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Authors

Sathaye, Jayant
Makundi, Willy
Goldberg, Beth
et al.

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Jayant Sathaye, Willy Makundi, Beth Goldberg, Kenneth Andrasko, and Arturo Sanchez, Editors

Environmental Energy Technologies Division

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Proceedings of the International Workshop on Sustainable Forest Management: Monitoring and Verification of Greenhouse Gases

Edited by

Jayant Sathaye, Willy Makundi, and Beth Goldberg
Environmental Energy Technologies Division
Lawrence Berkeley National Laboratory

Kenneth Andrasko
Climate Policy and Programs Division
Office of Economy and Environment
Office of Policy, Planning, and Evaluation
U.S. Environmental Protection Agency

Arturo Sanchez
Research Center on Sustainable Development
University of Costa Rica

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Acknowledgments

We wish to express our sincere appreciation for the contributions of the participants who prepared papers and presented results of their studies during the workshop. The important role of experts and government officials who participated in the workshop to learn about and share their experiences in monitoring and verification of forestry projects is gratefully acknowledged. We specifically commend the following individuals for providing leadership, overall planning, and organization of the workshop: Robert Wolcott, U.S. Environmental Protection Agency, for his initiative and support, Max Campos, Central American Project for Climate Change, and Eladio Zarate, Regional Committee on Water Resources, for their initiative in designing, planning, and organizing the workshop, Catrinus Jepma, University of Groningen, Open University, and the University of Amsterdam, The Netherlands, for organizing the participation of the Dutch government, and Ted Gartner, LBNL, for his excellent technical editing of the papers. Special thanks are due to the working group leaders and rapporteurs for volunteering to lead their group discussions and preparing the group summaries.

Foreword

The International Workshop on Sustainable Forest Management: Monitoring and Verification of Greenhouse Gases was held in San Jose, Costa Rica, July 29-31, 1996. The main objectives of the workshop were to: (1) assemble key practitioners of forestry greenhouse gas (GHG) or carbon offset projects, remote sensing of land cover change, guidelines development, and the forest products certification movement, to offer presentations and small group discussions on findings relevant to the crucial need for the development of guidelines for monitoring and verifying offset projects, and (2) disseminate the findings to interested carbon offset project developers and forestry and climate change policy makers, who need guidance and consistency of methods to reduce project transaction costs and increase probable reliability of carbon benefits, at appropriate venues.

The workshop brought together about 45 participants from developed, developing, and transition countries. The participants included researchers, government officials, project developers, and staff from regional and international agencies. Each shared his or her perspectives based on experience in the development and use of methods for monitoring and verifying carbon flows from forest areas and projects.

A shared sense among the participants was that methods for monitoring forestry projects are well established, and the techniques are known and used extensively, particularly in production forestry. Introducing climate change with its long-term perspective is often in conflict with the shorter-term perspective of most forestry projects and standard accounting principles. The resolution of these conflicts may require national and international agreements among the affected parties. The establishment of guidelines and protocols for better methods that are sensitive to regional issues will be an important first step to increase the credibility of forestry projects as viable mitigation options.

The workshop deliberations led to three primary outputs: (1) a Workshop Statement in the JI Quarterly, September, 1996; (2) the publication of a series of selected peer-reviewed technical papers from the workshop in a report of the Lawrence Berkeley National Laboratory (LBNL 40501); and (3) a special issue of the journal *Mitigation and Adaptation Strategies for Global Change*, Kluwer Academic Publishers. The outputs will be distributed to practitioners in this field and to negotiators attending the Framework Convention on Climate Change (FCCC) deliberations leading up to the Third Conference of Parties in Kyoto, in December 1997.

On behalf of the Costa Rican Ministry of Natural Resources and Mines, US EPA and all the organizers, we wish to express our sincere gratitude for the support of the Central America Project for Climate Change (CAPCC), the Regional Committee on Water Resources (CRRH), the Research Center on Sustainable Development of the University of Costa Rica (CIEDES-UCR), US Initiative on Joint Implementation (USIJI), and the Netherlands' Ministry for Development and Cooperation. We would also like to thank experts from the Lawrence Berkeley National Laboratory for their technical and administrative support for this workshop.

Robert M. Wolcott
Acting Deputy Assistant Administrator
of Policy, Planning and Evaluation
US Environmental Protection Agency

Marco Antonio González,
Vice-Minister of Natural Office
Resources and Mines,
Government of Costa Rica

EDITORIAL

**Jayant Sathaye, Kenneth Andrasko,
Willy Makundi, Arturo Sanchez-Azofeifa and Beth Goldberg**

With the increased recognition of the potentially beneficial role of forests in climate change, there is growing interest in ensuring that forestry mitigation activities lead to carbon sequestration, or reduced emissions, that are sustainable over the long term. Traditional forestry has long required accounting of forest inventories, timber management plans, and harvest off-take for timber production in silvicultural systems, and of environmental benefits, such as reduced soil erosion. Climate change mitigation imposes new demands on existing institutions to monitor the associated carbon and other greenhouse gas (GHG) flows to ensure that these global benefits are sustained.

Forestry mitigation activities may be classified into three categories; (1) slowing deforestation and assisting regeneration, (2) forestation, including plantations and agroforestry, and (3) fossil fuel substitution. Implementation of these options requires many transactions, incurs administrative burdens, and requires policy changes or implementation that have slowed the introduction and penetration rate of earlier forestry projects. These barriers have raised concerns about the credibility of claims regarding the long-term sustainability of forestry projects. **Sathaye** and **Ravindranath** discuss the types of monitoring that are needed for each category of mitigation option.

The set of papers in this volume reflects two major scales of assessment: (1) project-level methods as described in the comprehensive review paper by **MacDicken**, and in papers by **Ravindranath** and **Bhat**, **De Jong** ***et al.***, and **Pinard** and **Putz**, and (2) top-down remote sensing of land cover change at national or regional scales, usually done using stratified sampling, such as that described in the paper by **Sanchez-Azofeifa, Skole** and **Chomentowsky**. The former include simple least-cost/least-precision methods, remote sensing, periodic carbon inventories, and traditional research methods. MacDicken suggests that carbon inventories are to be preferred since they are cost-effective, provide measurements with known levels of precision, and allow monitoring of other values such as biodiversity and commercial timber volumes.

The two types of methods can have very different applications. National or regional scale monitoring is important to determine the base-year inventory of forest stock, but it is also essential to check for leakage from a project (*i.e.*, the shifting of activities with GHG implications outside the project boundaries). Project-level methods, on the other hand, are important for assessing the carbon and other benefits of climate change projects, particularly those whose activities are being jointly implemented under the Activities Implemented Jointly (AIJ) pilot phase of the FCCC. During the pilot phase, participating countries are not exchanging credits for the carbon benefits of a project. However, a full-scale joint implementation program may require the transfer of GHG benefits from developing or transition countries to industrialized countries providing funding in return for credits. Adequate and verifiable monitoring of this exchange will be necessary to ensure that each government receives its fair share of the claimed benefit.

Forestry projects store carbon in soil, above- and below-ground vegetation, and wood products, whose fate is difficult to track and may cross national boundaries. This was one of the key topics of the discussions at the workshop. The working groups noted that the current Intergovernmental Panel on Climate Change (IPCC) methodology does not account for the movement of carbon in wood products across countries. As **Marland, Schlamadinger,** and **Canella** point out, it is not easy to track the fate of products across national boundaries, particularly if one is to track the amount and type of fossil fuel that would be displaced through their use. Tracking of fossil fuel displacement is important since the indirect carbon benefits from such substitution can be two or three times the direct benefits of carbon sequestration of a project.

The ecological and socio-economic benefits of forest management projects are likely to be the primary reason for many developers or governments to pursue them. Sustenance of joint or multiple benefits may become an essential feature of such projects. This raises an important issue as to what should be monitored in projects to sequester carbon or reduce emissions. Should the monitoring be confined to carbon flows, and perhaps other greenhouse gases, or should it be broader and cover ecological and socio-economic aspects critical to the sustainability of these projects? **Makundi** describes the efforts to create sustainable forestry projects, which requires adherence to criteria that include all these aspects. Providing a single definition of sustainability, however, has proven difficult, and each proponent appears to have a different notion depending on the discipline or group he/she represents. Makundi cites several examples of guidelines/protocols that have been developed for sustainable forestry. None of these appears to satisfy the demands of a protocol for forestry and climate change. One of the protocols has been set forth by the International Tropical Timber Organization (ITTO), which calls for a distinction to be made between certified timber that is harvested from forests/plantations, where sustainable practices are employed, and other types. **Van Soest** and **Jepma** explore the relationship between the timber certification market and climate change. They suggest that merely monitoring timber production at the micro- or project-scale is not sufficient to maintain tropical forests if no macro-conditions or guidelines are attached to the certification process to detect and avoid leakage. In a similar vein, **Fearnside** points to the fickleness of government policy in sustaining project benefits. Citing the example of Brazil, he argues that government policies ought to be the primary target for monitoring rather than project-specific activities.

