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Review

Achieving forest carbon information with higher certainty: A five-part plan

D. James Baker[a,*], Gary Richards[b], Alan Grainger[c], Patrick Gonzalez[d], Sandra Brown[e], Ruth DeFries[f], Alexander Held[g], Josef Kellndorfer[h], Peter Ndunda[i], Dennis Ojima[j], Per-Erik Skrovseth[k], Carlos Souza Jr.[l], Fred Stolle[m]

[a] The William J. Clinton Foundation, 8031 Seminole Avenue, Philadelphia, PA 19118, USA
[b] Land Management Branch, Department of Climate Change, Government of Australia, GPO Box 854, Canberra, ACT 2601, Australia
[c] School of Geography, University of Leeds, Leeds LS2 9JT, UK
[d] Center for Forestry, University of California, Berkeley, CA 94720-3114, USA
[e] Winrock International, 621 N Kent St., Suite 1200, Arlington, VA 22209, USA
[f] Department of Ecology, Evolution and Environmental Biology, Columbia University, New York, NY 10027, USA
[g] Environmental Earth Observation/CSIRO Division of Marine and Atmospheric Research & CSIRO-BoM Centre for Australian Weather and Climate Research, GPO Box 3023, Canberra, ACT 2601, Australia
[h] Woods Hole Research Center, 149 Woods Hole Road, Falmouth, MA 02540-1644, USA
[i] The Green Belt Movement, Hughes Building 1st floor, Muindi Mbingu Street, Kenyatta Avenue Wing, Nairobi, Kenya
[j] The H John Heinz III Center for Science, Economics, and the Environment, 900 17th Street NW, Suite 700, Washington, DC 20006, USA
[k] International Programmes, Earth Observation, Norwegian Space Centre, P.O. Box 113 Skoyen, N-0212 Oslo, Norway
[l] Instituto do Homem e Meio Ambiente da Amazônia (IMAZON), Rua Domingos Marreiros 2020, Fátima, Belém, Pará CEP 66060-160, Brazil
[m] World Resources Institute (WRI), 10 G St. NE, Suite 800, Washington, DC 20002, USA

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ABSTRACT

International negotiations on the inclusion of land use activities into an emissions reduction system for the UN Framework Convention on Climate Change (UNFCCC) have been partially hindered by the technical challenges of measuring, reporting, and verifying greenhouse gas (GHG) emissions and the policy issues of leakage, additionality, and permanence. This paper outlines a five-part plan for estimating forest carbon stocks and emissions with the accuracy and certainty needed to support a policy for Reducing Emissions from Deforestation and forest Degradation, forest conservation, sustainable management of forests, and enhancement of forest carbon stocks (the REDD-plus framework considered at the UNFCCC COP-15) in developing countries. The plan is aimed at UNFCCC non-Annex 1 developing countries, but the principles outlined are also applicable to developed (Annex 1) countries. The parts of the plan are: (1) Expand the number of national forest carbon Measuring, Reporting, and Verification (MRV) systems with a priority on tropical developing countries; (2) Implement continuous global forest carbon assessments through the network of national systems; (3) Achieve commitments from national space agencies for the necessary satellite data; (4) Establish agreed-on standards and independent verification processes to ensure robust reporting; and (5) Enhance coordination among international and multilateral organizations.

* *Corresponding author*. Tel.: +1 215 939 2021; fax: +1 215 247 8708.
E-mail addresses: djamesbaker@comcast.net, djames.baker@clintonfoundation.org (D.J. Baker).
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1. Introduction and background

1.1. Introduction

Enthusiasm for including a Reducing Emissions from Deforestation and Degradation (REDD) scheme in the post-Kyoto Protocol agreement of the UN Framework Convention on Climate Change (UNFCCC) has been increasing steadily in recent years, and it featured strongly in the Copenhagen Accord reached at the 15th Conference of the Parties (COP-15) (UNFCCC, 2009). However, diplomatic support has been balanced by critical scientific analysis of the difficulties of implementation, involving such issues as leakage, additionality, permanence and overall environmental impacts (Miles and Kapos, 2008). Crucial to overcoming these difficulties is the introduction of robust systems for Measuring, Reporting and Verification (MRV). These are needed to enable governments to plan their national REDD schemes in ways that contribute to their own sustainable development, and gain reliable information on progress so that this can be reported to the COP of the UNFCCC in a manner that will gain the confidence of international donors and markets and can be independently verified. However, this will require a quantum leap in the collection of global forest data by remote sensing and field surveys, and in the design of methods for processing these data into information at a frequency and scale not hitherto achieved. It will also require effective new systems for converting this information into a form which can be efficiently transmitted to governments and other stakeholders, and easily used by them as the basis for transparent decision and policy making.

This paper contributes to filling this gap by outlining a five-part plan for MRV systems that integrates national and global components in a coherent way. After this section, Section 2 outlines relevant scientific and methodological issues; Section 3 describes the plan in detail and Section 4 contains concluding remarks.

1.2. Background

The Intergovernmental Panel on Climate Change (IPCC) has documented that greenhouse gas emissions from human activities have caused the earth to warm and that higher temperatures are harming ecosystems and human well-being (IPCC, 2007a,b). An acceleration of the impacts of climate change makes the reduction of greenhouse gas emissions even more urgent. Tropical deforestation caused close to 20% of global anthropogenic CO_2 emissions in the 1990s (IPCC, 2007b) and 12% in 2008 (Le Quéré et al., 2009). Combined emissions from deforestation, forest degradation, and peatland fires caused about 15% (range 8–20%) of global anthropogenic CO_2 emissions from 1997 to 2006 (Van der Werf et al., 2009). Reducing deforestation, restoring degraded land, and improving agricultural practices could reduce atmospheric carbon dioxide concentration by 40–70 parts per million by 2100 (House et al., 2002). These significant impacts have been the basis for including forest-related climate actions in international agreements.

