Climatic Change (2009) 93:69–101
DOI 10.1007/s10584-008-9526-6

National forest carbon inventories: policy needs and assessment capacity

Krister Andersson · Tom P. Evans · Kenneth R. Richards

Received: 6 February 2006 / Accepted: 22 September 2008 / Published online: 21 November 2008

Abstract Previous research has identified the importance of the role of land cover in the global carbon cycle. In particular, forests have been identified as a significant carbon sink that can mitigate the rate of global climate change. Policy makers are faced with complex and difficult challenges in getting timely and useful information in monitoring global forest resources. Recent advances in the tools and methods of forest carbon accounting have produced new, innovative approaches to forest-based carbon inventories. But it is important as new tools are developed that scientists understand the needs of policy makers and that policy makers understand the capabilities and limitations of forest inventory methods. This paper explores four different policy applications that rely, or could benefit from, national carbon inventories. The goal is to help build a bridge between the communities of climate policy makers and scientists specialized in forest carbon inventories. To this end, we pursue three specific objectives: First we provide an overview for policy makers about approaches to forest carbon inventories, paying particular attention to the contributions of remote sensing technologies. Second, we outline the issues particularly relevant to forest inventory scientists who are interested in responding to public policy needs. We then discuss the tradeoffs between information cost, accuracy, precision, transparency and timeliness that need to be balanced in long-term monitoring of forest carbon. Finally, the article concludes with a series of observations and

K. Andersson
University of Colorado, Boulder, CO, USA

T. P. Evans
Indiana University, Bloomington, IN, USA

K. R. Richards (✉)
School of Public and Environmental Affairs, Indiana University,
Bloomington, IN 47405, USA
e-mail: kenricha@indiana.edu

recommendations for the implementation of forest carbon inventories as increasingly central components of global climate change policy.

1 Introduction

Climate change and global warming threaten to disrupt both the natural world and humankind's health and welfare (i.e. Solomon et al. 2007; McMichael 1993; Stein 2001). Protection and expansion of terrestrial carbon sinks are likely to play an integral role in any meaningful international effort to stem the rise of atmospheric carbon dioxide that leads to global warming. Terrestrial ecosystems play an important part in the global carbon cycle, with land-use change contributing approximately 20% of gross global carbon emissions, while terrestrial absorption of carbon removes just slightly more (Watson et al. 2001). Hence, terrestrial ecosystems, taken as a whole, appear to be a net sink for carbon. The potential, however, is much greater. A modest decrease in emissions from land-use change and a small percent increase in terrestrial absorption could significantly reduce net carbon emissions to the atmosphere, at least for the near term (Dyson 1977; Nabuurs et al. 2007).

Forest carbon sinks are now an integral element of international greenhouse gas (GHG) policy under the United Nations Framework Convention for Climate Change (UNFCCC 1992) and its Kyoto Protocol (KP-UNFCCC 1997). Beyond these immediate international agreements, there have been calls for carbon sequestration to form a larger part of national and international climate change policy (see, e.g., Watson et al. 1995; Kauppi and Sedjo 2001; Stavins and Richards 2005). This means that the capacity to measure the size and changes in carbon sinks at the national level has become an essential issue in the policy arena.

There are four distinct but interrelated climate policy functions for which the capacity to conduct national inventories of forest carbon sinks is critical.

The reporting function. Conducting recurring national forest carbon inventories forms an integral part of complying with existing international climate treaties. All countries that have signed the UNFCCC are committed to "develop, periodically update, publish and make available to the Conference of the Parties … national inventories of anthropogenic emissions by sources and removals by sinks of all greenhouse gases not controlled by the Montreal Protocol"[1] (UNFCCC 1992, Art. 4.1(a)). In addition to the UNFCCC, signatory countries to the Biodiversity Convention, The Convention to Combat Desertification, and the World Heritage Convention as well as member countries to the United Nations Forum on Forests and the Food and Agriculture Organization (FAO) are required to report regularly on national-level changes in a variety of forest characteristics—such as total forest area, woody biomass, and diversity of tree species—some of which are useful input variables for estimating national forest carbon stocks (Braatz 2002).

The policy formation function. As countries explore alternative policy responses to global warming, it is important for each country to be able to gauge the size and

[1] "The Montreal Protocol stipulates that the production and consumption of compounds that deplete ozone in the stratosphere—chlorofluorocarbons (CFCs), halons, carbon tetrachloride, and methyl chloroform—[were] to be phased out by 2000 (2005 for methyl chloroform)" (CIESIN n.d.).

trends of its forest carbon stock.[2] This information is useful in diagnosing existing limitations in terrestrial systems' offset capacity and for setting policy goals and targets related to the use of such systems in mitigating the rise in atmospheric carbon dioxide.

The policy evaluation function. For countries that engage in afforestation and reforestation project activities under the Clean Development Mechanism and Joint Implementation of the Kyoto Protocol, national forest carbon inventories might play an important role in gauging the aggregate effects of individual projects. Moreover, as the parties to the UNFCCC discuss the possibility of introducing a compensation scheme for reduced emissions from deforestation and degradation in developing countries (the so-called REDD initiative) in the post-Kyoto climate agreement, the evaluation function of national forest carbon inventories promises to become even more essential (UNFCCC 2008; Gibbs and Herold 2007). More broadly, for any country that is pursuing a goal of enhancing carbon sequestration—through special forest policies, programs, or even projects—it is important for purposes of ex post evaluation to assess actual changes in carbon stocks that may have occurred as a result of such policy response activities.

The policy implementation function. Some studies have suggested that under certain circumstances it may be more effective to reward gains in carbon storage at the national level rather than at the project level (Andersson and Richards 2001; Santilli et al. 2005; Schlamadinger et al. 2005). Such an approach, which introduces country ownership of carbon, could involve an international carbon trading regime in which periodic national allocations of allowances are adjusted to reflect gains or losses in terrestrial carbon stocks.[3] The REDD initiative takes a similar approach in that it also relies on national level accomplishments and introduces financial incentives to countries that voluntarily commit to reduce deforestation to a baseline, which will be either historical, projected or negotiated (see Mollicone et al. 2007; UNFCCC 2008). In both contexts, the capacity to conduct timely and accurate national inventories is essential to the success of these programs.

Consequently, national forest carbon inventories represent a critical tool in the international efforts to mitigate climate change. However, many policy analysts and government officials who develop and implement climate change policy are not technical specialists in forest carbon inventories or the tools and instruments available for their implementation. Without an understanding of these tools and instruments, many members of the policy community continue to have difficulties in assessing viable policy options and answering critical questions, such as: how accurate are

[2]It is important to distinguish two terms related to terrestrial carbon sinks. The first concept is that of a *stock*. This term refers to the amount of carbon held by an ecosystem at a given point in time. In this article, when we refer to a terrestrial carbon inventory we are referring to a stock. The second term used in discussions of carbon sinks is *flow*. Carbon flows refer to how much carbon has been added to, or lost from, a stock during a given period of time. One measure of a flow in a given period of time is the difference between the stock at the beginning and at the end of the time period. Lack of clarity with regard to this distinction has led to confusion in the past.

[3]A trading regime that reflects changes in national terrestrial carbon stocks would not necessarily be confined to changes in forest carbon stocks only. There are many opportunities for enhancing carbon stocks on agricultural land as well, but this paper will confine the discussion to national forest carbon inventories to support policy goals.

national forest carbon inventories? What steps would improve the capability to conduct accurate national forest carbon inventories? How much would such steps cost? Despite a rapidly growing technical literature on forest carbon inventories, much of this literature does not target policy communities and is therefore excessively technical and practically inaccessible to many policy makers (Peskett et al. 2006; UNFCCC 2008; Nabuurs et al. 2007).

At the same time, many of the scientific experts in the field of forest carbon estimation have focused on the technical challenges of estimation, often operating within a traditional research paradigm in which they expect their research to speak for itself and be absorbed by policy makers (Dilling 2007; Moser and Dilling 2007). Some researchers argue that there is a dearth of co-production of knowledge about climate change policy at the national level largely due to unsystematic or ineffective dialogue between the two camps (Social Learning Group 2001; Specter 1988; McNie 2006), While there are some important forums for science–policy dialogue about forest carbon at the international level, such forums are less common at the national levels, especially in many less developed nations (Braatz and Doorn 2005). We are thus in a situation where decisions related to the formation, monitoring, and enforcement of carbon sequestration commitments are often not based on an integrated understanding of the policy, science, and technology of forest carbon sinks. This article is an effort to facilitate a more effective dialogue between policy makers and scientists by clarifying and discussing some of the core issues associated with the implementation of national forest carbon inventories.

We have three specific objectives. First, the article is intended to provide an overview of approaches, methods, and tools used to develop national-level forest carbon inventories. Because of their increased importance to national inventories in both industrial and non-industrial nations, we pay particular attention to remote-sensing tools. The discussion is intended to be accessible to policy analysts and government decision makers who are interested in understanding the methods, requirements, and issues related to developing national inventories of carbon stored in forests.

Second, the article is intended to inform the technical experts working in the fields of remote sensing, biomass and carbon modeling, and land-use analysis regarding the types of information that will be useful to the policy community as it begins to implement carbon dioxide mitigation programs at the national and international levels. To achieve these first two goals Section 2 discusses the types of information that would be most useful in policy formation, implementation, and evaluation. The article also provides the policy community with an introduction to approaches to national carbon inventory estimations. Section 3 briefly examines the tools and methods that are available to provide that information.

The third objective of this article is to provide a discussion of the types of tradeoffs that will be necessary in designing policy, given the combination of resource constraints and limitations in the state of the art for national assessments. Specifically, we examine four critical factors regarding the organization and implementation of forest carbon inventories: cost, accuracy and precision, timing, and transparency. The tradeoff among cost on the one hand and the other three factors on the other is discussed in Section 4. Section 5 discusses policy implications and outlines conclusions.

The article provides several insights:

1. Of the several identifiable policy functions that national carbon inventories might serve, the most demanding is likely to be the fourth—supporting the implementation of an international carbon sequestration program that allocates carbon emission allowances to countries. This function requires frequently repeated, highly accurate and precise estimates of changes in terrestrial forest carbon stocks.
2. Remote-sensing technology is a useful tool for efforts to monitor changes in forest cover areas, and as such it represents a valuable resource for the estimation of carbon stocks.
3. The utility of remote sensing as a monitoring tool increases with the spatial extent of the monitored resource system (i.e., remote sensing is particularly useful when the area being evaluated is large).
4. Policy makers need to understand that remote sensing is not a stand-alone, off-the-shelf method for accurate carbon monitoring. To be most useful for estimating carbon stocks, remote-sensing data need to be combined with field observations and allometric modeling.
5. Policy decisions regarding investments in acquiring forest carbon inventory data need to consider a tradeoff between costs, timeliness, accuracy/precision, and transparency.
6. These tradeoffs have implications for both policy formation and implementation with regard to the use of national forest carbon inventories in international efforts to mitigate global warming.
7. Substantial investments in the science and practice of carbon inventory science—particularly the development of country-specific approaches to make creative use of existing expertise, organizations, and forest data—will be required before the state of the art catches up with the potential demands of policy makers.