Several papers provide excellent examples of specific methods that are being used to monitor carbon flows in forestry projects. In this regard, the paper by **Pinard** and **Putz** is particularly instructive. It describes the research approach to monitoring carbon sequestration benefits from reduced-impact logging in Malaysia, based on a project that is being financed by New England Electric Systems (NEES) and a consortium of US-based utility companies, Utilitree. **Ravindranath** and **Bhat** describe the approach they are using for monitoring a forestry project in the Western Ghat region in India. The paper points out that the costs of monitoring the project's performance, including carbon flows, are about 10% of the total costs of the project. Despite the small share of the cost, there is little documented evidence of monitoring efforts in forestry projects to date in India. **De Jong,**

Tipper and **Taylor** present a self-reporting system with on-the-spot checks for monitoring and evaluation of a widely dispersed, small plot farm forestry project in Chiapas, Mexico. The system is expected to be inexpensive, but more importantly, it will give farmers an understanding of the carbon service they will be providing.

To what extent can project-, stand-, or site-specific data be extrapolated to represent regional or national values for the amount of carbon stored in forests? This issue is pertinent to the climate change debate since each country is required by the FCCC to prepare an inventory of its GHG flows for a base year. To date, most countries have produced inventories for 1990. **Hamburg et al.** point out that their analysis of forest-stand-specific data on carbon storage for Russia yields allometric equations which provide reasonably accurate estimates of forest carbon, potentially allowing the use of allometric methods with known accuracies when local project data are scarce. **Greenough, Apps** and **Kurz's** evaluation of carbon inventory for Canada using seven alternative procedures yields results that make Canadian forests a substantial sink or a significant source of emissions, depending on the procedure used. The authors suggest that the IPCC procedure provides inadequate coverage by focusing only on emissions associated with human activities, and that the monitoring of natural fluxes, including forest fires, which vary considerably by region and year, particularly in the unmanaged areas of Canadian forests, is critical to providing a more accurate estimate of carbon flux from forests.

In summary, the workshop participants suggested that monitoring activities are routinely carried out by forestry-project implementers, and that including the monitoring of carbon flows is not by itself a difficult or expensive task. Well-known techniques for monitoring are available and have been used in production forestry. Having said this, the participants emphasized that there are many issues particular to climate change which need better resolution:

(1) The determination of project and national baselines and whether the project ones should be revisited on a regular basis after the start of the project;

(2) Who, the nation or the developer, should assume responsibility for carbon benefits over the long term, if a developer's abandonment of a project results in the stored carbon being emitted? Agreements between the developer and the national government, and among Parties to the FCCC are needed to resolve these issues;

(3) The establishment of adequate verification systems to ensure that carbon benefits are sustained; and

(4) The establishment of a protocol for monitoring and verification, which would ensure that the regional differences in regulatory, institutional, and other concerns are adequately addressed.

The following Workshop Summary Statement and the articles contained in this report provide a more detailed discussion of these issues.

INTERNATIONAL WORKSHOP ON SUSTAINABLE FORESTRY MANAGEMENT: MONITORING AND VERIFICATION OF GREENHOUSE GASES

SUMMARY STATEMENT

Edited by

Jayant Sathaye, Willy Makundi, and Beth Goldberg
Lawrence Berkeley National Laboratory, Berkeley, California, USA

Kenneth Andrasko
U.S. Initiative on Joint Implementation, Secretariat
U.S. Environmental Protection Agency, Washington, D.C., USA

Arturo Sanchez
University of Costa Rica, San Jose, Costa Rica

In addition to presenting their papers, workshop attendees shared experiences concerning the development and monitoring of regional and national forestry projects, through their participation in one of two working group sessions. The discussions focused on institutional, economic, methodological, and data availability problems. Group 1 concentrated on data collection and methods for monitoring and verifying GHG flows, while Group 2 discussed the key institutional issues associated with monitoring and verification. Within their focus areas, both groups addressed the questions of what should be monitored, how should monitoring and verification be done, and how can leakages be managed.

The main findings of the working groups were

1. Proven methods exist for the monitoring of GHG flows and carbon stocks in forestry. Monitoring programs can be designed to provide credibility to forestry carbon offset projects. The effectiveness, cost, and reliability of methods vary by type of project, scale, and the fluxes being monitored.
2. Monitoring should focus on all significant carbon pools or GHG fluxes that are vulnerable to significant change. This should apply to leakages and secondary benefits as well.
3. All forestry sector GHG mitigation projects must ensure that they meet accepted standards for sustainable forest management.
4. As a mitigation option, forest sector activities serve primarily to delay the release of carbon stocks to the atmosphere. Wood harvested from sustainable forests, when used to substitute for fossil fuels and fuel-intensive products, may significantly multiply carbon benefits.
5. Project developers expect carbon credits for limited duration forestry projects, in which the fate of carbon after the project is over is unknown. This expectation conflicts with the need to maintain carbon stock in perpetuity.

Resolution of the conflict is an important challenge for project participants, national governments, and the international community.

6. A without-project baseline (reference case) must be established for estimating future C benefits from a project. Due to the long duration of forestry projects (in comparison to most energy and other projects), the estimated baseline may be amenable to periodic revision on the basis of new data and information monitored from control plots or gathered from other sources.
7. Monitoring is the primary responsibility of the project implementers, and should satisfy appropriate professional standards. Verification should be carried out by external third-party auditors.

The working group summary statements provide additional detail on these and other issues that were discussed at the workshop.

GROUP 1 — DATA AND METHODS*

The discussion of Working Group 1 focused on data collection and monitoring and verification methods for mitigating greenhouse gas emissions through individual and national forestry projects and policies.

INDIVIDUAL PROJECT-LEVEL MONITORING AND VERIFICATION PROGRAMS

Monitoring programs should be designed to measure all significant carbon flows associated with a project. A verification program should be aimed at evaluating the accuracy and reliability of the monitoring program. Project participants should decide who will monitor, what will be monitored, and how the flows will be monitored based on their best understanding of the implications of the project and appropriate professional standards; verification should be done by professionals that are independent of the project.

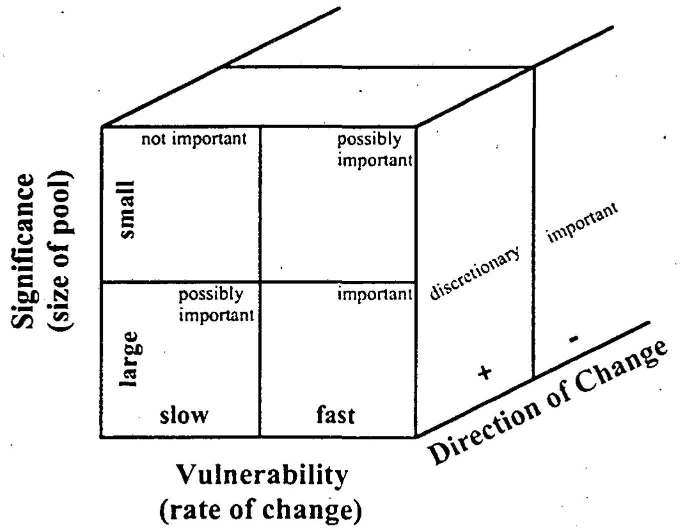
To ensure that forestry projects used for GHG mitigation are of high quality and are effective at sequestering carbon, guidelines are needed that provide structure and direction to project developers. These guidelines need to be flexible so that they are broadly applicable and do not discourage innovative approaches.

* Co-chairs for Working Group I are Steve Hamburg, *Brown University, Providence, Rhode Island, United States;* Michelle Pinard, *University of Aberdeen, Aberdeen, United Kingdom.* Participants included Mike Apps, *Forestry Canada, Northern Forestry Center, Edmonton, Alberta, Canada;* Xavier Baulies, *Cartographic Institute of Catalonia, Barcelona, Spain;* Salvadurai Dayanandan, *University of Massachusetts, Boston, Massachusetts, United States;* Arturo Sanchez, *Central American Project on Climate Change, San Jose, Costa Rica;* Ben De Jong, *ECOSUR, San Cristobal, Mexico;* David Skole, *University of New Hampshire, IGBP-LUCC, United States;* Philip Fearnside, *Institute for Research in the Amazon, Manaus, Brazil;* Willie Makundi, *Lawrence Berkeley National Laboratory, Berkeley, California, USA.*

WHAT SHOULD BE MONITORED?

All significant carbon pools that are vulnerable to significant change should be monitored. A three-dimensional matrix illustrates a procedure for ranking carbon pools according to their significance (size of pool), vulnerability (rate of change), and direction of change (Figure 1). Changes that are directly related to project activities should be the focus of monitoring efforts, but changes in all potentially important carbon pools need to be evaluated. For example, a pool that is relatively small and unlikely to change would not be important to monitor. Alternately, a pool that is relatively large and likely to change would be important to monitor. For potentially important pools (i.e., large pools that change slowly or small pools that change quickly), the direction of the change should be determined. If the change is expected to be positive, the project should not be required to monitor the pool. However, if the change is expected to be negative, the pool should be monitored. Only pools that are monitored can be included in any claim for carbon credits. All decisions about what pools to monitor should be conservative. If there is any doubt about the direction of change of a pool it needs to be monitored. The scientific literature provides good evidence for the direction of change associated with many pools and project types, but not all. If reliable data are not available the pool needs to be monitored.

