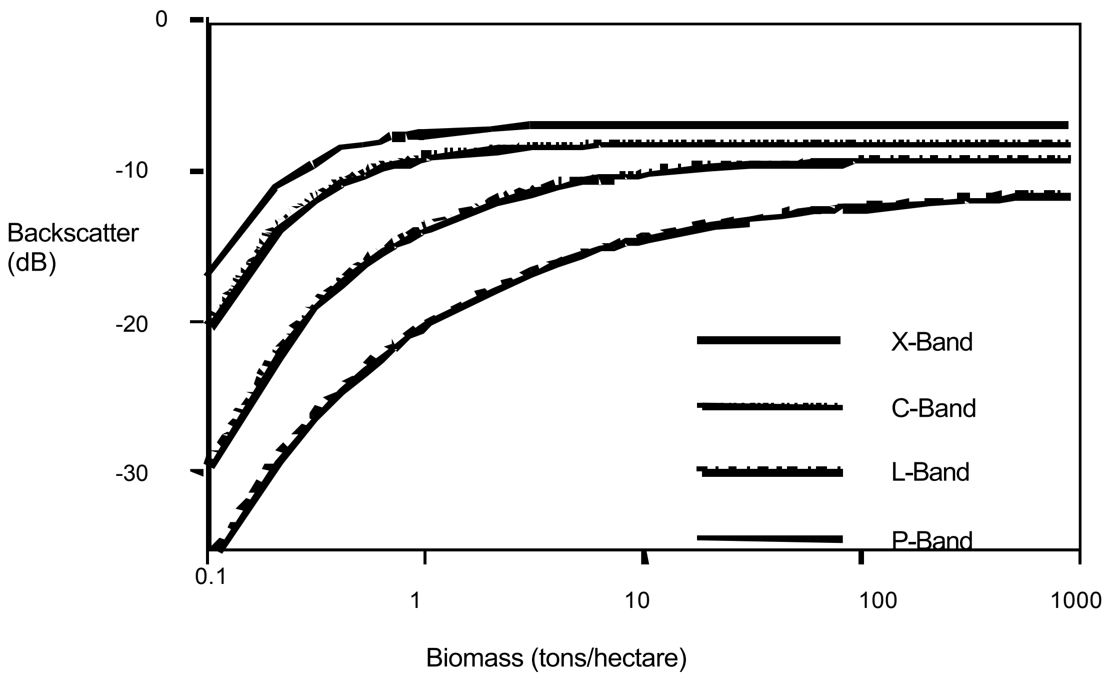
Various aspects which complicate the measurement of carbon sequestration are presented below. Many of them relate to differentiating nature and human-induced changes, however, general concerns are also included. This list is not meant to be exhaustive and only represent some of the areas that should be considered in any future studies of how to implement the measurements into a carbon sequestration accreditation process.

<u>*SAR Saturation Limits*</u>

The target-dependent backscatter characteristics of SAR will potentially lead to regional, in particular latitude (and altitude) differences in the ability to measure carbon sequestration. The saturation limits of L-band is a simple example of this. The saturation limits range from 60, to 200 t/ha depending on the forest type measured (Le Toan *et al* 1992, Luckman *et al*, 1997, Kasischke *et al* 1997). Figure 4 (taken from Luckman *et al* 1998) depicts the backscatter characteristics for a Tropical forest for multiple frequencies and polarizations. Figure 5 (taken from Saatchi, 1998) indicates how P-and L-band have higher saturation limits while C- and X-band have lower limits.



Fitting SAR Backscatter to Biomass Density
Figure 4



Modeled Behavior of Radar Backscatter vs. Biomass
Figure 5

An independent study of how much the biomass could be underestimated because of these saturation limits is presented in the Appendix. The figures contained there illustrate that although in a case where 16% of the area of a forest is mismodeled, only 2% of the biomass is not measured. A normal distribution of biomass per area with a mean value equal to 4 standard deviations (σ) was assumed along with a saturation limit of 1 σ above the mean. The results for other normal distributions are presented below. Although these are reasonable values, the parameters and normality of real forests may be somewhat different. Obtaining and analyzing the statistics of actual forest is a recommended follow-on study.