Forest-related climate actions are among the least expensive and most immediate way to reduce the rate of increase of carbon dioxide in the atmosphere, buying time for development and use of technologies for reducing emissions in other industrial sectors. An added benefit of including land use in future carbon-related financial arrangements (for example, as payment through fund or market mechanisms, direct payments for reduced tons of carbon emissions, or payments to adjust policies and practices) is the hope that new livelihoods can be created to reduce poverty in developing countries. Such actions also have co-benefits for environmental services such as biodiversity (Miles and Kapos, 2008; Shvidenko et al., 2005) and water resources.

In recent years, the United Nations Framework Convention on Climate Change (UNFCCC) has led discussions on ways developing countries could contribute to climate mitigation by Reducing Emissions from Deforestation and forest Degradation (REDD), forest conservation, sustainable management of forests, and enhancement of forest carbon stocks (REDD-plus). The 1997 Kyoto Protocol did not include forests for reasons discussed below, but the 2007 UNFCCC Conference of the Parties (COP-13) included REDD in the Bali Action Plan. In 2009, despite a failure to reach an emissions reduction agreement at COP-15, the UNFCCC Ad Hoc Working Group on Long Term Cooperative Action came close to an agreed text and will continue discussions on REDD-plus issues at COP-16 in 2010 (http://unfccc.int/resource/doc/2009/cop15/107.pdf). Moreover, the governments of Australia, France, Japan, Norway, the U.K., and the U.S. announced at COP-15 that they would provide US$3.5 billion for financing REDD-plus activities in developing countries (http://unredd.wordpress.com/2009/12/16/agreement-on-3-5-billion-initial-funding-for-redd/).

Although the details of a REDD-plus agreement are not yet formally agreed on, it is understood to be a process that implies the design of low-carbon development strategies and the adoption of a new land-use paradigm. As defined, REDD-plus represents a new opportunity for partnership between developing and developed countries—developing countries participate by undertaking REDD-plus actions, and developed countries help by sharing the costs of those actions. In particular, the process is likely to include a GHG-based instrument that rewards performance on the basis of quantified forest emissions and removals against agreed-on reference levels (Meridian Institute, 2009). The achievement of quantifying forest emissions in developing countries is the focus here, but the principles outlined are applicable to developed countries as well.

The IPCC has compiled the best available scientific methods into published guidelines (IPCC, 2006) for estimating forest emissions. These guidelines have defined tiers and approaches for national greenhouse gas inventories of different levels of scientific uncertainty. IPCC (2006) includes agriculture, forestry, and other land use (AFOLU), which are partially covered in developed country Kyoto Protocol targets, in recognition of the important role of forests in reducing greenhouse gas emissions. The national GHG inventories of the UNFCCC currently require deforestation and forest degradation emissions information at the national scale. The emerging financial arrangements based on forest carbon and various other national efforts to develop new climate change mitigation policies also require accurate and verifiable information to estimate and validate forest emission reductions. Despite these requirements and the continuing work on sub-national scale projects in developing countries, consistent and uniform broad-scale data on national and global forest carbon stocks, changes in stocks, greenhouse gas emissions, and trends in forest conditions are still needed in those countries.

The two main reasons for the delay of an international agreement on the use of forests to mitigate emissions are scientific uncertainty about emissions estimates and policy concerns. The former issue arises from the lack of consistent and uniform broad-scale data arising from an insufficient number of sustainable national forest carbon Measurement, Reporting, and Verification (MRV) systems in developing countries. The latter issue is being addressed in UNFCCC discussions on REDD-plus. In any case, forest carbon MRV systems must be designed so that they provide the information necessary to address the policy issues of leakage, permanence, baseline, and additionality (see box below).

Leakage: the potential for a climate mitigation project in one area to displace emission-generating activity to another area, rather than abate total emissions. National wall-to-wall monitoring of changes in land cover and land use and global assessments may help detect leakage.
Permanence: the persistence of emissions reductions made in forest carbon activities. This can be addressed in policy through crediting mechanisms. Permanence policies must be supported by a continuous time-series of spatially consistent forest monitoring.
Baseline: net changes in carbon stocks that would occur in the absence of a proposed project activity. Time-series consistent monitoring from archival data can provide a baseline of historical trends. Spatially explicit baselines also allow for insights into sub-national trends.
Additionality: emissions reductions of a project activity are additional if: (1) the activity will reduce emissions over and above baseline reductions and/or (2) the activity was not previously funded, but is only economically viable with proceeds from financing emissions reduction activities.

Other issues such as control and monitoring of forest degradation and land ownership and carbon rights also arise, but are outside the scope of this paper which focuses on technical issues related to tracking GHG emissions only.

The inclusion of forest information in global climate change agreements has been hindered in the past by poor information on changes in forest area and carbon stocks, especially in developing countries. One reason for this is the infrequency of national forest surveys and the lack of operational global forest monitoring systems (Grainger, 2009). Contributing to this are deficiencies in the global and regional coverage of satellite image data sets. Rosenqvist et al. (2003) have called for space agencies to implement systematic data acquisition strategies in support of international environmental conventions. The situation is now changing with the development of satellites with new mission concepts that provide wall-to-wall remote sensing of forest and other vegetation cover, along with the development of modeling techniques to extrapolate from ground-based forest measures. Combined, earth observations and models can be incorporated into MRV systems to reduce the sampling needed to estimate changes in areas of forest cover, and reduce the number of ground samples needed to quantify local variation within various forest types (for example, as caused by terrain).