Figure 1. A matrix for identifying the carbon pools that are important to monitor in forestry projects developed to mitigate climate change. Pools that are important to monitor, or not important to monitor, can be identified based on their significance (size of pool) and vulnerability (rate of change). Pools that are possibly important to monitor, based on significance and vulnerability, can be further evaluated based on the anticipated direction of change in the carbon pool. If, based on credible evidence, the pool is expected to gain carbon over time (+), monitoring is discretionary. If the pool is expected to lose carbon over time (-), monitoring is important.



The carbon pools listed in Table 1 represent those pools most likely to be affected by a forestry project. Forestry projects that involve a harvest of products should evaluate the fate of the carbon in the products for its potential influence on the overall carbon balance of the project. Furthermore, for projects that include use of biomass burning as an energy source, there needs to be a complete energy balance for the project, to ensure that any crediting for fossil fuel displacement is valid. The calculations need to be made during the development phase of a project. In any given project, only a subset of the pools listed may require monitoring (based on scheme outlined above, Figure 1). However, during project proposal development, every project should consider all of the pools and present a justification for their proposed monitoring program that includes an evaluation of each of the pools.

Table 1. Carbon pools to be evaluated for their significance (i.e., pool size) and vulnerability (i.e., rate of change) in relation to proposed forestry projects.

Phytomass: above- and below-ground biomass
Necromass: woody debris, standing dead trees, litter
Soil carbon: organic, mineral
Forest products: timber and/or non-timber products
Energy: particularly if biomass burning is part of the proposed project

HOW SHOULD THE POOLS BE MONITORED?

Monitoring protocols should be set at the professional standards that are appropriate for the region. Decisions about appropriate methodology should be based on the relative importance of the individual pools (i.e., their significance, vulnerability to change, and direction of change). The intensity of the monitoring should relate to a scale appropriate for the project, appropriate both in time and space, with consideration of the rate of change in important carbon pools. Therefore, for any given project, not all variables would be measured at the same level of precision, nor on the same temporal scale. Financial investment in monitoring will generally reflect the relative importance of the pools.

LEAKAGE

Leakage or secondary effects that influence the project's overall carbon balance should be addressed at the project level. Some leakage issues, however, are beyond the scope of any individual project. For example, complex social issues may be addressed at the national level. Definition of project boundaries is important for determining which carbon fluxes are the responsibility of the project and which fall outside the project.

Individual forestry projects need to be set in the national context. The linkage between projects and national reporting is essential, not only for addressing leakage issues but also for evaluating the relative importance of individual projects and, in some cases in defining the project baseline. By referencing individual projects to the national carbon balance, perspective may be gained for evaluating the credibility of individual projects.

COUNTRY-LEVEL MONITORING AND VERIFICATION PROGRAMS

The discussion of data collection and monitoring and verification methods appropriate for national programs identified the following components of any program: area stratification, area change, stocks of carbon, and changes in stocks over time. Accuracy assessment was identified as important but was not discussed due to lack of time.

Area stratification provides the baseline condition or land-use classification. For establishing the baseline, the data may be geo-referenced or aggregated. It was recognized that the availability of data is highly variable across the globe, as is the reliability of these data.

Area change refers to an area per unit time that is changing either in its classification or changing within its class in terms of carbon stocks. Again, the data available for establishing area change may be static or geo-referenced. Land-use classes or types of disturbance that are potentially important are agricultural land (considering crop types and intensity), forestry lands (by type of activity and intensity), natural disturbances (e.g., fire, blowdowns, floods), afforestation and reclamation of degraded lands, and urbanization (permanent loss of biotic cover). Because transitions between land-use classes or categories are not necessarily equivalent, in terms of changes in carbon stocks, the monitoring of area change requires not only total area changing but also the rate of change between different categories.

Types of data available for indicating cover or area change include remote sensing with high resolution data, archival data, and fire detection data. Remote-sensing data (e.g., LANDSAT and SPOT) may be useful for estimates of deforestation rates. Limitations of remote sensing data include: (1) the quality of the data varies spatially (e.g., cloud cover in the tropics); (2) although these data may be useful for identifying general land-use classes, the subclassifications within the general need to be verified regionally, and often cannot be differentiated; and, (3) the variation within land use classes or categories may be as great or greater than among classes. Archival data may be useful for estimating change in agricultural or forest cover but often these data are inaccurate and are not standardized. Also, some countries have access to remote sensing data specifically developed for detecting fires.

Stocks of carbon that are significant to monitor should be evaluated on a hierarchical scheme as was considered appropriate at the project level. The pools that may be relevant to monitor may be the same as were identified in Table 1. Forestry inventory data, country studies sponsored by the EPA, and data sets compiled by the FAO, are potentially useful for estimating biomass. For agricultural areas, some universal data are available for biomass. For non-tree crops, soil carbon may be the most significant pool. Several soil pedon data sets are currently available and potentially useful (e.g., ISRIC, USDA, FAO, ZINKE). Because land-use change may influence soil-bulk density, a standard mass, rather than a standard depth, may be preferable for estimates of soil carbon.

Within land-use classes or categories, estimates are needed of changes in carbon stocks over time (e.g., carbon sequestration rates in secondary forests). Measuring change as an increment may be preferable to measuring change as the difference between estimates of stores at two points in time. The advantage of using increments would be more apparent when large errors are associated with the estimates of stocks.

Methodologies for estimating land- use change and associated changes in carbon stores over time are not yet well-integrated. National assessments are dependent on temporal data. Technologies for collecting the data vary over time and the utility of any particular methodology varies regionally. Because the available data sets for countries will range from very good to extremely poor, it was suggested that if minimum data requirements could be established, individual countries whose existing data sets fall below the minimum requirement may be assisted by GEF money in order to raise their standard to the minimum

GROUP 2 — INSTITUTIONAL ISSUES*

GENERAL OBSERVATIONS

Considerable skepticism surrounds AIJ-forestry projects. Some fear these projects may harm the interests of local populations, while others suspect they may be based on non-sustainable forest-management practices, or that the causes of emissions (e.g., due to deforestation) are shifted rather than reduced. These fears reinforce the need for a monitoring and verification system that addresses these concerns.

Until now, reporting on AIJ pilot projects has shown that the monitoring process still needs improvement beyond developing a common format of reporting. Such an improvement is required before the system can be considered ready for a full-blown crediting regime.

Given the desire to keep AIJ project transaction costs under control, however, the impression emerges that the methods needed for baseline determination and monitoring have been largely developed in order to (if properly combined) allow for an acceptable monitoring process. This is not withstanding the fact that the

* Chair for Working Group 2 is Catrinus Jepma, *Department of General Economics, University of Groningen Groningen, The Netherlands*. Participants included Jayant Sathaye, *Lawrence Berkeley National Laboratory, Berkeley, California, United States;* Daan Van Soest, *Department of General Economics, University of Groningen, Groningen, The Netherlands;* Gregg Marland, *Oak Ridge National Laboratory, Oak Ridge, Tennessee, United States;* Noel Cutright, *Wisconsin Electric, United States;* Ken MacDicken, *Winrock International, Snohomish, Washington, United States;* Tom Sullivan, *New England Power Service, United States;* Lisa Carter, *Climate Policy And Programs Division, USEPA;* K.D. Singh, *United Nations Food and Agriculture Organization;* Mariclos Alfaro, *FUNDECOR, San Jose, Costa Rica,* Steve Petricone and Franz Tattenbach, *OCIC, San Jose, Costa Rica*

methodologies will undoubtedly continue to improve as the establishment of the AIJ regime progresses.

WHAT SHOULD BE MONITORED?

Monitoring requirements will depend on the type of forestry project. If the project is based on a nationwide sustainable forest-management program aimed at slowing the overall deforestation/forest degradation process — rather than a small and overseeable forestry project — a much wider assessment framework, based on sectoral and even multi-sectoral analysis, will be required.

Monitoring should take into account the direct carbon changes in the above- and below-ground vegetation, soil, and litter, according to standardized assessment procedures. Monitoring should also address the project's implications with regard to other GHGs. In all cases, leakages have to be taken into account, both in designing the baseline and in the subsequent monitoring activities, to determine the complete carbon impact of the project.

Leakages can be either negative (e.g., encroachment shifting to an area outside the project area) or positive (e.g., employment created for people outside the project area, who otherwise would have destroyed the forest). If the AIJ project has a regional or even a national scope, leakages should be taken into account during the planning phase and incorporated in the baseline and mitigation scenarios, if possible. If such leakages were unforeseen and are significant, they should be considered within the project evaluation and revision mechanism.

Monitoring should be periodic during the lifetime of a project. The monitoring process should include not only direct measurements, but also check that the agreed upon procedures are properly followed.