Table 3
Proportion of Biomass Underestimated

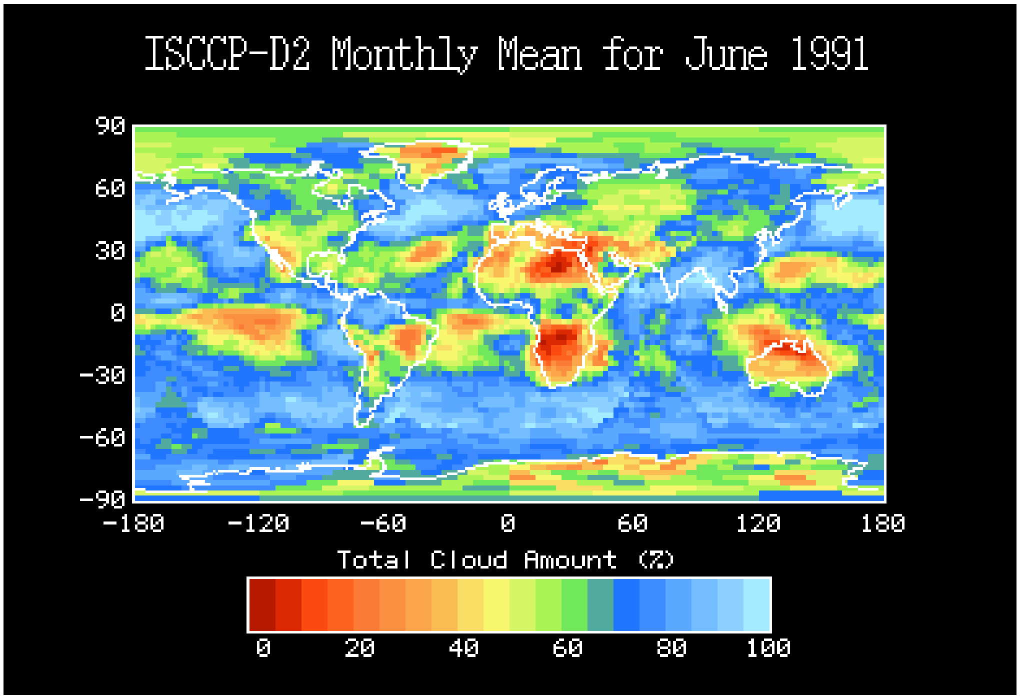
Sat Limit (σ's above μ)	Total Biomass = μ = Z_U (σ's)	Lost Biomass (σ's)	Lost Biomass %
1.5	2 / 3 / 4 / 5	.0094/.0269/.0292/.0293	0.5 / 0.9 / 0.7 / 0.6
1.0	2 / 3 / 4 / 5	.0521/.0802/.0832/.0833	2.6 / 2.7 / 2.1 / 1.7
0.5	2 / 3 / 4 / 5	.1552/.1940/.1977/.197	7.8 / 6.5 / 4.9 /

		8	4.0
0.0	2 / 3 / 4 / 5	.3450/.3945/.3988/.398 9	17. / 13. / 10. / 8.0

From the table, the amount of biomass that is not measured is under 10% when the saturation limit is at least 0.5□ above the mean. Further the lost biomass is still only around 10% when half the forests are mismeasured if the standard deviation is a typical 1/4 of the mean value. This is encouraging news for the forests which have means below the saturation limits for SAR's. However, the symmetric argument implies that when the saturation limit falls below the mean value there is a rapid increase in the amount of biomass not measured.

Cloud Cover

Obscuration by clouds is a major issue affecting the availability of measurements in wavelengths for which clouds are opaque (optical and IR). This is particularly important for forested areas which are routinely covered by clouds. In the important tropical rain forests, this can be year-round. But even the more common world-wide case of constant clouds occurring just during the rainy season can impose constraints on recognizing the characteristics of regrowth. Several sources of cloud data were investigated. Two products were considered: maps with average (daily, biweekly, monthly, seasonally and/or annually) cloud cover overlays and the actual raster data so statistics could be generated for the areas of interest. These products are useful for not only this study but many other applications. Monthly cloud products were obtained by disc from the Langley DAC for the International Satellite Cloud Climatology Project (ISCCP). Special software has to be used to extract the specific data but as Figure 8 (taken from their website http://isccp.giss.nasa.gov/dataview.html) shows, pictures of the information required are easily available. Other potential sources at Goddard include the researchers in long-term climate and the Landsat organization. The latter are doing cloud cover predictions for cloud removal algorithms designed for Landsat 7 data.



Example of an ISCCP Monthly Cloud Coverage Map
Figure 6

Soil Content

There are several ways that soil content is important for sequestration discussions. Two will be discussed here. The first involves the direct changes of soil carbon content from various activities. A comparison of Tables 5.2 and 5.3 of Schlesinger (1997) emphasizes the importance of the below-ground carbon since it can be up to twice the above-ground value for certain forest types. Further he discusses how cultivation can reduce the amount of organic carbon in the soil by 20 to 30% in just a couple of decades. Thus the net changes from deforestation, cultivation, abandonment and reforestation all have time-dependent adjustments due to their effects on the soil. However since remote sensing can not directly measure the below-ground content, it can not help in quantifying these adjustments. They will have to be derived from ground measurements and modeling. Whether or not these adjustments are included in any sequestration process will have to be determined in the future.

The second consideration is the indirect effect that agriculture can have when it removes nutrients such as nitrogen and phosphorus from the soil. This is further complicated by the natural (acid rain) and human-made fertilizers which add back these nutrients. However, the general trend is that the ability to regrow forests to their previous carbon content decreases as the time of cultivation increases. This is another potential study that could be done with a combination of ground and remote-sensing data. Further, the general trend of decreasing vegetation density increasing the amount of soil erosion exacerbates both the carbon and nutrient losses. These levels of complexity would probably not be included in the first round of sequestration accreditation but it should be kept in mind.