2 The information needs of the policy community

To facilitate the discussion between policy practitioners and scientists in the fields of remote sensing and forest carbon inventories it is important to identify, at least generally, the needs of the policy community.In the previous section we identified four policy-related functions that national forest carbon inventories support. Each function places different demands on the organization of the inventory process. To assess the requirements for each of the four functions of the national inventories, we consider three characteristic of inventory information (1) the timing of national inventories; (2) the precision and accuracy of the estimates; and (3) public transparency—and their relation to costs.

The first characteristic—timing—includes both frequency and lag. Frequency, or periodicity, of national inventories refers to the length of time that elapses between new estimates. For example, the frequency of national reports under the UNFCCC, as discussed above, appears to be about every 3 years. The lag of a report refers to the amount of time that passes between the actual measurement of the data and the reporting of the result. If data collection occurs in 1997 and the results are processed and reported in 1999, there is a 2-year lag in the report. Generally, both increased frequency and decreased lag are desirable, but are often costly to achieve simultaneously.

Regarding the second characteristic, we define precision as the degree of agreement between individual measurements, values, and results. Accuracy refers to the degree of conformity of an estimated or measured value to its actual or "true" value. Both of these are desirable characteristics. Generally, however, to increase the precision and accuracy of estimates almost always implies significant increases of costs.

Transparency also has multiple implications. In its narrowest use, transparency refers to the ability of external actors to verify the integrity of the reported results. Hence, in the case of a system of national carbon inventories, the reports themselves should be verifiable by independent third parties such as other treaty signatories and environmental organizations. More generally, transparency refers to public understanding and, ultimately, legitimacy and trust of the system. Transparency is critical to public acceptance and support of government programs. But increasing transparency also increases costs as it will often imply instituting new working routines for data handling, processing, and communication. Personnel need to be trained in the new routines, and new infrastructure may be needed to support these routines (e.g. web-based database and digital library). Table 1 summarizes the information requirements for each of the functions of the national forest carbon inventories.

2.1 Reporting

National governments that have signed the UNFCCC and the Kyoto Protocol are bound by these agreements to report the results of periodic national inventories of GHG emissions and removals, and forest carbon inventories form an integral part of these national inventories. Under the Kyoto Protocol, each country listed in Annex I of the UNFCCC (1992) is responsible for providing detailed "data to establish its level of carbon stocks in 1990 and to enable an estimate to be made of its changes in carbon stocks in subsequent years" (KP-UNFCCC 1997, Art. 3.4). Article 5.1 requires Annex I parties to have a national system for estimating removals of GHGs by sinks (KP-UNFCCC 1997). To support the requirements of Article 5.1, Article 5.2 requires the Conference of the Parties (COP) to the Kyoto Protocol to develop "methodologies for estimating anthropogenic … removals by sinks of all greenhouse gases not controlled by the Montreal Protocol" as well as adjustments to be applied when the accepted methods are not used (KP-UNFCCC 1997).

Table 1 Summary of forest carbon inventory requirements, by policy function

Policy function	Timing		Precision and accuracy	Transparency
	Frequency	Lag		
Reporting	Every 3–4 years	3–7 years	Low–Medium	Low
Policy Formation	One time	5 to 10 years	Medium	Low
Policy Evaluation	Irregularly	3 to 5	Medium	Medium
Policy Implementation	Every 2–5 years	2 to 4 years	High	High

Under the UNFCCC, the COP decides the content and intervals of the different types of reports that the signatory parties must submit to the UNFCCC secretariat. The COP decisions to date have asked Annex 1 countries to submit national communications of estimates on an annual basis while Annex 2 countries are asked to do so "periodically." In reality, however, the national communications have not been produced according to the original UNFCCC agreement. National communications are reported sporadically as requested by the COP. T he current UNFCCC registry includes reports for most Annex 1 countries for 1995, 1998, 2001 and 2005, which means that the actual reporting interval is approximately 3–4 years. To date, very few developing countries have provided any national communications at all. When it comes to the content of the reported information, the COP has decided that countries should follow the approaches described in Good Practice Guidance (GPG) by the Intergovernmental Panel on Climate Change (IPCC 2004). The GPG provides countries with a set of flexible and adaptable approaches to "estimate, measure, monitor, and report changes in carbon stocks and anthropogenic greenhouse gas emissions by sources and removals by sinks resulting from land use, land-use change and forestry activities under Article 3, paragraphs 3 and 4, and Articles 6 and 12 of the Kyoto Protocol" (IPCC 2004, 1.5). As scientifically sound as the content of the GPG is, its effectiveness in producing more reliable and valid inventory estimates depends to a great extent on the technical and administrative capacity among national government entities that are responsible for the implementation of these practices. Countries that lack human and financial resources to carry out such practices gain little from such guidelines (Peskett et al. 2006; Noordwijk et al. 2007). In this paper, we explore the policy implications of this apparent mismatch between scientific rigor and countries' existing technical and administrative capacities to govern forest carbon inventories.

To calculate the greenhouse gas emissions and removals by LULUCF activities, national forest inventories (NFIs) represent a key source of information (Braatz 2002; Kauppi and Sedjo 2001; Tomppo and Czaplewski 2002; Austin et al. 2003). According to agreements at the eighth Conference of the Parties to the Kyoto Protocol (COP8), Annex 1 countries should report changes in forest carbon stocks annually, but because few countries carry out NFIs more frequently than every 5, or even 10 years, the national reports normally rely on projected quantities of carbon emissions and removals from forests and land use change for the reporting period (Forner 2002; Kleinn 2002). So, for example, when the Canadian government submitted its national reports for 1995 to the UNFCCC, it reported projected changes in its terrestrial carbon sink based on the results of the 1991 and earlier national forest inventories (Government of Canada 1995). Similarly, in the 2003 inventory of GHG emissions and sinks, the estimates for forest carbon were based on modeled projections and extrapolations based on data gathered from 1990 to 1999. The development of national reports is left up to individual governments. Each country is encouraged to develop estimation approaches that are designed for the country's special geographic, technical, and economic circumstances. The UNFCCC sends out an expert review team to all Annex 1 countries to verify the results of reports submitted, but because the economic stakes, so far at least, have been so low and the methodological flexibility so high, accuracy in reporting seems to be largely a matter of national honor.

2.2 Policy formation

Reliable information from national forest carbon inventories are needed not only to fulfill international commitments, but also for effective policy formation. This function requires a clear problem orientation, which in turn relies on a thorough quantitative understanding of the problem at hand. If the problem that policy decision makers seek to address is about recent increases in GHG emissions from deforestation and forest degradation in a particular region, data from national forest carbon inventories can help provide answers to several critical questions. For example, what are the approximate sizes of forest carbon stocks that have been converted? What land uses have replaced forestry? What is the over-time trend in carbon sinks at the various levels of aggregation and what is the rate of change in each region and forest type? This ex ante climate change diagnostic of the sources of emissions and sinks allows the policy makers to assess possible alternative responses to the problems and to define policy targets and goals. This policy function requires the development of historic trends of national inventories of carbon, in some cases dating back several decades. In many cases, it is also useful to develop expected forecast scenarios in the absence of policy interventions.

2.3 Program evaluation

Once forest carbon sequestration policies, programs, and projects are in place, it will be important to conduct ex post evaluation. This includes assessing the aggregate effects of the initiatives as well as disaggregating the effects for causation. Politicians and policy analysts will want to know whether past policies have been effective and, if they have not, to seek to modify the existing policies. Have the national policies aimed at enhancing forest carbon sinks had their intended effects? Do the accomplishments of individual sequestration projects add up to real, measurable increases in forest-stored carbon? Are estimates of changes in carbon stocks meaningful, given the uncertainties in the estimation process? National forest carbon inventories may be used to answer these questions. Generally, this type of ex post policy evaluation is conducted a few years after the implementing agency has carried out program activities to allow for lag effects to materialize. The purpose of program or policy evaluation is to determine the additional contribution of the program—to distinguish the effects of the program from other exogenous changes, those that would have occurred even without the program.[4] The implication of this goal, however, is that national forest carbon inventories need to achieve high enough precision for the effects to be quantitatively discernible.

2.4 Policy implementation

Arguably, policy implementation could place the greatest demands on carbon inventory capabilities. The specific requirements for national forest carbon inventories

[4]The ex post evaluation of program impacts can be a challenging exercise. The US Department of Agriculture has implemented a Conservation Effects Assessment Program to provide better analysis of the actual impacts of government expenditure on the environment (http://www.ars.usda.gov/research/publications/publications.htm?seq_no_115=182878).

depend, of course, on the specific design of the sequestration program. Consider one potential type of program and the information needs that it implies. There have been several proposals suggesting that within an international regime of carbon trading, sequestration gains and losses should be assessed and rewarded at the national level (Andersson and Richards 2001; Santilli et al. 2005; Schlamadinger et al. 2005). This approach is in contrast to the more widely recognized path, embodied in the Clean Development Mechanism provisions of the Kyoto Protocol, of rewarding offset credits to individual sequestration projects. The advantages of the national approach relative to the project-by-project approach include a decrease in the problems of leakage and baseline definition, an increase in the breadth of approaches to sequestration that can be rewarded, a shift in focus from local project effects to the more meaningful aggregate effects, and an improvement in program manageability at the international level due to a substantial decrease in the number of reporting entities that must be monitored (Andersson and Richards 2001).[5]

An international program based on gains to national inventories of carbon would require frequent—likely at least every 5 years—estimations for every country participating in the program. Moreover, given the high stakes involved, the process of estimation would need to be highly transparent to garner broad public support. Finally, the estimations of changes in forest-carbon stocks based on the national inventories would need to be highly accurate to generate confidence among all parties involved that the increments in carbon allowance allocations correspond to actual accruals of carbon.

To see the latter point consider the following example. The size of the total global carbon pool in vegetation was estimated at 466 GtC (gigatonnes of carbon) in 2000 (IPCC 2002). Suppose that during a particular 5-year commitment period there is in fact no change in the size of the global carbon sink. However, if there were even a 1% drift in the measurement of that carbon stock, say to the positive side, it would appear that there had been a gain of approximately 4.7 GtC over the commitment period, or approximately 0.94 Gt/year. According to IPCC's fourth assessment report, the annual global emission of carbon from industrial sources in 2004 was approximately 9.5 Gt (Solomon et al. 2007). Even if the global community aimed to reduce annual emissions by 10% (they have not been so ambitious), that would suggest that net emissions must decline by only 0.95 Gt/year. In this example, because of the small error in measurement of the size of the global carbon stock in sinks, countries would estimate that they had practically met their entire emissions reduction targets based on sinks alone and not be obliged to undertake any source reduction actions. In fact, when estimates based on existing carbon inventory techniques are subject to uncertainty analysis, it is not uncommon to see 15–60% error margins in a country's forest carbon pool estimates even in countries following IPCC guidelines and using advanced technologies (Noordwijk et al. 2007; Jonas et al. 1999; Nilsson et al. 2000; Balzter and Shvidenko 2000). Hence, the uncertainty in the sink measurements could substantially undermine efforts to reduce net emissions by overwhelming the carbon source emission estimates. It is therefore important to determine just how precise

[5] It is beyond the scope of this article to explore the specifics of the argument about the national- versus project-level focus for program implementation. See Richards and Andersson (2001) for a discussion of these issues.

the measurements of carbon stands need to be to support an international trading program.