In the case of broad or even nationwide AIJ programs, monitoring should focus on the overall impact of the program. In such cases, clear rules with regard to monitoring cannot be specified beforehand, but should be worked out on a case-by-case basis.

There is a need to integrate nationwide forest resources-monitoring techniques with those for national forest products inventories so that sources and sinks can be related on a reliable basis. Past experience indicates that the two types of accounting (viz., resources and products) often cannot be balanced.

If the AIJ project involves forest exploitation such as harvesting of timber, the assignment of credit or responsibility for the carbon in products remains complex. The group suggests that the carbon in products should be handled in a manner that is consistent with how the IPCC addresses forest products in the national inventories methodology.

HOW TO MONITOR?

The number of credits attached annually to the carbon performance of a project for a given year depends on (a) the specification of the baseline preceding the project, and (b) the actual project performance.

Similar methodologies should be used to develop baselines for similar types of projects.

For instance, the projection of the deforestation rate without the project should employ a similar method across similar projects. Many of the relevant methodologies have already been applied in the various pilot projects, but consensus is needed regarding how advanced the required methodology should be. In deciding on this, a proper balance has to be found between scientifically sound and relatively cost-effective methods.

If investor and host have agreed upon the project baseline, and it has been formally approved via the project approval procedure, the parties should be confident that the baseline, and particularly the baseline's fundamental assumptions, cannot easily be altered. A lack of such confidence might hamper investment. Therefore a procedure needs to be designed which describes exactly how often (for example, every 10 years) and through what process, one can conclude that the project baseline needs adjustment. How often the baseline is reviewed for adjustment might depend on the type and lifetime of the project. An adjustment can be either increase or decrease the amount of credits vis-à-vis the earlier stage.

The baseline will be established in the year of the investment decision. If a project is expanded after several years, the new element of the project will be based on an updated baseline projection.

If the monitoring process shows that the project is performing below expectations, there will be correspondingly fewer credits, even if the under-performance was the result of factors beyond the parties' control. In the latter case it is up to the parties involved to determine how they take measures to carry and distribute the risks. If the project performance is less than the baseline, credits need to be reimbursed.

THE ASSESSMENT OF LEAKAGES

Leakage assessment is crucial to any credible baseline establishment and monitoring/verification system. Without involving leakages AIJ may well be criticized as creating biased outcomes. The measurement of leakages will, for instance, need to involve the analysis of economic and mobility characteristics of people living in and around the project area.

DURATION OF THE FORESTRY PROJECTS

Most forestry projects have a relatively long duration. However, since credits are, in principle, disbursed annually because they compensate for annual carbon storage services, discounting is not really an issue. As time proceeds, the monetary value of credits may change depending on the changes in the market conditions.

As soon as the project has been finalized, the investor is no longer responsible for what happens with the former project's forests. For instance, if the host country destroys the forest shortly after the project's end, the investor cannot formally be held responsible if it no longer has any GHG emission-reduction obligations (although special "opt-in conditions" for non-Annex I countries may be established by the UNFCCC as a prerequisite for AIJ participation). In order to evaluate the extent to which countries behave responsibly with respect to their forest resources, national forest management reports should be developed for all countries that wish to participate in the AIJ pilot phase . These reports may, over time, have policy implications in the UNFCCC context. It is also likely that the parties may have a contractual agreement relating to the fate of the biomass with regard to reconstitution as a new AIJ project, etc.

Investors can start AIJ projects in any host country with which they can reach an agreement, regardless of whether the host country carries out a sustainable forest management policy. However, AIJ projects can only be carried out if the project's execution does not conflict with the principles of sustainable forest management. In other words, an AIJ project should not significantly contravene accepted principles of sustainable forest management relevant to the type of project. It should be the responsibility of host and investor to agree on this conformity except where a blatant disregard of good resource stewardship is evident by other interested parties. In such cases, the FCCC Secretariat may have a say on the viability of the venture as an AIJ-project.

Monitoring and verification

It is yet to be determined if and how the AIJ monitoring process of sustainability aspects can be harmonized with timber certification monitoring which is conducted according to the ITTO criteria for sustainable timber management.

It is up to the parties involved in a particular AIJ project to determine if they want to share credits and, if so, how.

Baseline negotiations, the proposed evaluation of the annual credits, and the monitoring of project performance can be carried out by a monitoring team attached to a particular project and consisting of host and investor countries' representatives with proven reputation. A neutral party may also be included if desired.

Project reports should be sent to both the host and investor governments for review and compilation before information on AIJ is submitted to the FCCC Secretariat, according to the official guidelines of the AIJ-pilot phase.

An independent international verification team should collect and evaluate the national reports on behalf of the FCCC Secretariat and give final approval. (When an AIJ project takes place between two Annex I countries, verification may, under some circumstances, not be needed at the project level. It might focus only on verifying the adjustment of national inventories to reflect GHG reduced as a result of AIJ.) In the case of projects between Annex I and non-Annex I parties, verification should review baseline assessments, monitoring procedures and credits attached to the projects. The frequency and extent of this verification will depend on the project characteristics, such as the age of the project.

To increase the confidence in the verifying process, the FCCC may have to set up a sound verification procedure and have the verifiers that are well trained for this type of work. This will reduce the need and the cost of frequent verification. These verifiers may be chosen by project participants, national governments or the FCCC secretariat from a list of private firms pre-approved by the FCCC Secretariat for AIJ verification work.

A feedback mechanism between monitoring, verification and the Secretariat (certification) should be established so as to increase the proficiency and cost effectiveness of credit certification. Capacity building for internal monitoring may be imbedded in the project or in the mitigation policy in case of a wider AIJ program.

POLICIES, MEASURES AND THE MONITORING NEEDS OF FOREST SECTOR CARBON MITIGATION

JAYANT SATHAYE
Lawrence Berkeley National Laboratory
1 Cyclotron Road, Berkeley, California, USA

N.H. RAVINDRANATH
Centre for Ecological Sciences
Indian Institute of Science
Bangalore 12, India

Abstract. Forest sector mitigation options can be grouped into three categories: (1) management for carbon (C) conservation, (2) management for C storage, and (3) management for C substitution. The paper provides background information on the technical potential for C conservation and sequestration worldwide and the average costs of achieving it. It reviews policy measures that have been successfully applied at regional and project levels toward the reduction of atmospheric greenhouse gases. It also describes both national programs and jointly implemented international activities. The monitoring methods, and the items to monitor, differ across these categories. Remote sensing is a good approach for the monitoring of C conservation, but not for C substitution, which requires estimation of the fossil fuels that would be displaced and the continued monitoring of electricity generation sources. C storage, on the other hand, includes C in products which may be traded internationally. Their monitoring will require that bi- or multi-lateral protocols be set up for this purpose.

Key words: Carbon dioxide, costs, forests, Joint Implementation, mitigation, monitoring, policies

1. Introduction

Forests constitute both a sink and source of atmospheric CO_2. Forests absorb carbon through photosynthesis but emit carbon because of the burning of trees due to anthropogenic and natural causes and through respiration and decomposition. Managing forests and forest products to retain and increase their stored carbon, and to use wood products as a fossil-fuel substitute, will help to reduce the increase in atmospheric CO_2 and stabilize climate change. The monitoring of the flows of greenhouse gases (GHGs) and stocks of carbon is an important issue that deserves increasing attention as the Framework Convention on Climate Change (FCCC) evolves into a protocol for reducing GHGs across nations. In this paper, we report on the national forest policies and measures, and international projects and programs, that may be successfully pursued to reduce net GHG emissions and the issues surrounding their monitoring and verification.

Forests currently cover about 3.4 Gha (Gha = 109 ha) (FAO, 1995). Fifty-two percent of the forests are in the low latitudes (approximately 0-25 N and S latitude), followed by 30% in the high latitudes (approximately 50-75 N and S latitude) and 18% in the mid latitudes (approximately 25-50 N and S latitude). The world's forests store large quantities of carbon, with an estimated 340 Pg C (1 Pg = 10^{15} g = 1 Gigatonne) in vegetation, live and dead above- and below-ground, and 620 Pg C in soil, mineral soil plus O horizon. An unknown quantity of C is also stored in wood products, buildings, furniture, paper, etc. Mid- and high-latitude forests are currently estimated to be a net C sink of about 0.7 ± 0.2 Pg C/yr. Low-latitude forests are estimated to be a net C source of 1.6 ± 0.4 Pg C/yr (Brown, Sathaye, Cannell and Kauppi, 1996) caused mostly by clearing and degradation of forests. These estimates may be compared with the C release from fossil fuel combustion, which is estimated at 5.5 ± 0.2 Pg C/yr for a comparable period, and is now past 6.0 Pg C/yr.

2. Technical Potential and Cost of Carbon Mitigation

Forest management practices that can restrain the rate of increase in atmospheric CO_2 can be grouped into three categories: (1) management for C conservation, (2) management for C storage, and (3) management for C substitution. *Conservation* measures include options such as controlling deforestation, protecting forests in reserves, changing harvesting regimes, and controlling other anthropogenic disturbances, such as fire and pest outbreaks. *Storage* measures include expanding forest ecosystems by increasing the area, and/or biomass and soil C density, of natural and plantation forests and increasing storage in durable wood products. *Substitution* measures aim at increasing the transfer of forest biomass C into products rather than using fossil-fuel-based energy and products, cement-based products, and other non-wood building materials.