Flooding

As an example of the intricate nature involved in discerning human-induced deforestation, consider the forests which are destroyed from flooding. As pointed out by Rignot *et al* (1997) flooded dead forests can be distinguished by the proper combinations of polarizations of either C- or L-band radar but not by Landsat TM or other radar measurements. Separating these dead forest from other disturbed forests is important because their destruction did not result from logging activities. However, it might be better to say "directly from logging". The causal relationship between logging and flooding depends on several factors such as the evapotranspiration rate of the trees, soil and topography. Further the flooding may have been caused or exasperated by such human activities as dam building. Thus after distinguishing flooded dead forests, the separation of natural and anthropogenic contributions may still remain. Note that the annual encroachment on and off the floodplain will not usually destroy trees, in particular not by rotting.

Selective Logging

Another pertinent example is evident in the discussion of Houghton (1994). He explains that when only land classification is considered, the biomass can be underestimated up to 40% if selective logging has occurred. This is because the desirable trees can be removed without changing the overall classification. This is relevant to imaging techniques which determine land classification as opposed to the penetration capability of radar which allows the texture and thus content of the forests to be determined (discussed further in the Analysis section). A further complication can occur if the degraded forests are subsequently completely removed, since the actual biomass lost would be less than destroying an intact forest. Thus the second party involved might get a larger proportion of the blame.

Forest Diversity

Single species vs. mixed forests is another important issue. Ranson *et al* (1997) describes two different approaches to measuring the biomass of mixed forests. The first approach is a two-step process which first classifies the cover type for different sections which besides separating the tree types (in their case Pine, Spruce and Aspen), would clearly define the forested vs. non-forested areas at a small scale. Then individual algorithms (in their case regression analysis) could be used for each individual section. This method would be successful where there is clumping of the same cover type. It also suggests that two separate remote sensing techniques might be used, for example, optical for step one followed by SAR for the second step. The other method uses one algorithm to go from the SAR measurements directly to the biomass values. This assumes an averaging of the different cover types. This might have to be used when the forests are well mixed in type or have very small clearings. So although this method requires just one remote sensing technique to be used, it is obvious prone to errors both overall and regionally due to spatial variations. The extent that biomass can vary in both open and closed forests is discussed in Brown *et al* (1991) when they compare different ground-based measurement methods.

Forest Fires

There are several interesting factors involved in considering the contribution of forest fires. A basic tenet to keep in mind is that fires existed as part of the natural process even before the rise of anthropogenic influences. In particular forest fires did not effect the level of atmospheric carbon dioxide, at least in the time scales when global climate and oxygen levels were constant. Humans disrupt this balance when they involve fire in a net change in global land cover. The slash-and-burn conversion to agriculture is the most obvious, but this is further complicated by the amount and type of abandonment and regrowth that occurs. Other aspects include fire suppression, and to a lesser extent, fires which are set, accidentally or otherwise for non-agricultural reasons. Another issue which has generated interest is the second order effect that an anthropogenic change in climate, in particular increased temperatures, regional variations in precipitation patterns, can lead to an increased number of natural fires. Thus small climatic changes can cause a small proportional but substantial absolute shift in the natural fire/growth balance and lead to further increases in greenhouse gas emissions.

Remote sensing has the advantage of being able to detect the effects of fire in several ways. Optical and infrared methods can detect the flames and smoke as the fire is occurring and shortly afterwards. As discussed previously, these methods plus SAR can also detect the change in land cover between before and after the fire disturbance. Implementation of this data will be analyzed in future studies, but as an example of the complications, consider the findings of Chen (1998). He discussed the presence of natural decadal fluctuations in the extent of fires (and diseases) in Canadian forests with subsequent regrowth. Obviously this type of phenomena will be of concern when the policy regarding sequestration accreditation is debated in the future.

Synthesis of Models

The measurement of carbon sequestration or specifically biomass content and change benefit from several other Earth science measurements. The value of a global land cover map is evident from many discussions in this document. A high-resolution (30m) DEM (Digital Elevation Map) is another global map which would be valuable for all remote sensing methods since the received signals are always dependent on the topography. Van Zyl *et al* (1993) discuss how this can corrupt SAR backscatter measurements but Van Zyl (1993) explain how this problem can be alleviated by including land cover information. Also, since soil moisture affects backscatter, seasonal measurements of the former would be desired. In addition, as stated by Wang *et al* (1993) the reduction of backscatter due to tree trunks being frozen can be larger than the variations due to stand density and species type. Thus, temperature information for measurement areas would also be useful. Of course, the availability of such combinations as topography, biomass, soil type/moisture and precipitation models implies that water and carbon balance models could be built for entire watersheds. However, this study will assume that such grand regional models are not available, at least to the extent that net primary production can not be used to directly infer carbon sequestration. Nevertheless, less direct inferences such as precipitation patterns being used to delineate humid, moist and dry forests are easily made. For example, in the case of deforestation occurring in an area which has a biomass density greater than a measurement saturation limit, simple models like these could help estimate the biomass not measured.

For helping to differentiate anthropogenic from natural changes, biomass change and population density maps could be correlated. This could only done to a limited degree however because human-induced changes can occur in sparsely populated regions. Perhaps what is more noteworthy is the common herringbone pattern in land use change which can be observed as development follows the construction of highways and secondary roads.