Field sampling will always remain essential both in its own right and as part of calibrating and validating satellite remote sensing and forest models. Combining spatially explicit satellite data, modeling, and field measurements improves the quality of information about landscape variability and reduces the cost of data acquisition. While sample-based inventories are applied at global, regional, and national scales, greater intensity of measurement is needed to make localised estimates. It is at this local scale where the cost effectiveness of estimates drawn from spatially explicit national systems finds its full benefit (Baccini et al., 2008).

Spatial data assumes greater importance as climate change, fire, disease, and other disturbances alter forest carbon patterns at fine spatial scale. Another strength of a spatially explicit approach to monitoring is the ability to visualize land cover changes over time. Time series also permit improved detection of classification errors and continuous refinement of classification results. This enhances both transparency and verifiability. When carbon results are also spatially explicit, rather than just statistically inferred from samples, it is easier to verify project level estimates. The use of Geographic Information Systems (GIS) is an important part of the spatially explicit approach.

A variety of activities is required to reduce the scientific uncertainty and to address the policy challenges of REDD-plus. Forest carbon measurements at the ground level, forest carbon mapping (extrapolation from field to national, regional, continental and global scales by statistical and modeling methods), forest cover monitoring, and associated modeling of changes in carbon stocks and GHG emissions all need to be brought together into national MRV systems. These systems must reflect national circumstances and be owned by the national governments. The information from a global network of national MRV systems will lead to continuous global forest assessments of stocks, emissions and trends that are validated, calibrated and accessible. This can only happen if there are commitments from space agencies to implement systematic acquisition strategies and to provide the necessary satellite data, including suitable terms for access and long-term continuity. In addition, international bodies – including the UN (for example, UNFCCC and FAO), non-governmental organizations and other scientific organizations – must collaborate, coordinate, and respond to the needs for operating standards, transparency and engagement of stakeholders. These groups should pay particular attention to the capacity building task sought by many national governments. The box below provides definitions, terminology, and a list of glossaries to help the reader in the following discussion.

Terminology and Glossaries:
MRV: Measurement, Reporting, and Verification for GHG emissions at local, regional, and global scales.
NCAS: National Carbon Accounting System. A National Carbon Accounting System (NCAS) is the national estimation tool—the measurement, modeling, and information delivery part of an MRV system.
Measurement: The determination of the values of parameters for forest carbon including forest and non-forest area and forest carbon stocks by field studies and inventories and remote sensing by aircraft and satellites. Monitoring refers to the measurement systems as well as systematic observations, data archiving and the means for making data available.
Reporting: The R in MRV is done through the UNFCCC guidelines as part of the National Inventory Report and Common Reporting Format standardized frameworks. For example, in the case of Indonesia, the NCAS supports a Forest Resource Information System (FRIS), which is the forestry-reporting tool. REDD-plus is one possible policy element that would be reported through a MRV system.
Verification: The V in MRV has many parts, and can include the Quality Assurance and Quality Control programs called for by inventory programs, accuracy assessment and validation of NCAS estimates, and the broader review process applied by the UNFCCC (see Step 4 below for more on verification).
MRV System: The MRV system incorporates the National Carbon Accounting System; must be comprehensive with flexibility to support any potential REDD-plus scope (which is yet to be decided); and includes more robust emissions reporting for the full scope of forest activities (and possibly timber resource inventories as is the case in Indonesia) at marginal cost versus benefits.
Decision Support Tools: The web-based software programs that allow decision-makers to draw on the information from the MRV system to make policy decisions about REDD-plus programs.
Glossaries for climate-related terms may be found at:
Meridian Institute (2009): http://www.redd-oar.org/, pp. 37–41.
IPCC Fourth Assessment Report 2007: http://www.ipcc.ch/pdf/glossary/ar4-wg1.pdf.
IPCC glossary: http://www.ipcc.ch/pdf/glossary/ar4-wg2.pdf, and http://www.ipcc.ch/pdf/glossary/ar4-wg3.pdf.
IPCC Special Report 2000: http://www.ipcc.ch/ipccreports/sres/land_use/013.htm.
IPCC 2006 Guidelines: http://www1.ipcc.ch/ipccreports/methodology-reports.htm.
UNFCCC Clean Development Mechanism: http://cdm.unfccc.int/Reference/Guidclarif/glos_CDM_v04.pdf.

2. Science and methodology

2.1. Scientific uncertainty

The major variables in estimates of global forest carbon emissions include: rates of deforestation, carbon stocks (biomass and soils) in forests before deforestation, and changes in carbon stocks within forests (that is, both gains from growth and losses from extraction of wood for timber and fuel). Satellite data can reduce uncertainties of these variables, with Landsat instruments as the primary satellite sensors used to detect forest cover change (DeFries et al., 2007). The full potential of satellites for biomass monitoring is yet to be realized. Research such as that by Lucas et al. (2006, 2008a,b), Quiñones and Hoekman (2004), and Asner (2009) are developing methods for interoperable use of hyperspectral, lidar, optical, and radar data for estimating above-ground biomass. But the availability of technologies does not automatically mean that they will be implemented into operational systems or that funding will be available. Houghton and Goetz (2008) suggest that lack of funding, not expertise, limits efforts to reduce uncertainties of estimates of biomass, reforestation, forest growth rates, and degradation.

A new challenge lies in estimating change in carbon stocks directly from remote sensing and then linking the information on forest carbon stocks and satellite derived maps of changes in forest cover to the estimation of emissions through statistical and modeling approaches. It is important to note that remote sensing technology cannot assess soil and dead wood carbon stock, thus indirect methods must be used (see, for example, Somogyi et al., 2007). GOFC-GOLD (2008) discusses limitations and applicability of current methods. Asner (2009) has shown a possible approach for measuring forest carbon in the Amazon by merging satellite and airborne lidar information.