Monitoring and verification requirements are quite different for each type of option. Conservation measures will require the monitoring of a designated area under threat of deforestation within a country, where leakage is likely to be of big concern. Storage measures, on the other hand, may involve the export of products across countries. Monitoring of carbon stored in these will be difficult, and no procedure exists at the moment for monitoring carbon stock in products that span international boundaries and might last over decades. Substitution measures require that the quantity of displaced fossil fuel be estimated. This estimation is similar to that encountered in energy efficiency and renewable energy projects that displace fossil fuel. Estimation and monitoring methods for these can range from simple to very complex and expensive ones.

The potential land area available for the implementation of forest management options for C conservation and sequestration is a function of the technical suitability of the land to grow trees and the actual availability as constrained by socioeconomic circumstances. Globally 700 M ha of land might be available for C conservation and sequestration, 345 M ha for plantations and production forestry, 138 M ha for slowed tropical deforestation, and 217 M ha for natural and assisted regeneration (Nilsson and Schopfhauser, 1995 and Trexler and Haugen, 1995). Table 1 provides an estimate of global potential to conserve and sequester carbon based on the above studies. The tropics (0-25 degree N and S latitudes) have the potential to conserve and sequester by far the largest quantity of C (80%), followed by the temperate zone (25-50 degrees N and S latitudes) (17%) and the boreal zone (3%) only. Natural and assisted regeneration and slowing deforestation account for more than half the tropical amount. Forestation and agroforestry contribute less than half of the tropical total sink, but without them regeneration and slowing deforestation would be highly unlikely (Trexler and Haugen, 1995).

Scenarios show that annual rates of C conservation and sequestration from all the aforementioned practices increase over time. Carbon savings from slowed deforestation and regeneration initially are the highest, but from 2020 onwards, when plantations reach their maximum C accretion, they would sequester practically identical amounts as slowed deforestation and regeneration (Figure 1). On a global scale, forests turn from a global source to a sink by about 2010 as tropical deforestation is offset by C conserved and sequestered in all zones.

Using the mean establishment or first costs for individual options by latitudinal region (Brown, Sathaye, Cannell and Kauppi, *et al.* 1996), the cumulative cost (undiscounted) for conserving and sequestering the quantity of C shown in Table 1 for the same scenario, ranges from $250 billion to $300 billion at an average unit cost ranging from $3.7 to $4.6 per Mg C. Average unit cost decreases with more C conserved by slowing deforestation and regeneration as these are the lowest cost options. At an annual discount rate of 3%, these costs fall to $77-99 billion and the average unit cost to $1.2-1.4 per Mg C. Land costs, the costs of establishing infrastructure, protective fencing, education, and training tend to be excluded and are not included in these cost estimates.

While the uncertainty in the estimates is likely to be high, the trends across options and latitudes appear to be sound. The factors causing uncertainty are the estimated land availability for forestation projects and regeneration programs, the rate at which tropical deforestation can be actually reduced and the amount of C that can be conserved and sequestered in tropical forests. In summary, policies aimed at promoting all the mitigation measures in the tropical zone are likely to have the largest payoff, given the significant potential for C conservation and sequestration in tropical forests. Those aimed at forestation in the temperate zone will also be important.

Table 1 does not include the costs of monitoring and verification for each type of option. Costs for monitoring of forestation projects have been estimated to be of the order of 10% (Ravindranath and Bhat, 1997 in this issue), which would amount to about US $28 billion. Monitoring the policies and measures to slow deforestation is more complex in that it may require the implementation of region-wide policies with both monetary and other costs associated with it. Fearnside (1997) for instance discusses that both carbon stock/flow and policies need to be monitored in order to ensure that appropriate policies are sustained over long time periods.

3. Policies, Programs, and Projects for Managing Forests for C Conservation and Sequestration

Forest management measures with the largest potential for C conservation and sequestration range (in declining order of importance) range from slowing deforestation and assisting regeneration in the tropics to forestation schemes and agroforestry in tropical and temperate zones (Table 2). To the extent the forestation schemes yield wood which can substitute for fossil-fuel-based material and energy, their C benefit will be multiplied. We examine the policies measures relevant to the implementation of each type of measure below.

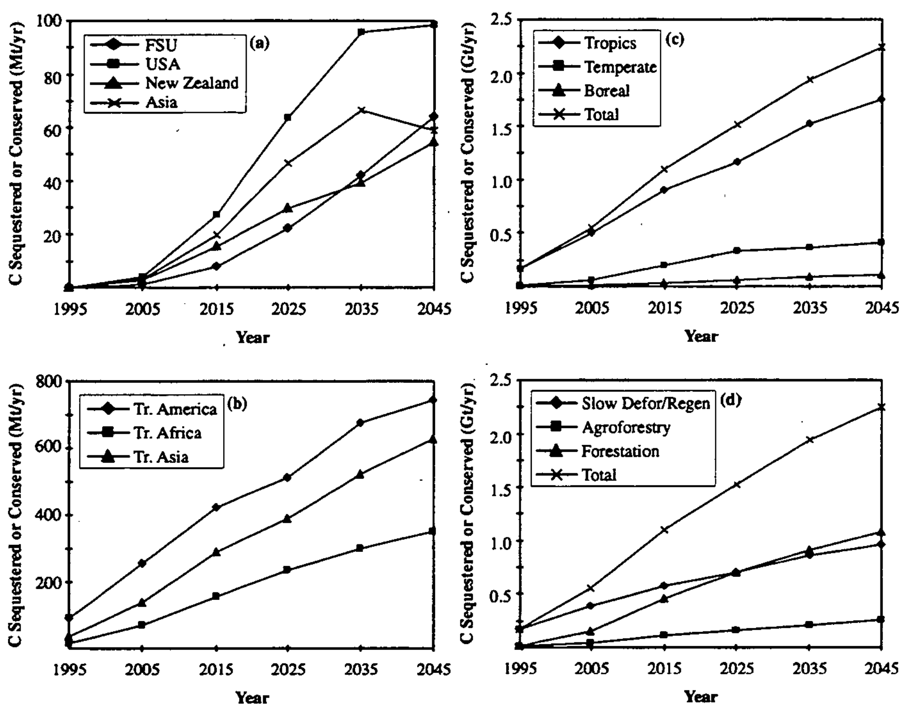


Figure 1. Average annual rates of carbon conservation and sequestration

Table 1. Global C that could be sequestered and conserved and related costs between 1995-2050

(1) Latitudinal Zone	(2) Measure	(3) C sequestered or conserved* (Pg)	(4) Cost+ (US $/Mg C)	(5) Total cost (10^9 US$)++
High	Forestation	2.4	8 (3-27)	17
Mid	Forestation	11.8	6 (1-29)	60
	Agroforestry	0.7	5	3
Low	Forestation	16.4	7 (3-26)	97
	Agroforestry	6.3	5 (2-12)	27
	Regeneration	11.5 - 28.7	2 (1-2)	
	Slowing deforestation	10.8 - 20.8	2 (0.5-15)	44-97**
	Total	60 - 87	3.7-4.6	250-300

Notes:
* Includes above- and below-ground vegetation, soil and litter C.
\+ Establishment or first cost (undiscounted). Average of estimates reported in the literature. Most estimates do not include land, infrastructure, protective fencing, education, and training costs. Figures in parenthesis indicate the range of cost estimates.
++ Cost figures in Col. 4 are per tonne of vegetation carbon. Total costs (Col. 5) are thus lower than the figure obtained by multiplying t C in column 3 by $/t C in column 4.
** For slowing deforestation and regeneration combined.
Source: Brown, Sathaye, Cannell and Kauppi (1996)

3.1 SLOWING DEFORESTATION AND ASSISTING REGENERATION

The causes of deforestation range from clearing of forest land for agriculture, mineral extraction, and hydro-reservoirs to degradation of forests for fuel wood. Land cleared for agriculture may eventually lose its fertility and become suitable only as range land. Various socioeconomic and political pressures, often brought about by the needs of rising marginal populations living at subsistence levels is a principle factor causing deforestation in the tropics.

Both forest-related and indirect, non-forest, policies have contributed to deforestation. These include short-duration contracts that specify annually harvested amounts and poor harvesting methods which encourage contractors to log without considering the concession's sustainability and also a royalty structure that provides the government with too little revenue to permit adequate reforestation in order to arrest forest degradation after harvesting (Gillis and Repetto, 1988). Non-forest policies, which lead to direct physical intrusion of natural forests, are a prime cause of deforestation. These may include land tenure policies that assign property rights over forest lands to private individuals, settlement programs for farmers living in marginal areas, investments promoting dams and mining, and tax credits or deductions for cattle ranching.