Note in Table 1 that policy implementation places the greatest demands on national forest carbon inventories. This means that national forest carbon inventories that meet the requirements for the policy implementation function will most likely also be adequate to serve the purposes of the other three policy functions of reporting, policy formation, and evaluation. The question then becomes whether forest science and remote sensing can support a program of carbon trading based on national inventories. That is a question that this article will help address. In doing so, we argue that sound climate mitigation policy relies on good and constant communication between government decision makers and members of the remote-sensing and forestry research community. The next section provides policy makers with a brief overview of the available methods and instruments for national forest carbon inventories.

3 Methods for the development of national forest carbon inventories

Despite recent technological advances, it is still impossible to measure directly how forest carbon stocks vary across a landscape or change over time. As a result, we have to resort to estimations of forest carbon based on direct measurements of more readily available attributes of woody biomass. Simply put, all forest carbon inventories consist of three basic components: (1) identification of forest types and estimation of their spatial extents; (2) identification of tree species and stem density for each forest type, and (3) calculation of volume and estimation of carbon content for each tree species and size class. The eventual cost and quality of the inventory estimation will, to a great extent, depend on how creative inventory mangers are when it comes to utilizing existing data in the design phase of the inventory as well as on how they decide to combine the activities under the three components. It turns out that one of the most important economic decisions of inventory managers regards the sequencing of the three inventory components: managers can save money by using information gathered at one stage of the inventory to inform decisions of resource allocations at subsequent stages.

Inventory managers can achieve important cost-savings by making intelligent use of existing data on woody vegetation. Even if a country has never formally conducted a national forest carbon inventory before, it does not mean that their inventory efforts need to start from scratch. Some data on forests—either from national or even sub-national forest inventories—are available at some scale in most countries. Such data can represent a gold mine for inventory managers as it will allow them to make strategic use of remote sensing data in the first stage of the inventory: the identification of forest types and measurement of the land areas associated with each forest type. Inventory managers with access to existing forest field data on forest types (e.g. dry tropical forests) and forest conditions (age, drainage, slope, and level of degradation) can use this data to interpret remotely sensed images and can proceed to stratify the landscape into a number of land cover categories, with similar levels of carbon stock density (Gibbs et al. 2007).

In the second and third stages of the inventory the establishment of sampling strata is crucial for the efficient implementation of field measurements. Because carbon stocks are often highly clustered in specific areas on the landscape stratification economizes on field measurements by allowing managers to sample more sites in areas that have higher variability in terms of carbon stock. Relative to stratified sampling of field sites, non-stratified sampling (random or systematic) will undersample highly variable areas and over-sample areas with low variability (Pearson et al. 2005; Gibbs et al. 2007).

With the growing interest in carbon-cycle models in general, and forest carbon inventories in particular, researchers have sought to develop more precise, accurate, timely, and cost-effective methods for providing estimates of the size and rate of change for carbon stocks. A number of researchers have drawn attention to the challenges faced in the development of national estimates of forest carbon (Gullison et al. 2007; Rokityanskiy et al. 2007; Noordwijk et al. 2007; Brown 2002; Foody 2003). Much of this work has focused on the integration of field-based inventory data, ecosystem process models, and remote-sensing products to develop biomass estimates for large spatial extents. There is acknowledged uncertainty or error in each of these sources in the carbon estimate equations. In this section we provide an overview of the two main elements of modern forest carbon estimation methods: Remote sensing data and field measurements. (For more extensive treatment of both of these methods, we refer to our on-line supplement to this article[6] and the recent literature, e.g. Gibbs et al. 2007; Rosenqvist et al. 2003; Rogan and Chen 2004; Myneni et al. 2001). Our overview follows the order of modern, multi-stage inventory processes, starting with the use of remote sensing instruments followed by field measurement techniques.

3.1 Remote sensing

Remote sensing has become a primary source of data for the assessment of carbon storage and fluxes (Cohen and Justice 1999; Running et al. 1999). The availability of new sensors and platforms presents researchers with the opportunity to develop ever more advanced and refined methods of data collection. One of the reasons remote sensing has become such a popular tool for forest carbon accounting is that it is often portrayed as offering considerable cost savings as compared to methods relying exclusively on field observations, which are costly for assessing large spatial extents (Brown 1999; Foody 2003). One of the central points of this article, however, is that the presumed savings in monitoring costs are not an automatic consequence of using remote sensing. Rather, the potential for cost reductions depends ultimately on which set of remote-sensing instruments is selected, and how the remote-sensing data are combined with field observations as input data to these models.

Many remote-sensing instruments can contribute data to the carbon inventory estimation process. Sensors fall under two main categories: active sensors and passive sensors. Passive sensors measure reflected solar radiation of the sun's illumination of Earth's surface, essentially various forms of photography. Active sensors transmit radiation that is reflected from Earth's surface and then measured, including Synthetic Aperture Radar (SAR) and Light Detection and Ranging (LIDAR) sensors.

[6]The online supplement may be accessed at http://sobek.colorado.edu/~anderssk/KA_TE_KR_CC_Supplement.pdf.

There are also two primary platforms for the sensors: airplane-based (airborne) and satellite. Airborne platforms are largely focused on orthophotography,[7] LIDAR, and various experimental phase technologies and tend to be occasional or irregular in schedule. They can also be expensive to operate. Airborne platforms serve as a test bed for sensors that are ultimately planned for a satellite-based launch. Satellites, in contrast, are continuously operating, space-based platforms. Satellite data are captured in a series of images as the satellite passes over Earth's surface. Thus, to cover large geographic areas, a mosaic or set of images covering different subsets of that area are used.

Table 2 provides a broad summary of the various types of instruments that could be employed in the development and maintenance of national carbon inventories. Airplane-based sensors such as LIDAR can have spatial resolutions as fine as a meter or less. In contrast, within the passive satellite-based instruments, the spatial resolution ranges from ultrafine (<5 m) to fine (~10–100 m) to medium (100–250 m) to coarse (>250 m), although there are differences of opinion within the research community regarding what is considered fine vs. medium resolution. In currently available products, the spatial resolution of satellite-based active sensors tends to be even coarser than the spatial resolution of satellite-based passive sensors.. The images also vary in terms of spectral resolution (the number of distinct ranges of the electromagnetic spectrum measured, and the overall range of wavelengths measured by the satellite's sensor), geographic coverage or extent for one image, frequency of pass over specific sites (temporal resolution), and time periods over which they have operated.

The remote-sensing instruments vary dramatically with respect to their suitability for the various tasks involved in developing carbon inventories. In general, the instruments with fine resolution (10–100 m) are well suited for the land classification function, while those instruments with ultrafine resolution (<5 m) and more specialized functions are better adapted for measuring forest variable inputs for the allometric models. These categories of spatial resolution are somewhat arbitrarily defined but are matched to general uses of each resolution type. For example, the medium and coarse resolution instruments (>100 m) are useful for measuring some types of forest variable data, but are more suited to monitoring changes in the spatial extent of forests and identifying geographic areas that warrant further, detailed, exploration. These coarse-resolution products are generally used for regional and national assessments. Very-high-resolution data (e.g., Quickbird) are extremely effective for local-scale assessments as was evident in attempts to monitor the impacts of Hurricane Katrina in the USA in 2005 and the tsunami that struck parts of Asia in late 2004. However, the spatial extent of one image scene ("image footprint") of ultrafine-resolution sensors is generally so small that the number of scenes necessary to cover large spatial areas is often prohibitive in terms of cost and processing time. As of April of 2008, the price for one unprocessed high-resolution IKONOS scene covering 121 km^2 of non-US land was about USD $3,500 (Space Imaging 2008).

Coarse-resolution sensors are better suited for assessing large areas because they generally have large image footprints; therefore, it takes fewer scenes to cover a

[7] An orthophoto is an aerial photo that has been tied to a specific geographic reference system and corrected for displacements due to elevation and topography.

Table 2 Summary of remote-sensing instruments for forest carbon estimation

Instrument	Advantages	Disadvantages	Suitability for land classification	Potential contribution to inputs of allometric models
Optical: aerial photography	Detailed images Flexibility in geographic targets	Small area Expensive Sensitive to daylight and cloud cover	Low	Canopy height Canopy cover Total area of stand
Optical: satellite (ultrahigh resolution: <5 m): (e.g., IKONOS, Quickbird)	High resolution able to detect very small patches of land cover and in some cases the canopy of individual trees	Sensitive to daylight and cloud cover Insensitive to differences in dense biomasses Small image footprint Low spectral resolution	Moderate	Canopy cover Leaf area index (up to level of 3 or 4) Total area of stand Leaf cluster index
Optical: satellite (fine resolution: 10–100 m) (e.g., Landsat TM, ETM+, MSS, SPOT, ASTER)	High resolution able to detect small patches of land cover, forest fragmentation Detect small (15 m^2) changes in land use and deforestation with ETM+ panchromatic Frequent global coverage (weekly to semimonthly) Long historical record of global images (e.g., MSS from 1972) Multiangle sampling can characterize forest structure	SLC issues with current Landsat 7 sensor Small image footprint compared to MODIS/AVHRR	High	Canopy cover Leaf area index (up to level of 3 or 4) Total area of stand Leaf cluster index
Optical: satellite (medium resolution: 100–250 m) (e.g., MODIS)	Hyperspectral data Products developed specifically for monitoring applications (e.g., NPP)	Lower resolution, difficulty in classifying heterogeneous areas	High	

Table 2 (continued)

Instrument	Advantages	Disadvantages	Suitability for land classification	Potential contribution to inputs of allometric models
Optical: satellite (coarse resolution: >250 m) (e.g., AVHRR, MISR)	Detect trends at the continental and global scale Very frequent global coverage (daily to weekly) Long historical record of global images (early 1970s)	Sensitive to daylight and cloud cover Coarse resolution	Low	Total area of stand
Synthetic aperture radar (e.g., JERS-1 SAR and BioSAR)	Not dependent upon daylight or cloud cover Use of multiple polarization can increase measurable density to 400 t/ha	Saturation at relatively low levels of biomass density Only used on relatively flat topography Lacks spectral resolution of Landsat/MODIS products	Low	Canopy height Total area of stand Forest type Leaf area index Branch surface to volume ratios
Synthetic aperture radar (VHF) (e.g., CARABAS-II)	Not dependent upon daylight or cloud cover Measures biomass density up to 1,000 t/ha	Airplane deployment only Only used on relatively flat topography Lacks spectral resolution of Landsat/MODIS products	Low	Canopy height Total area of stand Forest type Leaf area index Branch surface to volume ratios
LIDAR	Characterizes 3-D structural characteristics of forests Useful in steeply sloped areas	Airplane deployment only Narrow coverage with each pass	Moderate	Leaf area index Canopy height Canopy cover Stems per unit area Bole height Crown width

particular land mass in comparison to higher-resolution products. Some of these such as the MODIS, may be downloaded from the internet free of charge (see http://modis.gsfc.nasa.gov). However, these sensors are subject to greater classification error because of the likelihood of multiple land-cover classes falling within a single pixel. Medium-resolution sensors are better for producing land-cover maps because they provide a balance between the benefits of a relatively fine resolution and large spatial coverage of a single image scene.