The scientific community is making progress on these issues and it will be important to incorporate the new information and methods into national accounting systems. For example, the data on forest carbon stocks at both continental and global scales is improving (Gibbs et al., 2007; Baccini et al., 2008). Enough knowledge exists to start now to set up national systems; the new information from the national systems will reduce the uncertainties over time. Improving the science should therefore be done in parallel with the setting up of national systems (Goetz et al., 2009). We begin our discussion here with a short review of the methodological guidelines of the IPCC.

2.2. IPCC National Greenhouse Gas Inventory Guidelines and Good Practice Guidance

The IPCC (2006) AFOLU Guidelines were designed to be adaptable for future reporting of greenhouse gas inventories to the UNFCCC, but did not necessarily anticipate the potential REDD-plus mechanism. A UNFCCC Subsidiary Body for Scientific and Technological Advice (SBSTA) workshop examined relevant methodological issues (UNFCCC, 2008).

The guidance, with tiers (representing different amounts of data, data quality and stages of methodological complexity) and approaches (representing different methods of land representation) as defined in the tables below, provides policy neutral methods for estimating national greenhouse gas inventories. The tiers and approaches have been designed so all countries, regardless of capacity, can engage. They do not address or preempt any political decision on accounting for greenhouse gas emissions and removals and therefore do not directly address issues such as leakage, additionality, baselines or permanence.

Tiers (IPCC, 2006)
Tiers represent the methodological complexity required to estimate the emissions and removals from a reporting category given its influence on a country's total inventory, data availability and national circumstances. The discussion below refers to developing country use of the Tier structure.
Emissions and removals are not directly estimated; rather estimates of changes in carbon stocks in the various carbon pools of a forest are converted to emission and removal estimates. Carbon stock or stock change information can be obtained at different Tier levels. Which one is selected is independent of the Approach to land representation selected, but not all Tiers and Approaches would logically combine.
- Tier 1 uses IPCC default parameters (for example, biomass in different forest biomes, and carbon fraction);
- Tier 2 requires some country-specific carbon data (that is, from field inventories and permanent plots); and
- Tier 3 uses highly disaggregated national data of carbon pools and assesses any change in pools through repeated measurements and/or modeling.

Moving from Tier 1 to Tier 3 increases the accuracy and precision of the estimates, but usually increases the complexity and the costs of monitoring.

Approaches (IPCC, 2006)
There are three Approaches to land-related data collection to represent land set out in the IPCC Guidelines. Countries may use a mix of Approaches for different regions and over time.
- Approach 1 identifies the total area for each land category—typically from non-spatial country statistics categorized into broad land use types at the time of any land use census or inventory. Information is not provided on the nature and area of conversions between land uses, that is, it only provides ''net'' area changes (for example, deforestation minus afforestation) between two inventories and thus is unlikely to be suitable for any REDD-plus policy framework;
- Approach 2 involves tracking of land conversions between categories, resulting in a non-spatially explicit land-use conversion matrix and hence changes cannot be directly linked to forest carbon maps, and
- Approach 3 extends Approach 2 by using spatially explicit land conversion information, derived from either sampling or wall-to-wall mapping techniques in time series.

While both Approaches 2 and 3 give gross-net changes among land categories, only Approach 3 allows for the estimation of gross-net changes within a category, that is, detection of deforestation followed by afforestation, which is not possible with Approach 2 unless detailed supplementary information is provided. Only Approach 3 directly addresses leakage (displacement rather than cessation of activity) and permanence (persistence in a particular activity).

Similar to current requirements for flexibility mechanisms under the Kyoto Protocol, it is likely that future monitoring for a REDD-plus mechanism would need identifiable and traceable land areas, and thus it is likely that Approach 3 would be necessary for REDD-plus implementation.

2.3. *GOFC-GOLD REDD Sourcebook*

An ad-hoc working group of the Global Terrestrial Observing System (GTOS) compiled a ''Sourcebook'' that addresses methods to quantify greenhouse gas emissions and removals through REDD (GOFC-GOLD, 2008) (GTOS is an international program aimed at facilitating terrestrial observations and networks, co-sponsored by FAO, UNEP, UNESCO, WMO, and the International Council for Science). The Sourcebook surveys methods to date within the context of the IPCC guidance, and provides technical guidance on a monitoring approach to measure gross national carbon emissions from changes in forest cover by deforestation and degradation. The Sourcebook analysis is also applicable to the broader REDD-plus framework.

The Sourcebook explains methods that support early actions and readiness mechanisms for national REDD monitoring systems. This is done in recognition that the REDD (or REDD-plus) policy framework and accounting rules have not yet been established. Final method requirements will be clearer when the policy frame and accounting rules are determined. The Sourcebook recognizes satellite remote sensing as an important tool for monitoring changes in forest cover, as well as the role of field studies for measuring carbon stocks in forests. The Sourcebook also provides clarification on applying the IPCC guidance for reporting changes in forest carbon stocks at the national level.

Noting that many developing countries may face difficulties meeting the requirements for completeness and accuracy, the Sourcebook proposes a conservative approach with improvement over time. It also notes that robust estimates of carbon stocks will be the basis of an accounting framework with an eventual assignment of economic incentives. The Sourcebook adopts a conservative approach that may simplify the requirements necessary for obtaining defensible estimates of reduced emissions from deforestation. This conservative approach means that when completeness, accuracy and precision cannot be achieved, the reported reduction of emissions (and thus the incentives claimed by the country) should not be overestimated, or at least the risk of overestimation should be minimized. This principle of neither over- nor underestimating emissions is a base inventory principle from the IPCC guidelines and the Marrakesh Accords to the Kyoto Protocol.