Table 2 shows the policies, programs and projects (PPP) whose successful implementation would slow deforestation and assist regeneration of biomass. Each of these will conserve biomass, which is likely to have a high C density, and will maintain or improve the current biodiversity, soil and watershed benefits. The capital costs of these PPP are low, except in the case of recycled wood, where the capital cost depends on the product being recycled. The first two policies are likely to reduce sectoral (agricultural) employment as deforestation is curtailed. The elimination of subsidies, however, may create jobs elsewhere in the economy to offset this loss. Sustainable forest management has the potential to create economic activity and employment on a sustained basis. The implementation of a forest conservation legislation requires strong political support and may incur a high administrative burden. Removing subsidies may run into strong opposition from vested interests. Jointly implemented projects are slow to take off as the perceived transaction costs are high and financing is difficult to obtain where C sequestration is the main benefit. While sustainable forest management is politically attractive, its implementation requires local participation, the establishment of land tenure

Table 2. Policies, programs and projects to slow deforestation and assist regeneration

	Environmental Results		Socio-economic Effects		
Policies, programs and projects	GHG Reduction	Other environmental considerations	Costs	Benefits	Institutional, Administrative and Political Challenges
Enact forest conservation legislation (including bans on logging)	Maintain C density, up to 300 Mg C/ha	Maintain biodiversity, soil conservation and watershed benefits.	- Low capital cost, high opportunity cost - Loss of agricultural and forestry jobs	- Potential for equitable benefits depends on implementation approach	- High enforcement burden - Requires strong political support
Eliminate subsidies for activities which encourage deforestation (cattle ranching, mining, agriculture, etc.)	As above	As above	- Loss of sectoral jobs	- Reduces government expenditure	- Low administrative costs - Strong opposition from vested interests
Jointly implement projects with bilateral and multilateral funding	As above - Potential for C trades	As above	- Concern regarding loss of sovereignty on land ownership	- Increased foreign investment - Increased technology transfer	- Higher transaction costs - Lack of access to appropriate financing - Monitoring and verification uncertainty
Promote sustainable forest management, which will require: - local commitment and participation - better defined tenure rights and improved forest management - explicit consideration of equity issues - development of institutional mechanisms to value scarcity	As above	As above	Higher operating costs beyond routine forest management	- Sustained job creation - Monetary benefits from product sales may outweigh costs	- Moderately higher administrative burden - Enforcing regulations may be difficult although politically desirable. - Global initiatives such as ITTO can strengthen this approach
Fuel wood conservation and substitution - Improved stoves - Charcoal kilns	- GHG potential as above. - Potential to reduce non-sustainably extracted share of 1.27 billion cubic meters of fuel woo	As above	Higher cost of efficient stoves	- Creates sustained rural employment - Reduces women's drudgery and improves health - Reduces time and cost of gathering fuel wood	-- Commercially feasible. -- Politically acceptable. -- High potential for replication - Need to overcome cultural barriers -- May require the establishment of formal markets for stoves
Promote recycling and more efficient use of wood products	As above	As above - Recycling may require disposal of contaminants from treated wood products	- Cost of recycling and more efficient use is product specific.	- Monetary benefit from more productive use of wood	- High replicability - Some administrative costs - Politically attractive

and rights, addressing equity issues, and the development of institutional mechanisms to value scarcity; all of which may incur higher administrative costs.

Monitoring of these measures to slow deforestation can be done either at a site or a regional level. Regional level monitoring has the advantage of being able to detect leakages from one deforested site to another potential one. Leakage may occur as deforesters move to other sites to pursue farming or other goals. Remote sensing can be expensive since it requires the analysis of satellite images over time accompanied by ground-truthing. Although the cost of satellite images is beginning to decline, some appropriate sampling technique, geographically stratified one for example, is necessary to reduce the required time and effort.

Although reducing deforestation rates in the tropics may appear to be difficult, the potential for significant reduction is high (Trexler and Haugen, 1995), and India is an example where the government has adopted explicit policies to halt further deforestation.

Since 1980, the Indian government has pursued a series of policies and programs that have stabilized its forested area at about 64 M ha (Ravindranath and Hall, 1995), and, as a consequence, forests are estimated to have sequestered 5 Tg C in 1990 (Makundi, Sathaye and Cerrutti, 1992). Prior to 1980, the government had a priority to increase food production by increasing area under food grains and to distribute land to landless poor. This had resulted in significant deforestation during the period 1950 to 1975, when about 4.3 M ha were converted largely to agriculture (FSI 1988). The Indian policies and programs to slow deforestation and assist regeneration include:

Policies:

(i) Forest Conservation Act 1980: the powerful legislation has made it very difficult to convert forest land to other uses.

(ii) Ban on logging on state-owned primary forests in many states since mid 1980s.

(iii) Significant reduction in concessions to forest-wood-based industry and promotion of shift to farmland for wood raw material.

Programs:

(i) Conversion of 15 M ha of forests to protected areas (national parks and wildlife sanctuaries).

(ii) Joint Forest Management (Society for Promotion of Wastelands Development 1993) program where degraded forest lands are revegetated jointly by the local communities and forest department.

These policies have survived for nearly 15 years, despite a growing population and increasing demand for biomass. The Indian government appears to have successfully relied on conservation legislation, reforestation programs, and community awareness to achieve forest conservation.

The India example illustrates national programs and policies, which were initiated for protecting or halting degradation of forested areas. In addition, protection projects supported by foreign governments, NGOs, and private companies are beginning to play a role in arresting deforestation and conserving and/or sequestering C. The Rio Bravo Preservation and Forest Management project in Belize, which has been approved under the US Initiative on Joint Implementation (US IJI), will purchase a 6000 ha parcel of endangered forest land to protect two adjacent tracks from conversion to farmland, and is estimated to sequester 3 Tg C (US IJI, 1996). The project participants include Wisconsin Electric Power Company, The Nature Conservancy, Programme for Belize, Detroit Edison Company, Citienergy and PacfiCorp. The ECOLAND project will preserve tropical forest through purchase of 2000-3000 ha in the Esquinas National Park, which is under threat of deforestation in southwestern Costa Rica (REF). The project partners include US, Costa Rican, and Austrian institutions.

The above examples illustrate policies, programs, and projects that are being implemented to slow deforestation; sustaining these will pose many challenges. In India, the declining rural population growth rates have helped policy makers sustain the slowed deforestation, Elsewhere, however, the fundamental challenge will be to continue to find alternative livelihood for dwellers, such as in Thailand, and/or deforesters, such as in Brazil, which may require integrating dwellers into the urban social fabric of a nation. Deforesters may be drawn to the forest for reasons other than land cultivation, and policy makers need to resort to largely non-forest policies in such situations. Another challenge in the protection of forests and national parks is to increase the government budget allocated for this purpose which are often inadequate to provide for enough forest rangers, fencing, and other infrastructure to halt land encroachment.

3.2 FORESTATION

Forestation means increasing the amount of C stored in vegetation (living above- and below-ground), dead organic matter, and in medium- and long-term wood products. This process consists of reforestation that is replanting trees in areas which were recently deforested, and afforestation, which implies planting trees on areas which have been without forest cover for a long time. In temperate regions, reforestation rates tend to be high: Canadian reforestation during the 1980s was reported to be 720,000 ha/yr (Winjum *et al.*, 1992) and that for the U.S. has averaged 1 M ha/yr between 1990-1995 (Moulton *et al.*, 1996). There is a significant afforestation effort in both tropical and temperate countries. China alone boasts of having planted 30.66 M ha between 1949 and 1990 (Xu, 1995), while India had 17.1 M ha planted by 1989 (Ravindranath, 1992). The U.S. had 5 M ha of forest plantations by 1985 (Winjum, *et al.*, 1992), while France has more than doubled the forest area since the beginning of last century from 7 Mha to 15 Mha.

The policies, programs and projects for forestation and agroforestry include (1) government investment programs targeted towards these measures on government-owned land, (2) community forestry programs that may be supported by government extension services, and (3) private plantations with subsidies provided by the government (Table 3). These PPP may be targeted towards production forests, agroforestry, and conservation forests. The management of conservation forests for soil erosion, water catchment, and like purposes ensures a high C density for forests that have many non-C benefits. Those managed primarily for C sequestration would have to be located on lands with low opportunity costs or else they would likely be encroached upon for other uses. Government subsidies may take the form of taxation arrangements that do not discriminate against forestry or those that provide easy access to bank financing at lower-than-market interest rates.

Monitoring of forestation programs will have to focus on not only the on-land carbon, but also that stored in products, which may be traded internationally. Compared to the monitoring of deforestation, which is likely to be national in scope, that of forestation programs may require coordination across countries. Institutionally, this will pose more significant challenges than in the former case. Monitoring of carbon in products that are exported may require a protocol between the two trading countries for this purpose. Such a protocol would have to account for the lifetime of the products, and if they substitute for energy-intensive products, then the fossil-carbon that is displaced would have to be estimated.