A key consideration for choosing an instrument to do land-cover classification is the spatial resolution of the remotely sensed data used to assess land-cover configuration and extent (Lambin 1999). Choosing an instrument for this exercise is a "Goldilocks" problem—resolutions must not be too fine or too coarse. Aerial photographs collected from airplanes, have long been used to estimate the extent of different types of land use over sizable regions. The difficulties with aerial photography are that the footprint of each image is relatively small and the sampling can be irregular and expensive. Similarly, high-resolution sensors with pixel sizes less than 5 m (e.g., IKONOS, Quickbird) are also largely impractical for monitoring large spatial areas because of the small footprint of individual scenes of data and the high cost of these products. In addition, there are unique classification challenges associated with high-resolution sensors, such as canopy shadowing, that are to a certain extent ameliorated by using medium-resolution data.

Coarse resolution data such as AVHRR and MODIS might be appealing because of the large image footprint and small data storage requirements relative to higher-resolution data (Achard et al. 2001). However, these data are subject to greater errors of omission and commission because coarse-resolution data consist of pixels that have relatively large spatial size. Despite the drawbacks associated with using coarse resolution sensors such as AVHRR and MODIS, the tradeoff between data management economies and classification errors is such that many researchers have chosen to use these to produce land-cover classification maps of large spatial extents for many areas of the world (Potter et al. 2003; Gamon et al. 2004; Gonzalez-Alonso et al. 2004; Potter et al. 2004; Veroustraete et al. 2004). MODIS has the added advantage of the availability of hyperspectral data, which provides more bands or layers of data—a total of 36 spectral bands (although only a subset of these is applicable to terrestrial systems). The MODIS product in particular has been explicitly designed to produce measures of gross primary productivity (GPP). Research continues to validate MODIS measures of GPP in different ecosystem types including boreal forests (Turner et al. 2003), temperate deciduous forests (Turner et al. 2003; Xiao et al. 2004), as well as to produce land-cover data for tropical forests (Huete et al. 2002).

Fine- and medium-resolution sensors have been used for regional- and national-scale monitoring but require many individual scenes of satellite data to be compiled to create a single seamless land-cover product. Measures of total land-cover change can be estimated for large geographic areas using a sampling of images, but a very high proportion of the total land area must be sampled to approach the actual measurement of land-cover change. For example, in an analysis of Bolivia, Columbia, and Peru Tucker and Townshend (2000) acquired imagery and found that more than 80% of scenes had to be processed to produce an estimate of actual total deforestation. A total of 147 scenes were needed to cover the land area of all three countries (Bolivia = 41 scenes, Columbia = 61 scenes, and Peru = 45 scenes).

Landsat Thematic Mapper (TM) and MultiSpectral Scanner (MSS) data have been extensively used to develop land-cover data for many types of biomes. These sensors present something of a middle ground given their moderate resolution (TM data are commonly resampled[8] to 30-m spatial resolution, while MSS data are usually resampled to 80 m). In contrast to high-resolution sensors (e.g., IKONOS) the footprint of a single Landsat scene is much larger, which facilitates the production of seamless datasets covering large spatial extents. Several projects have used Landsat data for regional- and national-scale monitoring of land cover. Examples include the North American Landscape Characterization project as well as research in the Brazilian Amazon (Skole and Tucker 1993).

A particular advantage of Landsat is the historical data available for the sensor. Landsat MSS data are available from 1972 and Landsat TM data from 1984. The long history of these sensors provides the opportunity to generate land-cover change products from the same sensor further back in time than more contemporary sensors. It might seem odd to policy makers that the availability of historic data would be an important consideration in choosing remote sensing data sets. After all, for policy purposes, particularly for policy implementation, we are primarily concerned with recent changes. An important use of historical data is to identify the land-cover change trajectory of areas in order to explore how previous land-cover change processes might lead to path-dependent outcomes in the future (Balmann 1999). As individual Landsat platforms have been phased out, newer platforms have been launched to provide continuity of Landsat-structured data. The latest product is the Landsat ETM+ series, but at this time this sensor is producing data with artifacts that have been limiting data quality (these may be resolved in the future, however). Landsat data have also been used as inputs into carbon and nutrient cycling research in various areas (Asner et al. 2004). Because Landsat has been heavily used by scientists over a long time period, there is a considerable understanding and familiarity with this sensor and issues of using Landsat data products in the context of classification error (Powell et al. 2004), cross-site analysis (Turner et al. 1999; Foody et al. 2003), and correlation with vegetative structure (Turner et al. 1999). It is expected that this same familiarity will emerge with more contemporary sensors, but Landsat remains one of the most used and most applied remote-sensing tools.

The conversion of remote sensing data to estimates of important forest characteristics is a geography- and biome-specific process. Thus, using remote sensing to develop land-cover categories for carbon stock estimation will require a substantial resource investment in regions for which less research has been done to match the remotely sensed data to the type of land cover. Because of the abundance of field data in developed countries, we can expect that the land-cover classifications for these areas will be more robust and reliable than classifications produced for areas where the vegetation is less well documented. Various synergistic projects such as the Long-Term Ecological Research program and the US-based Gap Analysis Program have resulted in the development and archiving of rich datasets that have facilitated the generation of land-cover classifications in some areas. Likewise, geographic areas

[8]Resampling is the process of converting a dataset from one spatial resolution to another spatial resolution. For example, a dataset with 30×30 m pixel size can be resampled to a resolution of 60×60 m. This resampling process results in a manipulation of the data and errors of omission and commission for land-cover classes.

where considerable land-use/land-cover change research has been conducted, such as the Brazilian Amazon, also have been relatively well documented by field data collection efforts. More remote and less developed areas are more problematic in terms of the availability of field data. In addition, some of the reasons inhibiting the collection of comprehensive field data (e.g., rough topography) also present methodological challenges in the processing of satellite imagery.

A major challenge of developing carbon estimates from remotely sensed products is establishing appropriate classification schemes suitable to the class distinction of different carbon stock categories (Achard et al. 2001). The process of classifying landscapes and the environmental gradients within those landscapes is complicated. How does one clearly define what a forest is? What individual tree density is required for a location to be considered closed forest vs. open forest? The use of different descriptors for land-cover classes complicates the comparison of land-cover classifications across locations. Some progress has been made by various organizations proposing universal classification systems that could be applied to the world's ecosystems (e.g., Di Gregorio and Jansen 2000), but to date these systems have not been universally adopted. This classification scheme issue is in part related to the scale of the sensor used. Coarse resolution sensors may require the incorporation of mixed category classes where the class definition explicitly incorporates multiple land-cover types within a single pixel, because the large pixel size increases the likelihood that an individual pixel is actually composed of multiple land-cover classes compared to higher-resolution sensors. Noordwijk et al. (2007) suggests that a classification that results in five to 10 land cover classes may lead to the lowest overall uncertainty.

Another challenge for developing national carbon inventories, particularly if remote-sensing approaches are an integral element in carbon inventory estimation, is to develop methods that can effectively account for forest degradation as well as detect forest clearing. Dramatic changes in land cover such as that associated with clear cutting or large-scale plantations are relatively easily detected using medium-resolution sensors (e.g., Landsat TM). However, the selective removal of certain tree species from mature forests can have a tangible affect on carbon storage in forests, and this is a process that is much more difficult to accurately detect using remote sensing. In addition, the removal of the species can in some cases have long-term impacts on the ecological trajectory of forests. This again suggests the importance of field sampling and ground-truthing. For high quality forest carbon inventory data, it is necessary to complement remote sensing data with direct measurements of woody vegetation on the ground.

3.2 Field measurements

To quantify the amount of carbon stored in trees, it may be necessary to harvest a sample of trees, let them dry and then weigh them. Westlake (1966) determined that dried biomass contains about 50% carbon in terms of its weight, and thanks to this discovery it is possible to convert the weighed biomass to carbon equivalents. This method, called destructive sampling, is known to produce accurate carbon stock estimates for individual trees but is not a practical approach for national forest carbon inventories as it is extremely costly in terms of time, effort, and natural resources (Brown 2002). Fortunately, there is a way of avoiding the need to harvest numerous trees whose carbon content are to be measured. The trees' rescue is found in the application of allometric equations—mathematical formulas that convert direct measurements of a tree's height and diameter at breast height (DBH) to estimated carbon content.

Allometric equations are developed by establishing statistical correlation coefficients between the measured forest attributes (typically DBH) and the measurements from the destructive sample of individual tree species, and sometimes for representative samples of trees found in certain forest types (see Keller et al. 2001; Gibbs et al. 2007). For highly diverse tropical forests, Brown (2002) shows that reliable carbon estimates may be derived by using only DBH measurements and allometric relationships for broad categories of forest types and ecological zones, because it turns out that DBH alone explains more than 95% of the variation in aboveground tropical forest carbon stocks, even in highly diverse regions (ibid).

In general, field sampling-based approaches require a substantial number of sample plots to account for the spatial variability of forest dynamics that affect carbon sequestration. For example, field inventories of wood volume and wood volume changes in the southeastern USA included approximately 4,000–7,300 sample plots and the measurement of over 100,000 individual trees in several states (Phillips et al. 2000). It is apparent that there is a considerable expense involved with these comprehensive field-sampling projects, and this is one reason why these samples are carried out rather infrequently even in developed countries. The interval between the inventory dates of the US Forest Inventory Assessment in the southeast USA is generally every 6–8 years (ibid), although the USDA recently decided to move toward an annual sampling process (USDA 2007). These field-based datasets provide the basis for carbon estimates as well as critical data needed to improve the accuracy of land-cover classifications from remotely sensed data.

Implementing an international carbon sequestration program will require improvements in the breadth, speed, and cost-effectiveness of inventories. Because field-based inventories are time-consuming and expensive, it is necessary to understand the role that remote sensing can play in a broad and sustained monitoring program that focuses on estimating carbon stock changes.

3.3 Monitoring changes in forest carbon

The measure of forest carbon sequestration is the change in forest carbon from one point in time to another. It may be more expedient to directly measure the change rather than the entire inventory each time.

When countries plan how to measure, estimate and report the GHG emissions and uptake from forestry for a given reporting period, it makes sense for them to consider the carbon-related forest data that existed before being asked to report GHG data to the UNFCCC. For example, Finland, built their national accounting system for GHG concerning land use, land cover, and forestry on existing data of their National Forest Inventories. Similarly, the USA rely principally on NFI field measurements to estimate changes in forest carbon stocks for a given time period. Australia, on the other hand, never established national coverage of field-based forest sample plots, and use much less field measurements for their estimation of changes in terrestrial carbon stocks and flows. Instead, they rely much more on remotely sensed images of land cover change for their estimates, than does either Finland or the USA.

The ultimate purpose of a national forest carbon inventory is to track the forest carbon stock over time. One option, then, is to repeat a complete inventory process for each country on a periodic basis. However, in the context of implementing an international program of incentives for avoided deforestation and the emission offset trading, the focus is on *changes* in the estimated stock rather than on the *absolute size* of the carbon stock itself. This suggests that it may be possible to economize on the carbon inventory monitoring efforts by concentrating resources for field measurements on the areas of forest where clear change patterns may be detected. With a well-established initial baseline for the national forest carbon inventory, remote-sensing techniques can be used to identify change in the spatial extent of forests and the degradation of existing forests relatively effectively.