3. Five-part plan

The new REDD-plus funding commitments at COP-15 underscore the urgent need for MRV capacity in developing countries. The commitments will enable a quantum leap in the ability of these countries to establish MRV systems. No single model for an MRV system will apply to all developing countries because of differences in ecology, institutions, and technical capacities. As DeFries et al. (2007) have noted, the capacity for deforestation monitoring is well advanced in a few developing countries and is a feasible goal for most others. For example, Brazil and India are well advanced, whereas some other countries have just begun to develop an assessment of needs. Nevertheless, there is a set of overall characteristics and elements required for all MRV systems and some common needs of countries. Herold (2009) and the UNFCCC (2009) analyzed information from global sources to provide country-specific indicators for tropical non-Annex 1 countries, and then made specific recommendations about measurement and monitoring, infrastructure, human resources capacity building needs, and costs to monitor for those countries.

3.1. First part: expand the number of national Measuring, Reporting, and Verification (MRV) systems in tropical developing countries

Countries planning to take part in international REDD-plus agreements will need scientifically robust forest carbon estimates with uncertainties reduced as much as practicable. Tier 1 estimates can have uncertainties as large as plus or minus 70% (Meridian Institute, 2009). Clearly substantial improvements (at least Tier 2) over that value will be required if countries are to meet international compliance standards. This requires national scale MRV systems that are reproducible, provide consistent results, meet standards for accuracy in emissions estimates and can be performed nationally (DeFries et al., 2007; Brack et al., 2006). The national systems should ideally provide a border-to-border (wall-to-wall) view of forest cover, integrating data from field inventories, modeling and remote sensing to estimate carbon stock and changes in stocks. The IPCC (Aalde et al., 2006) provides advice on how to achieve this goal (see also McKenzie et al., 2000, 2008).

A global network of national MRV systems that comply with IPCC guidelines, at least a Tier 2 or Tier 3 level with Approach 3 spatially explicit data, is the ideal situation for monitoring emissions and removals of greenhouse gases with a sufficient level of certainty and confidence. Achievement of the Tier 3 level will not be possible for all countries in the near term, but the systems could be designed flexibly so the modules responding to the more immediate REDD-plus policy needs could be carried out (for example, providing best quality data in areas most subject to change). Countries should demonstrate that implementing such systems yields unbiased estimates. As information improves with the addition of new satellite data and more comprehensive field sampling, the higher-level Tiers and Approaches can be used more comprehensively.

The issues of leakage, additionality, baselines, and permanence are addressed by having transparent integrated systems that use wall-to-wall information and are coupled to data and models that represent the variability in biological, physical, and socioeconomic processes that cause emissions and removals. MRV systems will also need that that information for verification.

Remotely sensed data, collected by instruments flown on satellites and aircraft that provide optical, radar, lidar, and hyperspectral data, are an essential element of national and global systems. Scientists have shown how readily available mid- and high-resolution optical data can provide estimates of forest cover in cloud free regions (for example, Eva et al., 2010), and they have used the newer radar instruments to collect forest cover information through clouds (for example, Hoekman and Quiñones, 2002). In short, the satellite imagery and ground measurement technology can now be considered mature enough for use in national systems. Further research and development in mapping will improve accuracy and detail (see for example, Asner, 2009).

Field sampling has been the traditional mode of estimating carbon stocks in forests, and will remain essential (see, for example, the IPCC (2006) guidelines and GOFC-GOLD (2008)). MRV systems will require the calibration and combination of remote sensing data and accurately referenced ground data measurements. Also, spatial interpolation models that can be used to produce forest carbon maps at both sampled and unsampled locations need to be calibrated with ground-measured data.

Much has been learned in the past two decades about using remote sensing with field studies and models for emissions estimation. For example, the Australian National Carbon Accounting System (NCAS), the Brazilian PRODES (Valeriano et al., 2004), and the Canadian forest sector carbon monitoring, accounting, and reporting system (Kurz and Apps, 2006) all use satellite data as the basis for broad scale estimations of forest cover change. The GOFC-GOLD Sourcebook also outlines methodological issues that combine field studies and remote sensing. DeFries et al. (2006) have presented considerations for monitoring and measuring as part of the GOFC-GOLD effort.

Countries need both to own and to be confident that MRV systems are adapted to their circumstances and needs. Developing countries can use the collection and integration of data for their MRV systems as an opportunity to develop the forest decision-support systems for management, for example, where to allow logging and where to enforce the law. This co-benefit is an important reason for those counties to make progress on these issues. Training for land managers, scientists, and technicians in developing countries is a prerequisite to achieving early impact and ensuring long-term success. The capacity-building activities must include physical and conceptual tools to improve national institutions and enable them to take responsibility for developing and maintaining national MRV systems.

National MRV systems will also assist individual sub-national projects by showing how they contribute to national outcomes. This is important because aggregation of forest carbon information to national levels will inevitably obscure the great diversity of landscapes and projects within a country. Therefore an approach should be adopted that combines national regulatory and monitoring capabilities with sub-national information and knowledge. There must be an accessible, continuous and free flow of information between local and national entities. National systems that are fully accessible can thus reduce the transaction costs for small landholders, a key factor in gaining public support.

Funding for the development of new national MRV systems is a critical issue. Establishing national systems and combining them into a viable global network will require considerable investment for capacity building and technology transfer in developing countries over the coming years. In the early stages, funds will be needed to establish historical databases and build the operating systems. Governments must ensure consistent operational support to sustain the systems. At the beginning, these funds are expected to come from foreign aid as noted by the agreement at COP-15 and then later through participation in carbon markets. Hardcastle et al. (2008) (see also Hoare et al., 2008; UNFCCC, 2009) estimate average costs for national systems of about US$1 million for upfront costs and US$500 000 for annual costs, depending on the size of the country. Given the unknowns in establishing such systems, these costs are indicative, but probably represent a minimum capability. Technology developments will help reduce costs.