Analysis

Comparison of Remote Sensing Techniques

There were three physical quantities considered in the previous Measurement Types section, namely Land Use, Land Cover and Biomass content. The first two (LULC) are usually defined as an areal extent of discrete classifications while the biomass density is a continuous variable averaged over the area of interest. This distinction is important when considering changes in their values. Changes in LULC imply shifting or creating new boundaries or discrete changes within these boundaries. Biomass changes can occur in this manner or by graduated changes within the same boundaries. A significant example of this was discussed above in Selective Logging. It is also important to remember that in the biomass case, detection of change can occur before the ability to measure the amount of change. However, when considering heterogeneous areas classification becomes more difficult. Different parcels may all be classified by their common predominant species but have varying amounts of different secondary land cover types. Further, in this case, changing the resolution could result in the creation or disappearance of sub-parcels of the various constituent land cover types. Biomass measurements do not have this scale complication, but as discussed above, they are also affected by forest diversity.

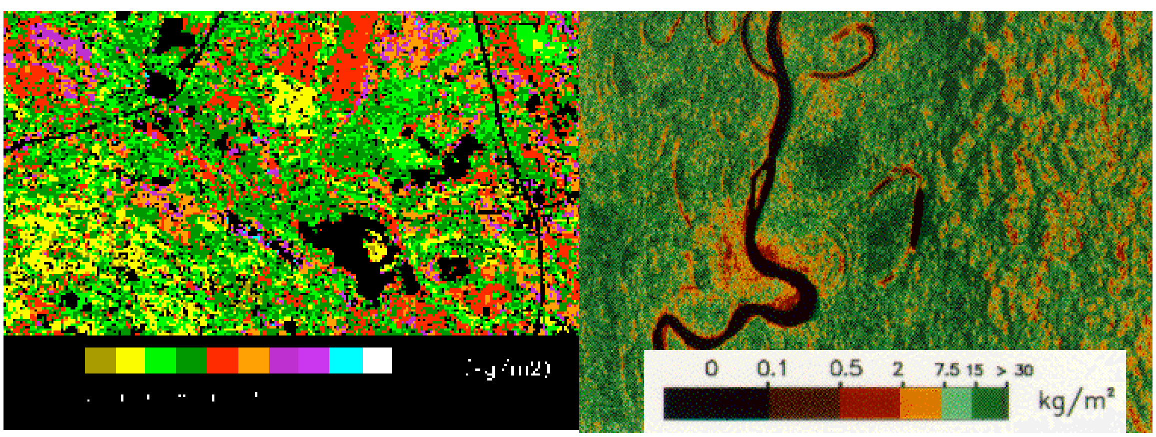
The distinction between LU and LC sometimes become blurred but it is useful to follow the definitions of Turner *et al* (1995). They are: *land cover is the biophysical state of the earth's surface and immediate subsurface and land use involves both the manner in which the biophysical attributes of the land are manipulated and the intent underlying that manipulation- the purpose for which land is used*.. The "human-induced" phrase in the Protocol would tend to imply that it is land use change which is of interest in this study. However in some cases of measuring forestry extent, determining the difference between changes in LC and LU will involve separating the results of natural growth and management practices.

The three measurement types introduced earlier (see Table 1) can be thought of as representing the products which must be combined in the carbon sequestration modeling process. The goal was to find the minimum set of instruments which provides the needed results.

The first product included both the LU and LC, absolute and change measurements. Optical/IR was chosen as the better technique for this, optical for LU since photos are the best to discern human activities and the difference of the two frequencies to determine vegetation indices and thus land cover. However, SAR images can do almost as well in the LC classification and provide better coverage. But the combination of SAR and optical provides the best accuracy and precision (number of cover classes).

The detection of biomass change (the second product) can be done very well by SAR. The SAR backscatter is a function of biomass (Dobson *et al*, 1992) especially using cross-polarization, however it has limitations. These include saturation limits which are discussed above, as well as misclassifications and calibration uncertainties. The latter two are greatly aided in having a pre-existing LC (plus LU if available) categorization (Rignot *et al*, 1997) and a topographical map (because reflection properties are a function of the effective slope of the scatterer). Studies (Freeman and Durden 1998) have indicated that SAR can detect a signature when half the tree trunks have been removed by selective logging. This moderate sensitivity agrees with Le Toan *et al* (1992) who found that although there is a good correlation between backscatter and biomass (r^2 up to 0.95 for cross-P), the correlation between backscatter and stand density is rather low (0.4 and less). Of course full-scale slash and burns should be detected by both SAR and the Optical/IR methods.

The third product includes the detection and measurement of absolute biomass and the related measurement of change of biomass. These are the most difficult of the measurements. Determining the amount of biomass change has the same difficulties as the absolute measurements. The former can involve very small changes but has less need for an absolute calibration (though the repeated measurements would have to be calibrated against each other).



Left - Biomass distribution estimated from AIRSAR data for the BOREAS test site (Saatchi and Rignot, 1997); Right - Biomass estimates for Manu National Forest, Peru from AIRSAR data (Rignot et al, 1995).