There is a rich literature in the remote-sensing community specifically focused on what are called "change detection" techniques. Here the primary objective is to use various methods to identify *changes* in land cover, vegetation, or biomass. Thus, these approaches are well suited to the estimate of net change even if a precise inventory is not produced as part of the processing. Methods vary from those requiring substantial user interactions, such as artificial neural network or SMA approaches (Lu et al. 2004), to those that are more automated, including image differencing or statistical approaches (e.g., Foody et al. 2003). Change detection techniques have been specifically applied to measurement of net carbon change (Riley et al. 1997), and it should be noted that change detection has been employed using both fine-resolution sensors (e.g., Landsat TM) and coarser-resolution MODIS data (Zhan et al. 2002).

Australia's carbon accounting system makes innovative use of such techniques, as they have developed what is known as one of the world's largest satellite monitoring programs related to the estimation of GHG emissions and uptake related to land cover change (Lowell et al. 2003). They use principally aerial photography (and some Landsat imagery) to map forest extent at 25 m resolution for several time periods since 1972 (Government of Australia 2000; Jones et al. 2004). After processing the remotely-sensed imagery so that the images are geographically and spectrally calibrated to a standard base, the NCAS image analysts employ statistical techniques to compare and validate changes in individual pixels, and eliminate false change records due to climatic or other environmental effects. They use this data to produce maps of forest cover, clearing and re-growth for any given time period. These map classes are then attributed for a specific cause of change, as the greenhouse account excludes change that is not attributable to direct human actions (Government of Australia 2000). Aerial photographs and high resolution satellite imagery, and to a lesser extent field data, are then used for verifying the change analysis (Lowell et al. 2003).

Another significant way in which remote sensing can help reduce the costs of forest carbon inventories is to use these instruments to aid in the field measurements of tree and forest characteristics. Several new instruments, such as LIDAR, have been used to measure biomass, canopy morphology and other forest characteristics with varying levels of success. In a comparison of three different biomes, Lefsky et al. (2002) found that a single regression equation could be used to relate canopy structure detected using LIDAR to aboveground biomass.[9] Currently, LIDAR data are only available via airborne, as opposed to satellite-based, platforms and, thus, can be very expensive for measurements over large spatial extents.

Although field-based measurements provide the very basis for carbon estimates as well as critical data needed to improve the accuracy of land-cover classifications from remotely sensed data, remotely sensed imagery can also provide useful data for the field measurement component of the national inventory. There may be instances when field crews are not able to access some parts of the country's forest resources, either because of extremely rugged terrain or remoteness. In such instances, high-resolution instruments such as IKONOS, Quickbird, or aerial photographs may provide critical data for the land cover classification process, and as such this technology might represent a second-best alternative to field measurements.

In sum, the state of the art of forest carbon inventories has developed rapidly since the UNFCCC first started asking countries to report annual GHG data in 1994. Most inventory experts seem to agree that the existing methods and technologies are sophisticated enough to produce reliable and valid forest carbon inventories (e.g. Rokityanskiy et al. 2007; Gibbs and Herold 2007; Rogan and Chen 2004). Despite recent technical advances, and large international efforts to assist countries in the GHG inventory procedures, many signatory countries have not taken advantage of the available methods and technologies. As a consequence, self-reported data related to LULCF activities may be of questionable quality. Many countries do not even conduct the most rudimentary form of forest carbon inventories. The next section explores plausible reasons for the current mismatch between the theory and practice of forest carbon inventories, and analyzes the extent to which the inventory approaches actually applied satisfy the needs of the four policy functions of forest carbon inventories.

4 Do current inventory approaches respond to policy needs and challenges?

In this section we seek to address how well current national forest carbon estimation approaches serve the four policy functions identified at the outset: reporting, policy formation, policy evaluation, and policy implementation. Particularly with respect to the policy implementation function, the design of an inventory program will involve making explicit tradeoffs between costs and three particular factors—timeliness, accuracy, and transparency.

In the abstract, if we think of these three characteristics as being measured along three different dimensions, then it is possible to describe any national inventory program as falling somewhere in "inventory space" (this of course assumes we are holding constant other important factors, such as the number of participating actors in the program). This inventory space is illustrated by Fig. 1, which expresses the coordinates of this space as measures of timeliness, precision/accuracy and transparency. Moreover, each point in this "inventory space" will have a cost associated with it, which we might measure in dollars per year. Collecting all of the points in

[9]However, this research did not include data from tropical field sites, a primary focus of the carbon sequestration issue, and thus the authors suggested additional research was needed before the approach could be considered applicable to a broad range of biome types.

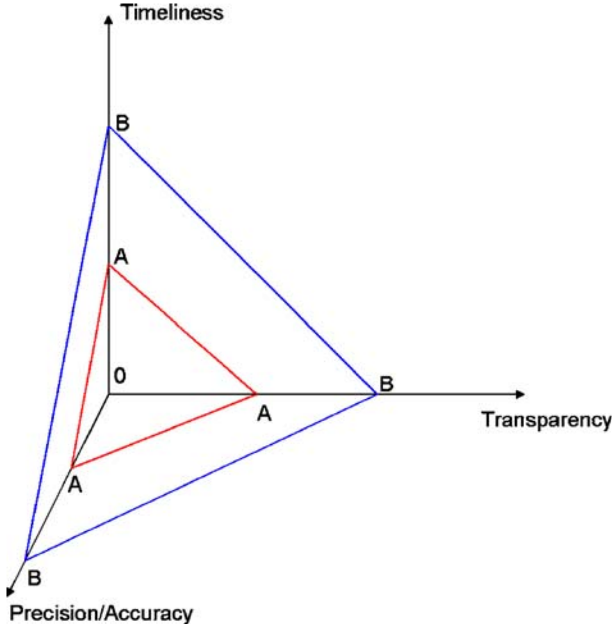

Fig. 1 Balancing three factors in development of national forest carbon inventories

the space that have a given cost, say A dollars per year, will provide a hyperplane that economists call an "isocost" curve. In Fig. 1, the isocost hyperplane A is a collection of all combinations of programs (each described in terms of timeliness, precision/accuracy, and transparency) that have a cost of A dollars per year. The hyperplane is depicted as flat, though the result could easily be a paraboloid.

This means that for any given cost, there are a host of inventory designs, each with a different level of timeliness, precision/accuracy, and transparency. Designing a program for a given cost will involve making tradeoffs among the three characteristics. For example, achieving increased precision and accuracy of inventory estimates might require managers to assign more resources to increase the sample size of field plots. Ensuring more transparency in the preparation and reporting of results also carries costs—more public scrutiny will require modifying working routines for data collection, analysis, processing, and communication of data, methods, and results (i.e. web-based database and library) as well as broader participation of non-governmental actors in all stages of the inventory. Finally, improving the timeliness of the reported results of the inventory will also require more resources to speed up the work during the data collection and processing stages.

Given these trade-offs, managers need to consider carefully which mix of these inventory attributes are the most important for achieving principal goals and will need to prioritize their resource allocation accordingly. If a fixed amount of resources is available for the inventories, the benefits associated with an investment to improve the accuracy and precision of estimates will come at the expense of transparency or timeliness of estimates, or both. It also means that to achieve simultaneous improvements on all three dimensions will require moving to a new, higher isocost curve, depicted in Fig. 1 as isocost plane B.

4.1 Uncertainty, precision, and accuracy in carbon assessments

Uncertainty associated with both measurement and sampling errors is a key issue to address in the development of national carbon inventories. IPCC's Guidelines for GHG inventories indicate that there could be 60% uncertainty on change estimates for some national carbon stocks—which is the component of the inventory with the largest uncertainty of all—and the ways in which forest-related emissions and uptake are accounted for represent a major source of this uncertainty (Noordwijk et al. 2007).

There are many points in the development of the forest carbon inventories where error is introduced. These errors can potentially propagate to larger errors in final products. In the case where remotely sensed data are used to produce land-cover classifications, which in turn are used to produce carbon estimates via allometric equations, there are a number of key junctures where error assessments can be used to identify the accuracy of carbon estimates. The land-cover classifications themselves may have errors. For example, classifications in the Brazilian Amazon have been documented with an overall accuracy of ~80–90% (Powell et al. 2004). However, particular classes such as secondary succession pose unique classification challenges because of the spectral similarity to other classes such as pasture or mature forest (Vieira et al. 2003), and for these land-cover types, classification accuracy may be as low as 60%. Remote sensing-derived land-cover classifications in other biomes have demonstrated similar levels of accuracy. For example, in a project studying the boreal region of northern Canada, accuracies of ~60–90% have been reached using a variety of sensors (Gamon et al. 2004). Classifications from coarse resolution sensors such as AVHRR pose particular challenges such as the potential to misclassify areas where forest cover is highly fragmented (Achard et al. 2001). But even a land-cover classification with 80 or 90% accuracy may not necessarily be effective as a short-term monitoring tool. This is particularly true in highly dynamic landscapes where it is less reasonable to make specific assumptions about the rate of land-cover change and the observed land-cover change trajectories in the context of the magnitude of classification errors. Because of the inherent error in land-cover classification maps derived from satellite imagery, special attention is needed in the development of products that are measurements of land-cover change (Shi and Ehlers 1996; Carmel et al. 2001). A classification for a single time point includes some pixels that are correctly classified and some pixels that are incorrectly classified. A land-cover change dataset produced by comparing which cells have changed over time then exhibits errors introduced from each time point used to produce the change dataset. Various methods exist for assessing the error in land-cover classifications and attempting to minimize those errors. Nevertheless, it is important whether a carbon budget is being produced at individual time points to produce a difference measurement or whether a carbon budget is being produced directly from a map of land-cover change. And while it may be possible to produce land-cover maps of high accuracy for some areas, research in locations such as the tropics has had less success in producing direct forest structure measures from remotely sensed data (Foody 2003).

The lack of reliable field data has been identified as a major obstacle to the monitoring of carbon budgets (Brown and Gaston 1995; Foody 2003). And as alluded to previously, the availability of comprehensive field forest biomass data is a critical component to the development of accurate land-cover maps as well as a satisfactory level of precision of carbon estimates from field data. Hence, the investments in increasing the availability of robust field measurements of forest data will go a long way to reduce the current levels of uncertainty in carbon inventories (Lunetta et al. 1998; Houghton and Hackler 1999). A case in point is the National Biomass Study (NBS) of Uganda, which uses a combination of SPOT satellite imagery and 6,000 permanent field measurement sites. The NBS has gathered these data since 1995. Based on the time-series data, the NBS estimated the changes in the aboveground, woody biomass between 1996 and 2001. According to the NBS, the resulting estimate of mean change in biomass had a reported sampling error of less than 15% for the 90% confidence interval (personal communication with NBS director Paul Drichi, September 4, 2002).

Since about 20% of the world's forests grow in Russia, several major studies have also been carried out to estimate that country's total forest carbon stock and how it is changing overtime (Sohngen et al. 2003; Nilsson et al. 2000; Heath and Smith 2000; Phillips et al. 2000; Smith and Heath 2001). The study by Sohngen et al. (2003) combined extensive ground measurements with remotely sensed products to construct biomass models that calculated the total terrestrial carbon sink. They estimated the size of Russia's forest carbon stock to 289.4 (±71.8) billion tons carbon equivalent. For the 90% confidence interval, the stock estimate translates into a sampling error of just under 25%, but the precision is reportedly higher when considering the estimated annual change in the stock (Sohngen et al. 2003).