3.2. Second part: implement continuous global forest carbon assessments

The second step, which can be done concurrently with step one, is to develop an accessible global forest data set with high enough certainty (at least equivalent to Tier 2 inventories) for policy makers. Despite the large body of work already developed, the uncertainty in global forest carbon assessments remains high (Grainger, 2008). The quality of country data collected and reported by the Food and Agriculture Organization (FAO) varies widely and cannot be relied on to accurately track the long-term changes in forest area, stocks and emissions. This is partly because of definitional issues about what constitutes a forest and what is not a forest (see Houghton and Goetz, 2008), and partly due to the difficulty of achieving good national data. One of the benefits of a national MRV system is that it shifts data from discrete classes (forest and non-forest) to a continuous variable (biomass carbon in all vegetation).

Currently available data do not allow tracking of long-term trends in global forest area, forest carbon stocks, or emissions. In a world that depends on responsible management of forests for climate change benefits and sustainable development, much better information is needed. FAO recognizes the flaws of the reported forest data and has begun to complement country reports with remote sensing surveys. The next FAO Forest Resources Assessment (FRA 2010, http://www.fao.org/forestry/fra/fra2010/en) will also have a remote sensing component, but will only use samples of remotely sensed data solely to create regional and global estimates of forest area and change. The remote sensing sampling will improve the accuracy of the data on a global and possibly regional level, but will be insufficient to provide data with any statistical confidence at the national and sub-national scale.

While the FRA 2010 will be an essential element of any global forest carbon assessment and should be reconciled with other assessments, its one degree by one degree sampling grid cannot provide the data needed to meet potential UNFCCC requirements such as monitoring leakage. Also, estimates of carbon stocks will not be included. The content of FRA will change over time to reflect estimates of forest areas and carbon stocks that governments regard as official, based on the inputs they receive from national and/or independent global monitoring.

The forest community should also encourage the creation of inventories of both carbon stock and merchantable volume (where relevant) in forest areas under pressure for change (clearing, logging, or other forms of disturbance) in countries where such inventories are lacking. These inventories, provided they are robust and transparent and use comparable data collection protocols, will provide essential information for developing an accurate assessment of global forest carbon.

Meeting these national and international needs requires a large leap in the quantity and quality of information. This suggests a need for a major new global program for the collection of accurate forest information from satellites and field measurements. Such a global program, under international auspices, would enable governments, research institutes, and other organizations to work together to develop a consistent time series of data for global forest monitoring. The program could also help to develop more cost-effective measurement and monitoring methods. It is beyond the scope of this paper to describe the details of such a program, but the following paragraphs list some of the essential elements.

The research community has a key role here and could help design a framework to analyze and validate global forest carbon information in consistent and repeatable ways. A global research network could provide the prototypes for image processing, field data measurements and models, and validation protocols to carry out the following tasks:

- digital processing of satellite imagery;
- compilation of a database of consistent global forest measurements;
- development of standardized methods to integrate remote sensing and field data;
- building and comparison of models to produce forest carbon maps and estimates of deforestation and forest degradation-caused carbon emissions; and
- development of platforms to make the information available.

Global forest carbon assessments can incorporate new technologies and data as they become available. Historical trends are also important for defining reliable baselines and the available historical data should be digitally processed as part of the global assessment.

Various organizations have already developed large-scale land cover assessments and are developing new tools that combine optical and radar satellite data with suitable reference ground data to achieve a richer time-series of regional assessments (see, for example, Hoekman et al. (in press) for Borneo, and Holecz et al. (2009) for Malawi). These efforts should be networked and coordinated by forming partnerships of existing activities in the developed and developing world. As new measurements are incorporated, the previous information should be reassessed to ensure full accuracy and time-series consistency, just as global climate data are reanalyzed every 5–7 years. Improving monitoring and measurements should go hand in hand with improvements in data collection, archiving, web access and use of GIS. This kind of independent global analysis could provide the confidence that country actions are significant. Moreover, in this way, a decision-making environment can be created with continuously available, reliable, accurate, and current information on land use and land-use change.

We recognize this is not the first time that such a continuous global assessment has been proposed; for example, Grainger (1984) proposed a strategy for a continuous satellite-based monitoring system for tropical forests more than 25 years ago, and Skole et al. (1997) repeated the call for all land cover 13 years ago. Now, for the many reasons we have presented here, we believe the time is right, the technology is mature enough for use in national systems and there is enough interest from funding sources to make it happen. The new funding commitments announced at COP-15 are sufficient to cover the estimated costs of developing national MRV systems. The eventual goal is for continuous annual national assessments forming a global forest monitoring system, recognizing that reaching the goal requires significant capacity building, resources to process and verify data, as well as coordinated action by governments and the scientific community to develop operational national MRV systems that are sustainable over the long term. This is a combination that has worked well for meteorology—lessons learned there could be applied in the forestry world. Examples include the World Weather Watch, the Global Atmospheric Research Program and the Global Weather Experiment in the 1970s and 1980s, which used global data from a new set of global weather satellites and ground-based instruments to reduce the uncertainty and improve the accuracy of weather forecasts.

3.3. *Third part: achieve commitments from satellite-operating space agencies*

Rapid coverage over broad areas as provided by satellite-borne sensing instruments is substantially improving our knowledge of the earth's forests. For example, the information collected by Landsat has long been used to determine deforestation rates (DeFries et al., 2002; Brack et al., 2006), logging (Asner et al., 2005), and degradation expansion (Laporte et al., 2007). The TREES project has led the way in producing satellite-based estimates of pan-tropical forest area deforestation rates since the 1990s (see, e.g., Achard et al., 2002, 2007). New satellite imagery, from moderate- to high-resolution optical and radar instruments, is also providing wall-to-wall information (Hansen et al., 2008; Rosenqvist et al., 2007). Asner (2009) has shown how satellites and aircraft systems can cover large areas for measurements. DeFries et al. (2005, 2007) note that remotely sensed data supported by ground observations are key to effective monitoring. Clearly for national carbon accounting systems and global assessments to have the ability to consistently and accurately monitor changes in forest and other land uses over time, governments and the scientific community will need continuous, systematic and free or low-cost access to both satellite observations and in situ ground-based observations (see Goetz et al. (2009) for an up-to-date assessment of different remote sensing systems).