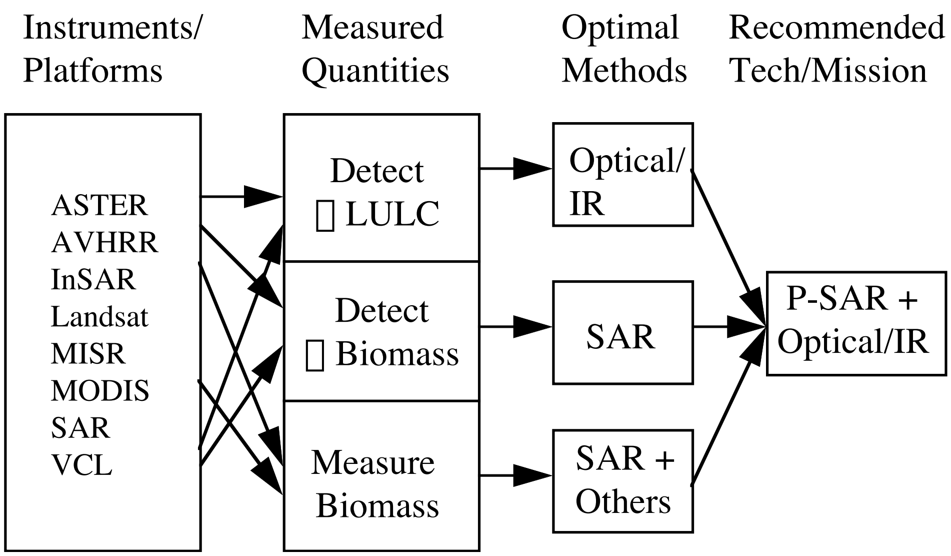
Examples of Biomass determined by SAR
Figure 7

As the saturation levels of Figures 4 and 5 indicated, early regrowth can be measured accurately by SAR but establishing the pre-existing biomass before a forest burn could be difficult for dense forests. Nevertheless, as Figure 7 indicates good results can be obtained, in this case using airborne SAR.

The VCL and IfSAR techniques can produce biomass estimates via tree height measurements and allometric algorithms. However, a recent analysis (Rodriguez 1996) indicates that the estimates are at least as much a function of measuring the spatial distribution of the forest as the individual tree heights. In summary, SAR has the best potential for measuring absolute biomass but further research should be carried out to determine the accuracy of the measurements.

Overall Recommendations

Figure 8 summarizes the above recommended choice of instruments: Optical/IR for LULC, SAR plus potentially others, for absolute biomass and SAR for changes in Biomass.



Selection Process for Instruments
Figure 8

Thus the modeling of carbon sequestration needs the data from both Optical/IR and SAR. This combination is further strengthened by the fact that the SAR results are greatly improved by the existence of the other data. Considering the needed capabilities suggests that at least an L-band SAR is required, but a P-band one is preferred. A two or three channel Optical/IR instrument should provide the classification capabilities required, in particular feature recognition, a rough vegetation index and fire detection. This instrument combined with a P-band SAR is similar to the BIOMES proposal submitted by Freeman *et al* (1998) but without the laser altimeter on board. Although the laser would provide some interesting comparison data, they do not justify its extra weight, power and cost, at least for the purpose of sequestration measurements. The SAR and Optical/IR both need to be of 100m resolution. This is in line with current SAR designs and is actually a reduction in the requirements for typical Optical/IR instruments.

Therefore, a simple Optical/IR instrument and the engineering involved in co-flying it with a SAR provide good technology development goals.

A recent review of the P-band BIOMASS mission (Harriss and Freeman, 1998) supported the science goals but voiced a concern about the validity of the P-band radar technology assumptions. Thus addressing this concern would be a prudent investment of Code Y Technology resources. The scope of this work could range from a short theoretical analysis to a space flight demonstration of the entire P-band system using the New Millennium Earth Orbiting program.

Conclusions and Suggested Follow-on Studies

The measuring of carbon sequestration will be difficult, even beyond that of just measuring biomass change. However, the above-recommended techniques indicate promising solutions to this problem. A follow-on study could investigate the process of implementing the projected measurement capabilities into a viable method for crediting sequestration in the context of the applications previously mentioned in Measurement Types section. A three-phase study is suggested, probably done in the following order:

a) further develop a working interpretation of the relevant paragraph from the Protocol. This would allow the generation of high-level requirements on the remote measurements, as well as recommend the data from other sources (ground-based measurements or records) that will be needed. The official interpretation of the Protocol will require extensive deliberations and carefully worded guidelines. The results of this study could provide valuable technical input for this and point out problem areas that need to be addressed.

b) translate the high-level requirements for the measurements into specific requirements on the various remote sensing techniques that will be used. This can be at the raw measurement level and at the classification product level. The former includes precision, temporal and spatial resolution while the latter focuses on accuracy and misinterpretations.

c) use the analyses to produce a vision of what kind of sequestration measurements should be available, in what time frames and to what accuracy. A range of values will probably be the outcome, with a corresponding scale of costs. These costs can be included in the market strategy as monitoring and transaction costs.