Finland has probably achieved the highest precision in a national inventory of aboveground, woody biomass. In the 1994 national inventory, a multisource method was introduced by which satellite imagery and aerial photographs were employed to complement the extensive field measurements.[10] This approach reportedly reduced the error margins from previous Finish inventories by over 50% (Tomppo 2000). According to the inventory report, the relative standard error for the estimate of volume increment was below 1% (Tomppo and Henttonen 1996).

In an effort to support developing countries to generate national forest inventory data that can be used for reporting to the UNFCCC, the Biodiversity Convention, and the Global Forest Resource Assessment Programme, the FAO has developed a low-cost alternative to the traditional and expensive high-intensity sampling designs that most industrialized countries use (FAO 2005). About a dozen countries, including Cameroon, Guatemala, Lebanon, and The Philippines, have completed their National Forest Assessments (NFAs) according to this approach. The reported precision in terms of the sampling error ranges from 4% to 9% for forest area estimates and from 9% to 17% for wood volume (Government of Cameroon 2005; Government of Guatemala 2004; Government of Lebanon 2005; Government of the Philippines 2005). This moderate level of precision needs to be put into perspective of total costs: The costs for carrying out the NFA ranged from US$400,000 (Guatemala) to US$1,200,000 (The Philippines) (Personal communication with FAO NFA program officer Mohamed Saket, March 6, 2005). Although carbon stock estimates have

[10]In the eighth National Forest Inventory of Finland, field measurements consisted of measuring over 150 characteristics of woody vegetation in over 70,000 forest plots; of a half million tallied trees, every seventh tree was measured in great detail (Tomppo 2000).

not yet been calculated for the forests in these pilot NFAs—reportedly for the lack of biomass-carbon conversion equations—the results are indicative of the investments necessary to get a reasonable level of precision and accuracy for national inventories in countries that do not have nationwide field-based data on forest carbon stocks.

4.2 Timing

The two important, interrelated dimensions with respect to the timing of inventories are frequency and lag time. Frequency is the interval between the dates for which inventories are estimated. Lag time is the time between the date for which the inventory is estimated and when the inventory data are available. For example, suppose a country had estimated its inventory for the years 1990, 1995, and 2000 and made those estimates available in 1993, 1998, and 2003. This pattern would be described as a frequency of 5 years with a lag time of 3 years.

In general, for purposes of implementing an international trading program, it is preferable to have more frequent inventories with shorter lag times. Shorter lag times allow quicker responses by domestic and international policy makers to changes in trends that are detected. If, for example, there is a lag time of 7 years, significant changes may occur in the interim. It is better to have the information within 3 years, if possible.

More frequent inventories prevent the buildup of inertia before policy responses can be developed. If there is a span of 10 years between inventories, even if the estimations are available 1 year after the data are collected, the amount of change could be much larger than in the case of a more frequent inventory of, say, 5 years. The amount of change to which policy must respond is smaller in the latter case. Infrequent inventories may also mask more subtle changes. For example, if an inventory were conducted every 10 years, a change that involved a decline in inventories during the first 5 years followed by an equal increase during the second 5 years would appear as no change. If, however, an international program involved discounted borrowing and banking of offset credits, this change would amount to an undetected borrowing of credits in the first 5 years followed by interest-free repayment in the second.

The issue of timing of inventories also relates to precision and accuracy. Every inventory, taken in isolation, has an uncertainty band associated with the estimation. Because levels of carbon in terrestrial ecosystems tend to be stable over time, subject to perturbation by human or natural effects, each time we conduct an inventory we gather information not only about the carbon levels at that point in time but about likely levels in the recent past and near future. This is similar to the rolling 3-day window used in political polling or the adjusted employment figures that are used to update US Department of Labor estimates. The very nature of time-series analysis is that the more frequent the estimates and the more data available on either side of a particular estimate, the smaller is the uncertainty associated with the estimate for any particular point in time.

The diagram in Fig. 2 illustrates this point. At time T_0 a carbon inventory is conducted. The uncertainty associated with that inventory is illustrated by the bands on either side of the point estimate. At time T_1 another inventory, which we assume is independent of the first one, is conducted. The result of the second inventory suggests that the level of carbon has risen slightly from the baseline level at time T_0. However,

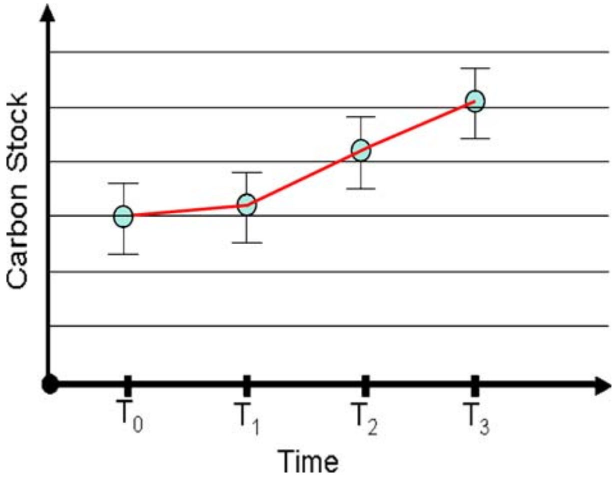

Fig. 2 Frequency and precision in a time series estimate

there is substantial overlap of the uncertainty bands at the two points in time. Given the range of these uncertainty bands, it is entirely possible that there has been no actual change in the carbon level, or it is even possible that the carbon level has declined. The estimates conducted at times T_2 and T_3 increase the likelihood that the actual level of carbon increased from time T_0 to time T_1. The later estimates have, in effect, decreased the error bars around the T_1 time estimate.

It should be noted, however, that Fig. 2 assumes independently sampled inventories, which is rarely the case in the real world. Most modern inventories use permanent sample plots because this can increase the cost-effectiveness of the inventory, by achieving higher precision of change estimates than inventories with the same sample size but with independent samples of temporary sample plots. This is so because the covariance of the sample points is subtracted when calculating the sampling error for the change estimate, rendering a lower error than would have been the case with independent sample points.

As international policy develops with regards to REDD and the possibility that national forest carbon inventories may in the near future be used to determine participating nations' eligibility to receive substantial financial rewards, it will be important for the policy community at both the international and national levels to consider how frequently national carbon inventories will be needed and how soon the inventory results must be reported. Since REDD particularly targets countries with tropical forests, which happen to be the countries with the most limited existing field-based data on forest carbon, it would be important to set frequency and lag standards that consider countries' inventory capacity in terms of their organizational structure, as well their available financial and human resources.

Even if most Annex 1 countries now conduct national forest carbon inventories every 5 years, this may not represent a realistic goal for countries that have never conducted regular national inventories in the past. A productive way of dealing with the diversity of conditions in participation developing countries may be to negotiate the frequency intervals and lag-times individually for each country as this would allow for adjusting these parameters progressively as the country builds its inventory capacity. Another advantage of this approach would be the possibility to adjust the frequency to optimize the precision and accuracy of the change estimates. A blanket-rule of one national inventory every 5 years for all countries does not make sense because the desirability of a certain frequency would depend on the country-specific biophysical context, observable land cover change patterns, available set of measurement technologies, as well as existing data organization and collection routines. It is conceivable that these contextual factors are such that a more frequent inventory will not render benefits with regards to improved accuracy and precision that warrant the increased costs. The pay-offs for implementing particular inventory standards seem highly context-dependent.

4.3 Transparency

A fundamental provision of good governance and public accountability is transparency (Esty and Ivanova 2004). Simply stated, this means that the mechanisms used to implement the policy must be understandable to the general public. All other factors being equal, the better the public understanding of how a program works the greater the possibility public officials will be held accountable. Two factors could increase public understanding and confidence in an international program on avoided deforestation and carbon sequestration. First, the program should be conceptually simple. The program should have clear baselines from which national gains or losses are measured, and the gains and losses that are counted should be clearly defined (Andersson and Richards 2001).

Second, the means by which the measurements of national inventories are made must be as open to public scrutiny as possible. This is going to be a challenge in a field that is as data intense and permeated with statistical analysis and professional judgment as carbon inventory development. There are many strategies to promote transparency, none of which is perfect. Most important, the data and methods employed to develop national inventories should be made freely available to the public in general and the scientific community in particular. The international community, acting through the Technical Support Unit of the IPCC's National Greenhouse Gas Inventories Programme, is already providing valuable assistance to countries in developing their national inventories. In the future this program might consider helping countries with the documentation of their results, translation of their results into lay terms, and extending funding for the engagement of non-government organizations and international experts to act as disinterested peer-reviewers and auditors of the results.

Finally, the best approach for any of the policy functions is likely to fall in the interior of the transparency-frequency-accuracy/precision continuum in Fig. 1. Thus, a major aspect that must be addressed by the policy community is the level of precision and accuracy needed in carbon inventories, how frequently these inventories are needed, and how much transparency should be demanded. This means that it is critical for the policy community to identify: (1) The level of accuracy and precision needed for national inventory carbon estimates; (2) The frequency of national inventory data needed; (3) The range of time-lags that are acceptable for published results, and (4) The degree of public scrutiny and peer-review inventory data should be subject to. As policy analysts and practitioners work to design national forest-carbon inventory programs that seek to address these issues, one of the most important conditioning factors is the history of national forest inventories for particular country contexts. Creative use of existing data may be the most influential determinant on the cost-effectiveness of inventory estimates in terms their accuracy and precision.

5 Discussion and conclusion

This article is intended to build a bridge between the policy and the scientific communities concerned with forest carbon inventories, two groups whose work on terrestrial carbon sequestration are critically related. By providing a review of the needs of policy makers, with special attention to implementation of an international sequestration program, and the methods, instruments, and capabilities of the carbon inventory community, we hope to facilitate greater understanding of needs, capacities, and limitations of each. The article develops several themes, or lessons, some of which are appropriate for one of the two audiences and some of which need to be heard by both.

For the policy community we have emphasized the basics of terrestrial carbon inventories and remote sensing. Several points bear emphasis. First, biomass and carbon estimates are based on allometric models that correlate key biophysical characteristics to estimated amounts of biomass and carbon in woody vegetation. Remote sensing provides input data for several key independent variables for estimating carbon stocks, but the utility of remote-sensing technology in forest carbon inventories is contingent upon its combination with direct measurements of vegetation on the ground. For purposes of implementing a global carbon sequestration program, the contribution of remote sensing in developing national inventories is currently limited by a lack of systematic ground measurements of forest and tree characteristics in many countries—ironically this dearth of data is particularly noticeable in the countries that have the highest rate of tropical deforestation, and are therefore targeted for participation in UNFCCC's REDD initiative. Other oft-cited constraints for the development of forest carbon inventories, such as limited in-country capacities to utilize remote sensing technology and field-based forest mensuration, are receiving increasing attention from the international community. Both the IPCC and the FAO are actively promoting national capacity building programs for forest carbon inventories, and as reported in this paper, have made considerable progress in the short time that these programs have been in place. The most significant challenge that both the policy and scientific communities need to answer before REDD can become operative seems to be an agreement on what specific set of tools, methods and approaches each participating country need to employ to provide sufficient precision and accuracy of carbon stock estimates to support an international trading/incentive program, such as REDD.

Second, no individual remote-sensing instrument will always provide all of the monitoring information that is needed for an accurate classification of carbon-relevant land cover classes on all landscapes. It is likely that some combination of instruments including optical, radar, and laser instruments will be required. Nations will need to plan ahead to ensure that the instruments are deployed and available to provide the temporal and geographic scope of coverage required.