Forestation programs are also likely to occur at specific sites in a country, which may be too small to justify the expense of using remote sensing techniques. Project-specific monitoring may be done using inventory techniques discussed elsewhere in this Special Issue. The flow and stock of carbon over a project's life will depend on the timing of thinning and harvesting of multiple products, that are typical of a self-sustaining project. The timing and frequency will be dictated by these items, and the cost and availability of adequate personnel for monitoring them.

An important issue in the forestation option is that the accounting of physical flows of carbon will show that at the end of a project, and the lifetime of its products, the stored carbon will be released to the atmosphere. In effect, the carbon sequestration project would have produced no net reduction of the carbon in the atmosphere. In order to maintain the carbon benefits of the project, either it has to continue in perpetuity or some other project has to take its place after it ends. The cost of carbon sequestration is then the discounted value of such a string of projects. Finally, it is important that the verification function be carried out by third-party institutions not directly engaged in the project itself in order to ensure its unbiased evaluation (Watt and Sathaye, 1994).

Government subsidies have been important for initiating and sustaining private plantations. Since World War II, 3.15 M ha have been afforested in France, and the 1995 French National Programme for the mitigation of climate change (French Republic, 1995) calls for afforestation rate of 30,000 ha/yr, which will sequester between 79-89 TgC over 50 years, at a cost of 70 \$/tC. Due to funding difficulties and some opposition from the farming community, they are currently anticipating about 11,000 ha per year through to 2000.

The Indian government has pursued a reforestation program of planting 1.5 to 2 M ha annually since 1980, which has been largely dominated by short-rotation softwood plantations of eucalyptus (FAO, 1993). The program is estimated to have produced 58 Mt of industrial wood and fuelwood in India annually since 1980 (Ravindranath and Hall, 1995). An interesting development in the last few years has been the planting of teak (tectona grandis) by private entrepreneurs with capital raised in private capital markets. This program, while occupying only a few

Table 3. Policies, programs and projects to facilitate adoption of forestation and agroforestry

Policies, programs and projects	Environmental Results		Socio-economic Effects		Institutional, Administrative and Political Challenges
	GHG Reduction	Other env. considerations	Costs	Benefits	
1. Production forestry/ agroforestry					
- Promote programs on government owned land - Provide extension services for community or private forestry - Provide financial and other incentives for private plantations	- Up to 75 tC/ha in standing vegetation (additional C conservation from avoided harvesting of primary forest) - Agroforestry may have lower C density	- Proper site and species selection needed for soil conservation and watershed benefits	- Capital cost $5-8 /tC - Other costs vary with type of land, soil quality and level of government intervention including infrastructure	- Benefit from timber and non-timber product sales - Creates jobs - Reduces timber imports and hard currency outflow	Requires - assured markets for products - unambiguous land tenure rights -- institutions to provide extension services
2. Conservation forests*					
- Managed for soil erosion, water catchment, windbreaks, microclimates, etc.	- High potential, up to 300 tC/ha, but C sequestration stops at maturity.	- Has soil conservation, watershed, etc. benefits	- Capital cost $5-8 /tC, - High opportunity cost of land	- Can create rural jobs - Yields non-timber forest products	
- Managed for C sequestration		- Proper site and species selection needed for soil conservation and watershed benefits	- Capital cost as above, but may have low opportunity cost of land		Difficult to justify politically and sustain over the long term.

NOTES: * -- Policies and programs for conservation forests will largely focus on government land, but also include provision of extension services for growing vegetation on non-government lands.

thousand hectares at present, has the potential to expand to 4 to 6 M ha of the 66 M ha of degraded lands (Ravindranath and Hall, 1995). The teak may be used in buildings and furniture.

In addition to national programs, those initiated and supported by foreign governments, NGOs, and private companies are starting in some countries. One example is RUSAFOR, which is a project approved by the US Initiative on Joint Implementation (US IJI) in the Saratov region of Russia (US IJI, 1996). The project has planted seedlings on 1200 ha of marginal agricultural land or burned forest stands. Initial seedling survival rate is 65%. The project will serve as an example for managing a Russian forest plantation as a carbon sink.

For government forestation and agroforestry policies to succeed, the formulation of a coordinated land-use strategy, agreed land tenure rights which are unambiguous and not open to legal challenges, and markets developed enough to assure a sustained demand for forest products will be essential.

3.3 SUBSTITUTION MANAGEMENT

Substitution management has the greatest mitigation potential in the long-term (Marland and Marland, 1992). It views forests as renewable resources and focuses on the transfer of biomass C into products that substitute for, or lessen the use of, fossil fuels rather than on increasing the C pool itself. The growing of trees explicitly for energy purposes has been tried with mixed success in Brazil, the Philippines, Ethiopia, Sweden, and other countries (Hall, Rosillo-Calle, Williams, and Woods, 1993). Wright and Hughes (1993) report that under optimistic assumptions regarding annual tree yield and thermal conversion efficiency, biomass energy systems could offset 20% of 1990 U.S. C emissions. Hall *et al.* (1993) estimate that 267 EJ/yr, or about 80% of global commercial non-biomass energy use, could be supplied by biomass plantations.

The establishment of plantations on deforested and otherwise degraded lands in developing countries and excess cropland in industrialized countries offers major developmental and environmental benefits (Table 4). Village biomass energy systems have the advantage of providing employment, reclaiming degraded land, and associated benefits in rural areas, which are particularly important to developing countries. In India, the Ministry of Non-conventional Energy Sources (MNES) has taken a conscious decision to promote renewable energy programs with a number of financial incentives such as tax and depreciation benefits. A comparison of a diesel-based system with an identical capacity wood gasifier system has shown that when life cycle costing is done, the cost of electricity for the wood-gas-based electricity is lower than a diesel alone system (Mukunda, Dasappa and Shrinivas, 1993).

In developing countries, the use of electricity in rural areas is low. In many countries, such as in Sub Saharan Africa, less than 5% of villages are electrified and in countries such as India even though over 80% of rural settlements are electrified, less than one-third of rural households have electricity. Appropriate government policies are needed that will (1) permit small-scale independent power producers to generate and distribute biomass electricity, (2) transfer technologies within the

Table 4. Policies, programs and projects to facilitate adoption of substitution management

Policies, programs and projects	Environmental Results		Socio-economic Effects		Institutional, Administrative and Political Challenges
	GHG Reduction	Other env. considerations	Costs	Benefits	
Promotion of biofuel (including biogas) and bioelectricity production from wasteland and degraded lands	C sequestration and conservation up to four times the C sequestered in the plantation	Can have soil conservation and watershed benefits Biofuels/ bioelectricity generally have lower non-GHG emissions	- Capital cost of plantations is $5-8 /tC - Additional capital cost of bioenergy equipment - Low opportunity cost of land	- Creates sustained rural employment - Also yields timber and non-timber forest products - May reduce fuel imports - Benefits may outweigh costs	- Requires commercialization - Energy pricing and marketing barriers need to be resolved - High potential for replicability - May need technology R&D and transfer
Substituting sustainably grown wood for non-sustainably harvested wood and non-wood products, (e.g., cement, steel, etc.)	Commensurate with the emissions avoided in the manufacture/harvest of substituted material or wood	As above	-- Retooling and retraining costs -- Loss of respective jobs	As above	- Long-term product markets not assured

country or from outside, (3) set a remunerative price for electricity, and (4) remove restrictions on the growing, harvesting, transportation, and processing of wood — except possibly restrictions on conversion of good agricultural land to an energy forest. Ravindranath and Hall (1995) report that by shifting to a decentralized bioenergy option, India could reduce its carbon emissions by 67 Tg C/yr.

The growing of trees to yield wood as a substitute for fossil fuels is likely to occur within a nation, given the high cost of transporting wood, which has a low energy density. Monitoring of the amount of fossil fuel that the wood will substitute for is no different than that for any other source of renewable energy or energy efficiency. Several approaches of varying complexity exist for this purpose and can be utilized for monitoring. The carbon credit claimed by the nation may be less than 100% depending on the accuracy of the method used to estimate carbon flows. Once the carbon emissions are avoided, the project developer or the nation can take credit for it in perpetuity, or for at least as long as the fossil fuel would have lasted, which may be measured in decades for oil and gas, and centuries for coal.

4. Conclusions

The potential land area available for C conservation and sequestration is estimated to be 700 M ha. The total C that could be sequestered and conserved globally by 2050 on this land is between 60 to 86 billion tC. The tropics have the potential to conserve and sequester by far the largest quantity of C (80%), followed by the temperate zone (17%) and the boreal zone (3% only).

Slowing deforestation and assisting regeneration, forestation, and agroforestry constitute the primary forestry-related mitigation measures for C conservation and sequestration. Among these, slowing deforestation and assisting regeneration in the tropics (22.3-59.5 billion tC) and forestation and agroforestry in the tropics (22.7 billion tC) and temperate zones (12.5 billion tC) hold the most technical potential of conserving and sequestering C. To the extent the forestation schemes yield wood, which can substitute for fossil-fuel-based material and energy, their C benefit can be four times higher than the C sequestered in the plantation. Excluding the opportunity costs of land, the monitoring costs, and the indirect costs of forestation, the costs of C conservation and sequestration average between $3.7 to 4.6 per tC. Monitoring may add up to 15% to these cost estimates.