In summary, a multidisciplinary approach for a future study would be beneficial, whereby the common theme of sequestration would provide a focus for the talents of the individuals working on each portion of this task.

Acknowledgments

This study was done at the Jet Propulsion Laboratory of the California Institute of Technology. It was funded from a grant from the Technology Office of NASA's Earth Science Enterprise. Additional funding was provided by JPL's Targeted Commercialization Office. The authors would like to thank Terrance Mason of this office for his thorough editing of this report.

References

Brown, Sandra, A. Gillespie, A. Lugo, "*Biomass of tropical forests of south and southeast Asia*," Can. J. For. Res. , Vol. 21, pp. 111-117, 1991

Butcher, P.N., J.M. Howard, J.S. Regetz, B.X.Semmens, M.A. Vincent, Evaluating the Carbon Sequestration Potential of Tropical Forests, Group Master's Thesis, Bren School of Environmental Science and Management, University of California at Santa Barbara, 1998

Chen, Jing M., W. Chen, J. Liu, J. Cilhlar, "*Carbon budget of boreal forests estimated from the changes in disturbances, climate, nitrogen and CO2. II: results for Canada in 1895-1996*," Global Biogeochemical Cycle, submitted July 1998

Dobson, M.C., F.T. Ulaby, T. Le Toan, Eric S. Kasischke, N. Christensen, "*Dependence of radar backscatter on coniferous forest biomass*," IEEE Trans. Geosci. Remote Sens., Vol. 30, No. 2, pp. 412-415, 1992

Freeman, A. and Durden, S., "*A Three-Component Scattering Model for Polarimetric SAR Data*," IEEE Trans. Geosci. Remote Sens., Vol. 36, No. 3, pp. 963-973, 1998.

Freeman, A., R. Harris, M. Inoff, M. Keller, D. Roberts, "*BIOmass Monitoring and Evaluation Satellite (BIOMES*)," NASA ESE Post-2002 Mission Concept, 1998

Goodman, A., "*Carbon Trading Up and Running*," Tomorrow Magazine: Global Environment Business , May/June 1998

Graham, H.L., "*Joint Implementation as a Policy Issue*," The Feasibility of Joint Implementation, (ed) C.J. Jepma, Kluwer Academic Publishers, Netherlands, pp. 233-248, 1995

Harriss, R. C. and Freeman, A., "*BIOmass MApping Satellite System (BIOMASS)*," Proposal in Response to NASA AO-98-ESE-01, Earth System Science Pathfinder Missions, 1998

Houghton, R.A., "*The Worldwide Extent of Land-use Change, Bioscience*," Vol. 44, No. 5, 1994

IPCC, (Intergovernmental Panel on Climate Change), Climate Change 1995, Impacts, Adaptations and Mitigation of Climate Change: Scientific-Technical Analyses. Working Group III Report, University Press, Cambridge UK, 1996

Kasischke, Eric S., J. M. Melack, M. C. Dobson, "*The Use of Imaging Radars for Ecological Applications-A Review*," Remote Sens. Environ., Vol. 59, pp. 141-156, 1997

Le Toan, Thuy, A. Beaudoin, J. Riom, D. Guyon, "*Relating Forest Biomass to SAR Data*," IEEE Trans. Geosci. Remote Sens., Vol. 30, No. 2, pp. 403-411, 1992

Luckman, Adrian, J. Baker, T. M. Kuplich, C. da Costa Freitas Yanasse, A. C. Frery, "*A Study of the Relationship between Radar Backscatter and Regenerating Tropical Forest Biomass for Spaceborne SAR Instruments*," Remote Sens. Environ., Vol. 60, pp. 1-13, 1997

Luckman, Adrian, J. Baker, M. Honzak, R. Lucas, "*Tropical Forest Biomass Density Estimation using JERS-1 SAR: Seasonal Variation, Confidence Limits and Application to Image Mosaics*," Remote Sens. Environ., Vol. 63, pp. 126-139, 1998

Ranson, K. Jon, G. Sun, R. H. Lang, N. S. Chauhan, R. J. Cacciola, O. Kilic, "*Mapping of Boreal Forest Biomass from Spaceborne Synthetic Aperture Radar*," Journal of Geophysical Research, Vol. 102, No. D 24, pp. 29599-29610, 1997

Rignot, Eric, W. Salas, D. Skole, "*Mapping Deforestation and Secondary Growth in Rondonia, Brazil, Using Imaging radar and Thematic Mapper Data*," Remote Sens. Environ., Vol. 59, No 2, pp. 167-179, 1997

Rodriguez, Ernesto, T. Michel, D. Harding, "*Interferometric Measurement of Canopy Height Characteristics for Coniferous Forests*," to be submitted, 1996

Rodriguez, Ernesto, "*Laser Profilometry vs. Interferometric/ Polarimetric SAR for Characterizing Vegetation Canopies (Coniferous Forests)*," ESE Trade Study Report, 1998