Third, given the tremendous variety of geographic, topographic, and ecological conditions among nations, international trading/incentive programs that incorporate national-level terrestrial carbon sinks—such as the proposed REDD program—would be wise to prescribe a diversity of recommended methods and approaches for developing inventories. In addition, when considering the extreme variation of biophysical contexts in combination with differences in the types and quality of *existing* inventory-relevant data from one country to the next, it seems reasonable to assume that the uncertainty levels among nations' estimates of carbon stocks will also vary a great deal. The design of international programs that seek to induce the avoidance of deforestation will need to accommodate that reality.

Fourth, despite the rapid evolution of remote sensing technologies that may assist forest carbon accounting, these technologies have not replaced the need for various degrees of direct measurements of tree and forest characteristics on the ground: Accurate land cover classification and precise carbon stock estimates both rely on these field measurements.

The article raises several points that should be of interest to researchers and practitioners involved in the development of forest carbon inventories. Perhaps most important, there are several applications for which the terrestrial carbon inventories will be useful, including national reporting to international bodies, formation and ex ante evaluation of policy proposals, ex post evaluation of policy effects, and monitoring of policy implementation. Of these, policy implementation is likely to put the greatest demand on the inventory capabilities. For each of these applications, the technical community should be asking what level of accuracy and precision is required, how frequently will the estimates be required, what lag time is acceptable and how transparent the process must be to the public. Effective policy responses to these issues require more than technical knowledge and financial resources. Our analysis suggests that the ways in which these issues are ultimately addressed (or ignored) depend on political processes at both the national and international levels. One of the practical implications of this insight is that viable solutions will not emerge from scientific groups alone, no matter how advanced and clever they are. Rather, progress in this area will depend on the ability of policy actors and scientists to co-produce solutions that are not only scientifically sound but also financially realistic and politically legitimate. The co-production of policy-savvy responses needs to be grounded in national and local processes of knowledge integration, but with inputs and support from the international policy actors.

For both the policy and scientific audiences, the article provides additional lessons for cooperation. Foremost, the optimal combination of tools and methods for the national inventories of forest carbon is the result of a series of tradeoffs between costs, precision, accuracy, timeliness, and transparency of data. Underlying such tradeoff decisions is an economic balancing of costs vs. benefits in achieving additional precision and accuracy, transparency as well as timeliness of inventory data. The information needed to make reasonable tradeoff decisions comes partly from the scientific research community but also from the policy domain itself. Optimal tradeoffs are therefore not possible without good communication between policy makers and scientists. Again, discussions between the policy and technical parties should clearly recognize and explicitly incorporate that tradeoff. As they design monitoring programs together, these two groups will also need to incorporate flexibility into their plans. As technology and fieldwork develop, it will be important for any program to allow incorporation of new methods. Finally, the fact that each country not only faces distinctive biophysical conditions but its existing resources and capabilities are also unique means that the “best practice” methods and approaches to forest carbon accounting need to be individually determined.

The international community’s toughest challenge when it comes to promoting national forest carbon inventories, however, is likely to be political rather than technical. According to the UNFCCC secretariat, so far only a fraction of signatory countries, let alone less-developed countries, actually carry out national forest carbon inventories according to the specified IPCC guidelines (UNFCCC 2004). The lack of political will to invest in more accurate and precise GHG accounting methods, such as forest carbon inventories, may be the biggest hurdle for future climate mitigation efforts.

Acknowledgements We benefited from constructive critiques from Glen Green and three anonymous reviewers. This research was supported by grants from the US National Science Foundation (SES008351 and SES0648447) as well as by center funding provided by the National Science Foundation to the Center for the Study of Institutions, Population and Environmental Change (SBR9521918). NOTES

References

Achard F, Eva H, Mayaux P (2001) Tropical forest mapping from coarse spatial resolution satellite data: production and accuracy assessment issues. Int J Remote Sens 22:2741–2762

Andersson K, Richards K (2001) Implementing an international carbon sequestration program: can the leaky sink be fixed? Clim Policy 1(2):173–188

Asner GP, Townsend AR, Bustamante MMC, Nardoto GB, Olander LP (2004) Pasture degradation in the central Amazon: linking changes in carbon and nutrient cycling with remote sensing. Glob Chang Biol 10:844–862

Austin JM, Mackey BG, Van Niel KP (2003) Estimating forest biomass using satellite radar: an exploratory study in temperate Australian eucalyptus forest. For Ecol Manag 176(2003):575–583

Balmann A (1999) Path dependence and the structural development of family farm dominated regions. In: IX European congress of agricultural economists, organized session papers, Warsaw (Poland), 24–28 August 1999, pp 263–284

Balzter H, Shvidenko A (2000) Map accuracy report—SIBERIA forest cover map, SIBERIA Working note 58. IIASA, Laxenburg, Austria

Braatz S (2002) National reporting to forest-related international instruments: mandates, mechanisms, overlaps and potential synergies. Unasylva 53(3):65–67

Braatz BV, Doorn M (Eds) (2005) Managing the national greenhouse gas inventory process. New York, NY: United Nations Development Programme and the Global Environmental Facility

Brown S (1999) Opportunities for mitigating carbon emissions through forestry activities: Paper prepared for the World Bank. Winrock International Institute for Agricultural Development, Arlington, Virgina

Brown S (2002) Measuring carbon in forests: current status and future challenges. Environ Pollut 116(3):363–372

Brown S, Gaston G (1995) Use of forest inventories and geographic information systems to estimate biomass density of tropical forests: application to tropical Africa. Environ Monit Assess 38: 157–168

Carmel Y, Dean DJ, Flather CH (2001) Combining location and classification error sources for estimating multi-temporal database accuracy. Photogramm Eng Remote Sensing 67(7):865–872

CIESIN (Center for International Earth Science Information Network) (n.d.) The Montreal Protocol on Substances That Deplete the Ozone Layer, CIESIN Thematic Guides, http://www.ciesin.org/TG/PI/POLICY/montpro.html

Cohen WB, Justice CO (1999) Validating MODIS terrestrial ecology products: linking in situ and satellite measurements. Remote Sens Environ 70(1):1–3

Di Gregorio A, Jansen LJM (2000) Land Cover Classification System (LCCS): classification, concepts and user manual. Food and Agriculture Organization of the United Nations, Rome

Dilling L (2007) Towards science in support of decision making: characterizing the supply of carbon cycle science. Environ Sci Policy 10:48–61
Dyson FJ (1977) Can we control carbon dioxide in the atmosphere? Energy 2:287–291
Esty D, Ivanova M (2004) Globalization and environmental protection: a global governance perspective. Yale Center for Environmental Law & Policy Working Paper No. 0402, Yale University, New Haven, CT
FAO (Food and Agriculture Organization) (2005) The state of the world's forests. FAO, Rome
Foody GM (2003) Remote sensing of tropical forest environments: towards the monitoring of environmental resources for sustainable development. Int J Remote Sens 24(20):4035–4046
Foody GM, Boyd DS, Cutler MEJ (2003) Predictive relations of tropical forest biomass from Landsat TM data and their transferability between regions. Remote Sens Environ 85(4):463–474
Forner C (2002) Forest-related reporting in the context of the United Nations Framework Convention on Climate Change. Unasylva 53(3):75
Gamon JA, Huemmrich KF, Peddle DR, Chen J, Fuentes D, Hall FG, Kimball JS, Goetz S, Gu J, McDonald KC, Miller JR, Moghaddam M, Rahman AF, Roujean J-L, Smith EA, Walthall CL, Zarco-Tejada P, Hu B, Fernandes R, Cihlar J (2004) Remote sensing in BOREAS: lessons learned. Remote Sens Environ 89(2):139–162
Gibbs HK, Herold M (2007) Tropical deforestation and greenhouse gas emissions. Environ Res Lett 2(045021):1–2
Gibbs HK, Brown S, Niles JO, Foley JA (2007) Monitoring and estimating tropical forest carbon stocks: making REDD a reality. Environ Res Lett 2:045023 (October–December)
Gonzalez-Alonso F, Cuevas JM, Calle A, Casanova JL, Romo A (2004) Spanish vegetation monitoring during the period 1987–2001 using NOAA-AVHRR images. Int J Remote Sens 25(1):3–6
Government of Australia (2000) Land clearing: a social history. National Carbon Accounting System Technical Report No. 4. Greenhouse Office, Canberra, Australia
Government of Cameroon (2005) Results of data analysis for the National Forest Assessment in Cameroon: final analysis. Unpublished Draft Document, Ministry of Agriculture, Yaounde
Government of Canada (1995) Canada's national report on climate change. Actions to meet commitments under the UNFCCC. Environment Canada, Ottawa
Government of Guatemala (2004) Evaluación de Los Recursos Forestales. Inventario Forestal Nacional 2002–03. Instituto Nacional de Bosques (INAB), Guatemala City
Government of Lebanon (2005) National forest assessment program: Lebanon data analysis report. Ministry of Agriculture, Beirut
Government of the Philippines (2005) National forest and tree resources assessment 2003–2005. Forest Management Bureau of the Department of Environment and Natural Resources, Quezon City, Philippines
Gullison RE, Frumhoff PC, Canadell JG, Field CB, Nepstad DC, Hayhoe K, Avissar R, Curran LM, Friedlingstein P, Jones CD, Nobre C (2007) Tropical forests and climate policy. Science 316:985–986
Heath LS, Smith JE (2000) An assessment of uncertainty in forest carbon budget projections. Environ Sci Policy 3(2–3):73–82
Houghton RA, Hackler JL (1999) Emissions of carbon from forestry and land-use change in tropical Asia. Glob Chang Biol 5(4):481–492
Huete A, Didan K, Miura T, Rodriguez EP, Gao X, Ferreira LG (2002) Overview of the radiometric and biophysical performance of the MODIS vegetation indices. Remote Sens Environ 83(1–2): 195–213
IPCC (International Panel on Climate Change) (2002) Climate change 2001: third assessment report of the intergovernmental panel on climate change. Cambridge University Press, Cambridge
IPCC (International Panel on Climate Change) (2004) Good practice guidance for land use, land-use change, and forestry, IPCC. Geneva, Switzerland
Jonas M, Nilsson S, Shvidenko A, Stolbovoi V, Gluck M, Obersteiner M, Oskog A (1999) Full carbon accounting and the Kyoto protocol: a systems-analytical view. Interim Report IR-99-025. International Institute for Applied Sciences (IASA), Laxenburg, Austria
Jones S, Lowell K, Woodgate P, Buxton L, Mager A, Liebchen S (2004) Update on the National Carbon Accounting System Continuous Improvement and Verification Methodology. National Carbon Accounting System Technical Report no. 46. Greenhouse Office, Canberra, Australia
Kauppi P, Sedjo R (2001) Technological and economic potential of options to enhance, maintain, and manage biological carbon reservoirs and geo-engineering. In: Metz B, Davidson O, Swart R, Pan J (eds) Climate change 2001: mitigation. Contribution of working group III to the third

assessment report of the Intergovernmental Panel on Climate Change (IPCC). Cambridge University Press, Cambridge, UK

Keller M, Palace M, Hurtt G (2001) Biomass estimation in the Tapajos National Forest, Brazil: examination of sampling and allometric uncertainties. Forest Ecol Manag 154:371–82