Thus the third major step to ensure satisfactory information flow is a commitment by national governments and their respective space agencies to maintain and enhance long-term satellite-based observational systems. These agencies should provide and sustain into the future both mid-resolution satellite observing systems and selected high-resolution systems (for calibration purposes). The United States Geological Survey has provided a model for satellite data access by placing an entire archive of Landsat data from 1972 on a public website (http://glovis.usgs.gov). Access to these data has proved very popular—in the first four months of 2009, more than 500 000 Landsat scenes were downloaded. This is important because the Landsat satellite series provides the longest time series of remote sensing data available, providing 30 m spatial resolution for much of that period. Data from the Chinese-Brazilian land remote sensing satellite series CBERS and the Japanese radar satellite ALOS-PALSAR is increasingly available as well. Continuity is the key here—governments and the private sector must commit to ensure the permanent presence of satellite systems with Landsat-equivalent or better resolution and with sensors that can be compared quantitatively.

The Japanese Space Agency (JAXA) has taken a leading role in data acquisition planning (http://www.eorc.jaxa.jp/ALOS/en/obs/overview.htm) and is ensuring the availability of consistent time-series of global land cover radar and optical data through the implementation of systematic acquisition strategies for its three instruments onboard the ALOS satellite. The cloud-penetrating PALSAR radar on ALOS (http://www.eorc.jaxa.jp/ALOS/en/kc_mosaic/kc_mosaic.htm) has provided gap-free coverage over all land areas on Earth on a semi-annual basis since 2006. Medium resolution mosaics are generated on an operational basis and provide for open use on a public website (http://www.alos-restec.jp). The Japanese government has approved the ALOS-2 (radar) and ALOS-3 (optical) systems to ensure long-term continuity. The European Global Monitoring for Environmental Security (GMES) program is now supporting several satellites which provide long-term optical and radar information about the land surface. The GMES data, together with data from other planned satellites, will improve comparisons of historic and future forest change. Satellite developers should also pursue next-generation measurement satellites, including radar and lidar sensors, which would provide enhanced forest and other land cover measurements.

The Group on Earth Observations (GEO) is a voluntary partnership of governments and international organizations with a mandate in Earth observation and related issues. GEO provides a framework within which these partners can develop new projects and coordinate their strategies and investments. As of September 2009, GEO's members include 80 governments and the European Commission as well as 58 intergovernmental, international, and regional organizations as Participating Organizations. GEO, through its development of a Global Earth Observing System of Systems (GEOSS), is playing an important role in coordinating the effective integration of satellite observations, in situ inventory data, and carbon modeling into an accessible global network of national systems with consistent output. Since the purpose of GEOSS is to move beyond coordination of observing systems to provide information for policy decisions, it is an ideal framework for forest carbon work. One possible option for those countries lacking their own observing satellites is to participate in this effort by providing both high-bandwidth downlink receiving stations and high-capacity ground systems for data archiving, processing and downstream distribution of value-added information, thus acting as regional centers or hubs.

To fulfill this integrating role, GEO has agreed to a ''Forest Carbon Tracking (FCT) Task'' to ensure that national-level in-situ observations and modeling, as well as critical satellite information from appropriate international bodies and national space agencies, is made available at least yearly. The goal is create a global forest monitoring network of national MRV systems, working closely with UN bodies such as the FAO, the World Meteorological Organization, and the Committee on Earth Observation Satellites (CEOS). The first step has been the establishment of a National Demonstrator program in Borneo, Brazil, Cameroon, Guyana, Mexico, Tanzania, and Tasmania to show the feasibility of combining satellite-based and ground forest monitoring information in support of future MRV systems.

GEO is working closely with CEOS, which aims to facilitate the coordination of remote sensing of the Earth. CEOS recognizes the urgent need for forest monitoring programs that can achieve such coordination of space-based observations (optical and radar) and secure long-term continuity of remote sensing commitments. CEOS members have agreed to a free exchange of land remote sensing data (http://www.ceos-sit23.com/pdfs/CEOS%20Forest%20and%20Carbon%20Communique_FINAL_V4.pdf).

We suggest that in order to strengthen this coordination, GEO and CEOS consider setting up a new Coordination Group for Land Surface Satellites, parallel to the existing and effective international Coordination Group for Meteorological Satellites (CGMS) (see World Meteorological Organization (WMO)) to deal with the specific aspects of making satellite land-surface measurements operational, just as satellite weather measurements are operational today. Because the amount of data from satellite systems can be enormous, the information technology industry can play an important role in providing data storage and visualization, measurement systems, and value-added services.

High-level government prioritization and budget commitments to support the relevant space agency programs are required to support these efforts by CEOS and GEO. Such commitments would ensure that government satellite programs, supplemented by private industry capacity, provide long-term and systematic earth observations, with an accelerated implementation of next-generation earth observation and measurement systems. The forest monitoring activities that will be required by the UNFCCC REDD-plus process will help convince governments to make these commitments.

Finally, we also want to recognize the importance of national government commitments to long-term support of in-situ, on-the-ground measurements, as noted in Section 1, which provide basic information and a reference for satellite measurements. Since GEO includes both satellite and ground-based information, GEO can help make the case for the ground systems by working with the Global Terrestrial Observing System (GTOS) to ensure that there are coordinated mechanisms to archive and share these data.