Saatchi, Sasan S. and Rignot E., "*Classification of Boreal Forest Cover Types using SAR Images*," Remote Sens. Environ., Vol. 60, No. 3, pp. 270-281, 1997

Saatchi, Sasan S., D. Tralli, T. Mason, R. Harris, "*SAR Technology Development for Carbon Offset Underwriting*," Proposal to JPL Director's Research and Development Fund FY '99, 1998

Schlesinger, William H., Biogeochemistry: An Analysis of Global Change, 2nd Edition, Academic Press, San Diego, 1997

Townsend, J. R. G., C. O. Justice, "*Selecting the spatial resolution of satellite sensors required for global monitoring of land transformation*," Int. J. Remote Sensing, Vol. 9. No. 2 pp. 187-236, 1988

Trexler, Mark C., and Haugen C., Keeping it Green: Tropical Forestry Opportunities for Mitigating Climate Change, World Resources Institute (Washington D.C.) Report, 1994

Trexler, Mark C., "*Carbon Offset Strategies: A private sector perspective*," The Feasibility of Joint Implementation, (ed) C.J. Jepma, Kluwer Academic Publishers, Netherlands, pp. 233-248, 1995

Turner, B.L., D. Skole, S. Sanderson, G. Fisher, L. Fresco, and R. Leemans, Land-Use and Land-Cover Change Science/Research Plan, IGBP Report No. 35, HDP Report No. 7, 1995

UNFCC, "http://www.unfccc.de/index.html," 1997

van Zyl, Jacob J., "*The effect of topography on radar scattering from vegetated areas*," IEEE Trans. Geosci. Remote Sens., Vol. 31, No. 1, pp. 153-160, 1993

van Zyl, Jacob J., B. Chapman, P. Dubois, J. Shi, "*The effect of topography on SAR calibration*," IEEE Trans. Geosci. Remote Sens., Vol. 31, No. 5, pp. 1036-1043, 1993

Vincent, Mark A., "*Scoping the Potential of using Remote Sensing to Validate the Inclusion of Carbon Sequestration in International Global Warming Negotiations*," Proposal submitted in response to the Terrestrial Ecology and Global Change (TECO) Research Announcement: NRA: 97-MTPE-15, 1998

Wang, Yong, J. L. Day, F. W. Davis, J. M. Melack, "*Modeling L-Band Radar Backscatter of Alaskan Boreal Forest*," IEEE Trans. Geosci. Remote Sens., Vol. 31, No. 6, pp. 1146-1154, 1993

Woodcock, Curtis E., A. H. Strahler, "*The Factor of Scale in Remote Sensing*, "Remote Sens. Environ., Vol. 21, pp. 311-332, 1987

Appendix

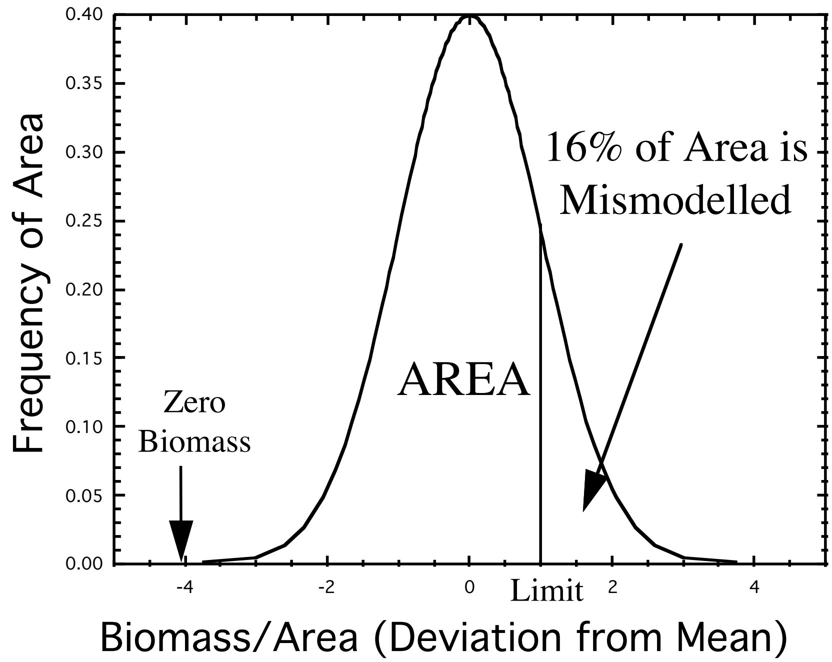
Calculation of the Underestimation of Biomass due to SAR Saturation Limits

This study investigated the consequences of saturation limits on the measurement of biomass. Only a general treatment using representative numbers plus examples are presented here. A follow-on study is planned which will include the actual statistics of different forest types. Two major assumptions will be made in this analysis. One, the biomass per area (density) values for the area units chosen are normally distributed. Real data suggests that this is a good assumption, though of course, the tails of the distribution are cut off at zero density and some maximum value. But as explained later, these truncations can be accounted for in the analysis.