Kleinn C (2002) New technologies and methodologies for national forest inventories. Unasylva 53(3):10–15

KP-UNFCCC (Kyoto Protocol to the United Nations Framework Convention for Climate Change) (1997) Conference of the Parties-3, Kyoto, Japan

Lambin EF (1999) Monitoring forest degradation in tropical regions by remote sensing: some methodological issues. Glob Ecol Biogeogr 8(3/4):191–198

Lefsky MA, Cohen WB, Harding DJ, Parker GG, Acker SA, Gower ST (2002) Lidar remote sensing of above-ground biomass in three biomes. Glob Ecol Biogeogr 11(5):393–399

Lowell K, Woodgate P, Jones S, Richards G (2003) Continuous improvement of the National Carbon Accounting System Land Cover Change Mapping. National Carbon Accounting System Technical report no. 39. Canberra, Australia: Greenhouse Office

Lu D, Mausel P, Brondízio E, Moran E (2004) Change detection techniques. Int J Remote Sens 25(12):2365–2401

Lunetta RS, Lyon JG, Guindon B, Elvidge CD (1998) North American landscape characterization dataset development and data fusion issues. Photogramm Eng Remote Sensing 64(8):821–829

McMichael AJ (1993) Planetary overload. Cambridge University Press, Cambridge

McNie EC (2006) Reconciling the supply of scientific information with user demands: an analysis of the problem and review of the literature. Environmental Science and Policy 10:17–38

Mollicone D, Freibauer A, Schulze ED, Braatz S, Grassi Z, Federici S (2007) Elements for the expected mechanisms on 'reduced emissions from deforestation and degradation, REDD' under UNFCCC. Environ Res Lett 2:045024 (7pp)

Moser SC, Dilling L (eds) (2007) Creating a climate for change: communicating climate change and facilitating social change. Cambridge University Press, New York, NY

Myneni RB, Dong J, Tucker CJ, Kaufmann RK, Kauppi PE, Liski J, Zhou L, Alexeyev V, Hughes MK (2001) A large carbon sink in the woody Biomass of Northern forests. PNAS 98(26):14784–14789

Nabuurs GJ, Masera O, Andrasko K, Benitez-Ponce P, Boer R, Dutschke M, Elsiddig E, Ford-Robertson J, Frumhoff P, Karjalainen T, Krankina O, Kurz WA, Matsumoto M, Oyhantcabal W, Ravindranath NH, Sanz Sanchez MJ, Zhang X (2007) Forestry. In: Metz B, Davidson OR, Bosch PR, Dave R, Meyer LA (eds) Climate change 2007: mitigation. Contribution of Working Group III to the fourth assessment report of the intergovernmental panel on climate change. Cambridge University Press, Cambridge, UK

Nilsson S, Shvidenko A, Stolbovoi V, Gluck M, Jonas M, Obersteiner M (2000) Full carbon account for Russia. Interim Report IR-00-021, International Institute for Applied Sciences (IASA), Laxenburg, Austria

Noordwijk Van M, Swallow B, Verchot L (2007) Avoided deforestation with sustainable benefits: a simple way to reduce carbon emissions from deforestation and degradation. Nairobi, Kenya: World Agroforestry Centre (ICRAF)

Pearson T, Walker S, Brown S (2005) Sourcebook for land use, land-use change and forestry projects. Winrock International and the BioCarbon Fund of the World Bank

Peskett L, Brown D, Luttrell C (2006) Can payments for avoided deforestation to tackle climate change also benefit the poor? Avoided deforestation could benefit the environment and forest dependent populations. Overseas Development Institute Forestry Briefing 12

Phillips DL, Brown SL, Schroeder PE, Birdsey RA (2000) Toward error analysis of large-scale forest carbon budgets. Glob Ecol Biogeogr 9(4):305–313

Potter C, Klooster S, Myneni R, Genovese V, Tan P-N, Kumar V (2003) Continental-scale comparisons of terrestrial carbon sinks estimated from satellite data and ecosystem modeling 1982–1998. Glob Planet Change 39(3–4):201–213

Potter C, Klooster S, Steinbach M, Tan P-N, Kumar V, Shekhar S, de Carvalho CR (2004) Understanding global teleconnections of climate to regional model estimates of Amazon ecosystem carbon fluxes. Glob Chang Biol 10(5):693–703

Powell RL, Matzke N, de Souza C Jr, Clark M, Numata I, Hess LL, Roberts DA (2004) Sources of error in accuracy assessment of thematic land-cover maps in the Brazilian Amazon. Remote Sens Environ 90(2):221–234

Richards KR, Andersson KP (2001) The leaky sink: persistent obstacles to a forest carbon sequestration program based on individual projects. Clim Policy 1:41–54
Riley R, Phillips H, Schuft M, Garcia M (1997) Resolution and error in measuring land-cover change: effects on estimating net carbon release from Mexican terrestrial ecosystems. Int J Remote Sens 18(1):121–137
Rogan J, Chen DM (2004) Remote sensing technology for mapping and monitoring land-cover and land-use change. Prog Plann 61:301–325
Rokityanskiy D, Benítez PC, Kraxner F, McCallum I, Obersteiner M, Rametsteiner E, Yamagata Y (2007) Geographically explicit global modeling of land-use change, carbon sequestration, and biomass supply. Technol Forecast Soc Change 74:1057–1082
Rosenqvist A, Milne A, Lucas R, Imhoff M, Dobson C (2003) A review of remote sensing technology in support of the Kyoto Protocol. Environ Sci Policy 6(5):441–455
Running SW, Baldocchi DD, Turner DP, Gower ST, Bakwin PS, Hibbard KA (1999) A global terrestrial monitoring network integrating tower fluxes, flask sampling, ecosystem modeling and EOS satellite data. Remote Sens Environ 70(1):108–127
Santilli M, Moutinho P, Schwartzman S, Nepstad D, Curran L, Nobre C (2005) Tropical deforestation and the Kyoto protocol. Clim Change 71(3):267–276
Schlamadinger B, Ciccarese L, Dutschke M, Fearnside PM, Brown S, Mudiyarso D (2005) Should we include avoidance of deforestation in the international response to climate change? In: Mudiyarso D, Herawati H (eds) Carbon forestry: who will benefit? Proceedings of Workshop on Carbon Sequestration and Sustainable Livelihoods, held in Bogor on 16–17 February 2005. Center for International Forestry Research (CIFOR), Bogor, Indonesia, pp 26–41
Shi WZ, Ehlers M (1996) Determining uncertainties and their propagation in dynamic change detection based on classified remotely-sensed images. Int J Remote Sens 17(14):2729–2741
Skole DL, Tucker C (1993) Tropical deforestation and habitat fragmentation in the Amazon: satellite data from 1978 to 1988. Science 260(5116):1905–1910
Smith JE, Heath LS (2001) Identifying influences on model uncertainty: an application using a forest carbon budget model. Environ Manag 27(2):253–267
Sohngen B, Andrasko K, Gytarsky M, Korovin G, Laestadius L, Murray B, Utkin A, Zamolodchikov D (2003) Stocks and flows: carbon inventory and mitigation potential of the Russian forest and land base. World Resources Institute, Washington, DC
Solomon S, Qin D, Manning M, Chen Z, Marquis M, Averyt KB, Tignor M, Miller HL (eds) (2007) Climate change 2007: The physical science basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK
Space Imaging (2008) Company web site: http://www.geoeye.com/
Specter C (1988) Managing remote sensing technology transfer to developing countries: a survey of experts in the field. Photogrammetria 43(1):25–36
Stavins R, Richards K (2005) The cost of U.S. forest-based carbon sequestration. Report for the Pew center on climate change, Arlington Virginia
Stein P (2001) Biomes of the future. The Rosen Publishing Group, New York
The Social Learning Group (2001) Learning to manage global environmental risks, vol 1 and 2. MIT Press, Cambridge, MA
Tomppo E (2000) National forest inventory of Finland and its role estimating the carbon balance of forests. Biotechnol Agron Soc Environ 4(4):281–284
Tomppo E, Czaplewski RL (2002) Potential for a remote-sensing-aided forest resource survey for the whole globe. Unasylva 53(3):16–18
Tomppo E, Henttonen H (1996) Suomen metsävarat 1989–1994 ja niiden muutokset vuodesta 1951 lähtien (Finnish forest resources and their changes since 1951) (in Finnish), Statistical Bulletin 354. Finnish Forest Research Institute, Helsinki
Tucker CJ, Townshend JRG (2000) Strategies for monitoring tropical deforestation using satellite data. Int J Remote Sens 21(6/7):1461–1471
Turner DP, Cohen WB, Kennedy RE, Fassnacht KS, Briggs JM (1999) Relationships between leaf area index and Landsat TM spectral vegetation indices across three temperate zone sites. Remote Sens Environ 70(1):52–68
Turner DP, Ritts WD, Cohen WB, Gower ST, Zhao M, Running SW, Wofsy SC, Urbanski S, Dunn A, Munger JW (2003) Scaling gross primary production (GPP) over boreal and deciduous forest landscapes in support of MODIS GPP product validation. Remote Sens Environ 88(3):256–270

UNFCCC (United Nations Framework Convention for Climate Change) (1992) United Nations, New York
UNFCCC (United Nations Framework Convention for Climate Change) (2004) Guidelines for the preparation of national communications, FCCC/SBSTA/2004/8
UNFCCC (United Nations Framework Convention for Climate Change) (2008) Report of the Conference of the Parties on its thirteenth session, held in Bali from 3 to 15 December 2007, Decision 2. FCCC/CP/2007/6/Add.1
United States Department of Agriculture (USDA) (2007) Forest inventory & analysis program history. FIA fact sheet series. USDA, Washington, DC
Veroustraete F, Sabbe H, Rasse DP, Bertels L (2004) Carbon mass fluxes of forests in Belgium determined with low resolution optical sensors. Int J Remote Sens 25(4):769–792
Vieira ICG, Almeida AS, de Davidson EA, Stone TA, de Carvalho CJR, Guerrero JB (2003) Classifying successional forests using Landsat spectral properties and ecological characteristics in eastern Amazônia. Remote Sens Environ 87(4):470–481
Watson RT, Zinyowera MC, Moss RH (eds) (1995) Impacts, adaptations and mitigation of climate change: scientific-technical analyses contribution of Working Group II to the second assessment of the intergovernmental panel on climate change. Cambridge University Press, Cambridge, UK
Watson RT, Noble IR, Bolin B, Ravindranath NH, Verardo DJ, Dokken DJ (eds) (2001) Land use, land-use change, and forestry: a special report of the intergovernmental panel on climate change. Cambridge University Press, Cambridge, NY
Westlake DF (1966) The biomass and productivity of glyceria maxima: I. Seasonal changes in biomass. J Ecol 54:745–53
Xiao X, Zhang Q, Braswell B, Urbanski S, Boles S, Wofsy S, Moore B III, Ojima D (2004) Modeling gross primary production of temperate deciduous broadleaf forest using satellite images and climate data. Remote Sens Environ 91(2):256–270
Zhan X, Sohlberg RA, Townshend JRG, DiMiceli C, Carroll ML, Eastman JC, Hansen MC, DeFries RS (2002) Detection of land cover changes using MODIS 250 m data. Remote Sens Environ 83(3):336–350