3.4. *Fourth part: establish agreed standards and verification processes*

Verification has been defined as ''independent third party assessment of the expected or actual emission reductions of a particular mitigation activity'' (Angelsen, 2008). Meridian Institute (2009) states that the purpose of verification is ''to assess whether the information is well-documented, based on IPCC methodologies, and transparent and consistent with the reporting requirements outlined in the UNFCCC guidelines.'' We have noted above that verification has many parts, and can include the quality assurance and quality control programs called for by inventory programs, accuracy assessment and validation of MRV estimates, and the broader review process applied by the UNFCCC. Clearly, there is a need for formal development and acceptance of the standards and verification for forest emissions estimation based on the data collected by national MRV systems.

As any verification system for REDD-plus is likely to be set up under the UNFCCC, it could parallel the existing review mechanism for Annex 1-country inventories. This mechanism includes international experts, with members of expert review teams selected by a secretariat from a pool of international experts nominated by Parties. Meridian Institute (2009) notes that the UNFCCC process for reviewing GHG inventories puts a heavy burden on the limited number of experts on the UNFCCC roster, and that using the UNFCCC as the prime reviewer of REDD-plus activities would clearly require more experts and approved verifiers for REDD-plus activities. They in turn will need to have access to a reliable set of global spatial forest information, obtained by the continuous global forest assessments we propose in part 2 of the plan. The lessons learned during the verification process for the Clean Development Mechanism (CDM) and for the voluntary carbon market can inform the standards development.

Moreover, there may well be a need for a new international body or regional bodies that can provide independent third party external validation and certification (for example, building on the Designated Operational Entities for the CDM). The charge to these bodies would be to validate the data being reported internationally against agreed standards and criteria. Such a body or bodies may have a formal charter, but would likely be made up of independent experts from both developed and developing countries. This is a topic that should be taken up by the UNFCCC, IPCC, GEO and UN-REDD (see below).

3.5. *Fifth part: enhance coordination among multilateral organizations, international agencies and other key bodies*

The Food and Agriculture Organization (FAO) has been the UN lead on forestry issues. Now, with new climate interests in maintaining forests, FAO has formed a partnership with UNEP and UNDP called UN-REDD. One of the key challenges in setting up a feasible scheme for dealing internationally with forestry and related issues is to ensure this new set of existing UN agencies can work together and with many different stakeholders, from national governments to the private sector, intergovernmental bodies, NGOs and research institutions. All of these entities have expertise to offer.

The World Bank's Forest Carbon Partnership Facility and Biocarbon Fund also play an important role in supporting forestry activities of developing countries. 3 countries are now part of the World Bank's Forest Carbon Partnership Facility, representing all regions of the developing world, and have created or are devising readiness plans for REDD-plus. With this background, we believe an important follow-up step would be to encourage the creation of national forest carbon MRV systems in a subset of these already identified countries. The World Bank's Biocarbon Fund, which links reforestation with land use management and avoided deforestation to the carbon market, can also play a key role here in working with UN-REDD. As a large global network for forest science cooperation, the International Union of Forest Research Organizations (IUFRO) may be able to assist developing countries with guidance and expertise.

To meet all the points noted above, particularly for data access and continuity, we believe that an expanded partnership beyond UN-REDD will be needed. It should draw on those groups responsible for global observing systems (GEO, WMO, GTOS, and others) to provide oversight, standards, capacity building, and ensure data archiving and data flow.

We also believe that GEO could have a role in these UN activities. As mentioned above, GEO is a voluntary partnership of national governments with a common vision, but is not a working organization (nor a formal member agency) of the UN. Giving GEO more visibility, especially in the developing world, could help give more formal recognition to its coordination, policy, and information role. GEO is a formal partner of UN-REDD and the GEO Forest Carbon Tracking task with its National Demonstrators and plans for a global forest monitoring system will help facilitate this coordination.

4. Conclusions

The major funding commitment to REDD-plus at COP-15 by a set of Annex-1 countries shows that the time is right to expand the existing set of national forest carbon MRV systems into a global network. The magnitude of the potential GHG emission reductions through implementation of REDD-plus justifies the establishment of a global network of forest carbon MRV systems. With this network, data will flow from satellites and field plots into archives and GIS systems and the information will enable decision-makers to meet their responsibilities and understand the climate change and economic development consequences of their actions. The financial commitments to REDD-plus made at COP-15 show it is now possible to move forward and to make these systems the norm rather than the exception. MRV systems could provide significant social, economic, and environmental benefits that will support many aspects of sustainable development. MRV systems with appropriate decision support tools could also make forest management planning more transparent and facilitate local input into natural resource management decisions.

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D. James Baker is the Director of the Global Carbon Measurement Program of The William J. Clinton Foundation. He is Co-chair of the Clinton Climate Initiative, Carbon Measurement Collaborative, and a member of the Commission on Climate and Tropical Forests. He is an adjunct professor at the University of Pennsylvania and at the University of Delaware, and a visiting senior fellow at the Center for the Analysis of Time Series at the London School of Economics and Political Science. He was previously the Administrator of the U.S. National Oceanic and Atmospheric Administration, and on the faculties of the University of Washington and Harvard University. He holds a Ph.D. in physics from Cornell University.

Gary Richards is Principal Scientist of the Land Management Branch within the Australian Department of Climate Change. Dr. Richards is also co-chair of the Clinton Climate Initiative, Carbon Measurement Collaborative, and is an active participant on the work of the Intergovernmental Panel on Climate Change. He holds a Ph.D. in Forestry and maintains an active interest at the Australian National University as a visiting fellow in the Fenner School of Resources, Environment and Society.