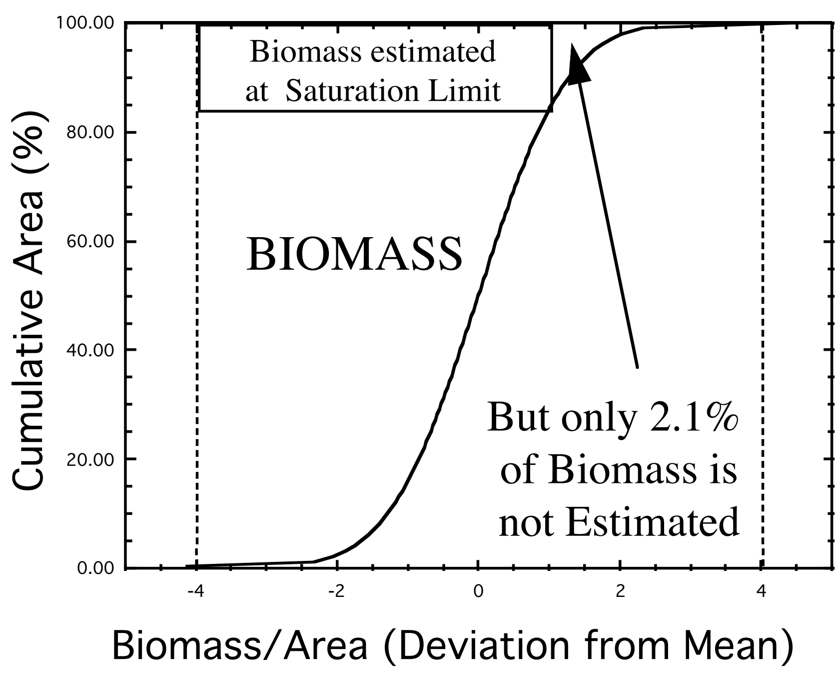
The second assumption is that the areas which produce saturated measurements are categorized as having the biomass right at the saturation limit. Thus the scenario envisioned is one where the biomass density is normally distributed but the mean and standard deviation are not discernible from the measurements (since knowing the mean alone would give the total biomass).

The familiar normal distribution curve is shown in Figure 9. For this example, the saturation limit is arbitrarily chosen to be one standard deviation higher than the mean biomass/area. Also in this case the mean biomass/area value is chosen to be 4 σ's above the zero biomass value. The region under the curve to the right of the limit line is the amount of surface area that will be mismodeled. Identical to the probability cumulative distribution function, this area is known to be about 16% for a limit value of 1σ. Thus in this case, 16% of the land area is mismodeled, however this does not indicate how much the biomass has been underestimated.

Figure 10 was constructed in order to graphically represent the amount of biomass not included,. The y-axis is the cumulative surface area per cent (the integral of the dependent variable of Figure 9). The sigmoid curve represents its value as a function of the biomass/area variable. However, it is better to conceptualize the curve as the biomass/area being a function of the cumulative area. Then it follows that any area bounded by the curve, the line corresponding to zero biomass and an upper and lower limit of cumulative area represents the integral of biomass/area with respect to area and thus the biomass belonging to this range of cumulative areas which has a corresponding range of biomass/areas. In other words, integrate along the y-axis rather than the x-axis.



Distribution of Biomass/Area
Figure 9



Under Estimation of Biomass
Figure 10

The total biomass is thus represented by the total area to the left of the curve and right of the line of zero biomass, but due to symmetry this is just half the area of the large rectangle bounded by plus and minus the zero biomass sigma value. Since the vertical dimension is one (unit area considered), the total biomass is just μ sigmas where μ is the value of mean value given in sigma units above zero biomass. Although this is somewhat of an awkward system of units when doing the proportional analysis to see how much biomass is not accounted for ("lost biomass"), the units will drop out.

Again, consider the case where the saturation limit is 1σ higher than the mean. As shown on Figure 10, the biomass which should be measured, the area of the small rectangle plus the 2.1% region, will instead get measured as the rectangular area only. To determine the relative lost biomass, the area of the small triangular region must be compared to the total biomass described above. Table 3 in the main body of this report presents the results of considering four saturation limits, a number of μ values and the corresponding lost biomass determined by numerical integration. The last column gives the respective percentages of biomass lost for these μ values by simple division. Note for the numerical integration it is simpler to integrate the corresponding region below the curve that has the same area but along the x-axis. However, it is even more simple to go back to the original concepts and integrate the product of the amount of biomass above the limit and its probability. This is the familiar form of the "expected value" of lost biomass:

$$\text{Biomass loss} = 1/\sqrt{(2\pi)} \int_{Z_L}^{Z_U} \left(x - Z_L\right) \exp(-x^2/2)\, dx$$

where Z_L and Z_U are the saturation limit and upper biomass/area value respectively, in the number of σ's above the mean. It is also worth noting that in the cases of μ only being 2σ, there is a significant portion of the curves less than the zero biomass/area point. Similarly, the curves may extend beyond the maximum biomass/area. However, as long as symmetry is conserved, using these "truncated normal curves" does not change the values considered and is properly accounted for in the above integral. And even in the asymmetrical case, the integral gives the correct lost biomass though the total and per cent lost have to be adjusted accordingly.