The Indian government has instituted policies and programs to halt deforestation. For these to succeed over the long term, enforcement to halt deforestation has to be accompanied by the provision of economic and/or other benefits to deforesters that exceed or equal their current remuneration. Monitoring of carbon flows has to be accompanied by that of other benefits in order to ensure that the stated beneficiaries are indeed receiving the claimed benefits.

National tree planting and reforestation programs, with varying success rates, exist in many industrialized and developing countries. Here also, adequate provision of benefits to forest dwellers and farmers will be important to ensure their sustainability. The private sector has played an important role in tree planting for dedicated uses, such as paper production. It is expanding its scope in developing countries through mobilizing resources for planting for dispersed uses, such as the building and furniture industries. Monitoring of forestation programs and projects poses many difficult questions about international agreements and the lifetime of projects and products, and these difficulties may limit the carbon credit that they can claim to less than their full potential.

Wood residues are used regularly to generate steam and/or electricity in most paper mills and rubber plantations, and in specific instances for utility electricity generation. Making plantation wood a significant fuel for utility electricity generation will require higher biomass yields and thermal efficiency to match those of conventional power plants. Governments can help by removing restrictions on wood supply and the purchase of electricity. Monitoring of the carbon benefits, however, should be relatively less complicated than that for forestation programs and no different than for any other renewable energy projects.

The ongoing jointly implemented projects address all three types of mitigation options discussed above. The lessons learned from these projects will serve as important precursors for the monitoring of future mitigation projects. Without their emulation and replication on a national scale, however, the impact of these projects by themselves on C conservation and sequestration is likely to be small. For significant global C reduction, national governments will need to institute policies and programs that can be readily monitored, and provide, local and national, economic, and other benefits while conserving and sequestering C.

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PROJECT SPECIFIC MONITORING AND VERIFICATION: STATE OF THE ART AND CHALLENGES

KENNETH G. MACDICKEN
Senior Forestry Specialist
Winrock International Institute for Agricultural Development
Arlington, Virginia, USA

Abstract. Adequate monitoring of carbon sequestered by forestry activities is essential to the future of forestry as a climate change mitigation option. A wide range of approaches has been taken to monitor changes in forest carbon attributable to project activities. This paper describes simple, least-cost/least-precision methods, remote sensing, periodic carbon inventories, and traditional research methods. Periodic carbon inventories are the preferred approach because they are cost-effective, provide measurements with known levels of precision, and allow the monitoring of other values such as biodiversity and commercial timber volumes. Verification of monitoring estimates is discussed as an auditing process designed to evaluate reported carbon sequestration values. The limitations of remote sensing for biomass determination and the potential for changes in monitoring approaches due to improvements in technology are briefly reviewed.

Key words: Carbon storage, Joint Implementation, monitoring, remote sensing

1. Introduction

Joint Implementation (JI) for increased carbon storage offers one strategy by which countries can reduce net CO_2 emissions. Carbon storage can be increased by expanding the area of tree plantations, agroforestry, and sustainable forest management, or by preserving natural forests or by substituting biomass fuel for fossil fuels. JI projects, now in the pilot stage, are being used to test alternative approaches to reduce net greenhouse gas emissions as a step toward a carbon-trading system. In JI land-use projects, carbon is, in reality, a commodity.[1] Developing the capability to measure carbon storage with identifiable levels of precision is essential to quantifying carbon as a traded commodity.[2] Technically-sound methods for forest carbon monitoring are therefore essential for Joint Implementation land-use projects.

Carbon storage may be one of the most important long-term environmental benefits of forestry projects because of the potential consequences of increased atmospheric CO_2. By quantifying changes in carbon storage, project managers and sponsors can help strengthen the basis for investment in forestry and agroforestry projects.

Despite the effort already given to global, regional, and national carbon inventories, little work has been done to monitor a project's impacts on carbon

[1] A commodity is an economic good, either a product of agriculture or mining

[2] *Precision* is the degree of agreement in a series of measurements. *Accuracy* is the closeness of a measurement to a true value.

storage. Yet unlike macro-level estimates, project-specific impacts can be measured with known levels of precision. The measurement of a project's carbon fixation employs specialized tools and methods drawn from experience with forest inventories and ecological research.

Reasons to monitor changes in forest carbon include (1) the United Nations Framework Convention for Climate Change (UNFCCC) will require JI[3] projects involving land use to monitor carbon changes if carbon credits are to be traded; (2) investors will require reliable, cost-effective monitoring; (3) measuring carbon impacts of forestry and agroforestry projects quantifies an important environmental benefit that will carry economic benefits in the near future; (4) improved monitoring could produce greater carbon benefits; (5) credible, internationally vetted methods could provide additional certainty to investors that will, in turn, increase investment in carbon offset projects.

What kind of accountability should we anticipate for forest carbon? Common sense suggests that the commodity most closely related to carbon is timber, which is bought and sold on the basis of the commercial forest inventory — largely because most of the carbon sequestered through project activities will usually be concentrated in large trees. In commercial inventories, accountability is often determined by the inventory client in the form of precision targets that are set before the inventory begins. At present this is also true for carbon, although international standards for monitoring precision will likely be set by international agreement.

What should be monitored in forestry-based carbon offset projects? In most projects, carbon changes in four primary terrestrial pools: above-ground biomass, below-ground biomass, soils, and the forest floor (litter and coarse woody debris). Accurate accounting of the net difference in each pool for project and non-project (or pre-project) areas over a period of time provides a complete assessment of project carbon impacts. By comparing these changes in the project area to changes in pools unaffected by project activities, monitoring can assess the quantity of carbon stored by the project. Experience to date suggests a set of generally agreed upon characteristics for forest carbon monitoring at the project level (Table 1).

In addition, there may be a need to monitor some aspects of leakage when this is anticipated to be a significant threat to sequestration benefits. In those cases, land-use changes in the "leakage domain" (i.e., the area in which leakage needs to be considered potentially important) may need to be measured or wood-processing centers monitored to determine changes in the origins of wood supplies. Given the difficulties and expense of monitoring leakage, project developers will wisely seek to avoid projects that pose a significant leakage threat. When projects do include a substantial leakage threat, the leakage domain needs to be defined in a way that can be monitored.

[3] The term *Joint Implementation* is used to describe cooperative development projects that seek to reduce or sequester greenhouse gas emissions and involve parties in two or more cooperating countries, as described in the UNFCC.

Table 1. Desirable characteristics for forest carbon monitoring at the project level

Characteristic	Properties
Reliability	Monitoring provides the basis for payments to the project implementors in a Joint Implementation project. Therefore, projects that depend on JI support based on the number of tons of C fixed are based on numbers that are reliable.
Cost-effectiveness	The monitoring system chosen is as cost-effective as possible while meeting the technical requirements specified by the project sponsors, government, or intergovernmental body .
Technically sound	Methods to be used should be, to the extent possible, standard approaches to measurement that are broadly accepted by technical authorities in forestry, ecology, soil science, and remote sensing.
Readily verifiable	The carbon reported through project monitoring can be readily verified using cost-effective methods.
Independent, objective	Monitoring should be done in a way that precludes the inflation of reported carbon storage due to vested interests in higher fixation rates.
Internationally peer-reviewed methods	Until international standards are adopted, a rigorous peer-review process should be used to minimize the risk of inadequate measurement practices.
User-defined levels of precision	Precision estimates are essential to establish confidence in monitoring estimates. Until international standards are set for minimum precision, the user/sponsor must be able to specify and demonstrate precision levels.

2. Challenges

While progress has been made in conceptualizing, designing, and implementing monitoring systems, a number of challenges remain. The following list is not all-inclusive, but provides a starting point for discussion of the monitoring issues critical to the success of carbon sequestration projects:

• *Time unit for measurement.* A major constraint in the comparison of sequestered carbon and reduced emissions is the fact that a ton of carbon emissions reduction is a simple calculation — it is not emitted and therefore counts as a 1 Mg reduction in net carbon emissions. One ton of carbon sequestered in biomass may be sequestered for a day, a year, a decade, a century, or a millennium — and still be claimed as 1 Mg of carbon stored. Clearly the question of what units to report is essential to the success of carbon offset programs.

Challenge: What units should be used for measuring carbon? Should a fixed time period be used for all projects or should there be a new unit of carbon storage (e.g., the ton-year or 1 Mg C stored for 1 year)? Are there other alternatives?

• *Frequency of measurement.* At present, projects are monitoring (or are planning to monitor) annually (CARFIX), biannually (Rio Bravo Carbon Sequestration Project in Belize), or less frequently. In some cases, the frequency of monitoring may be linked to the schedule of payments for carbon credits.

Challenge: What should the frequency of forest carbon monitoring be? How should it be determined at the project level?

• *Acceptable approaches to forest carbon monitoring.* While a range of methods can be used to produce estimates or measurements of carbon sequestration, some rely more heavily on assumptions. As of 1996, the most cost-effective approach to monitoring with known levels of precision is based on commercial forest inventory methods.
Challenge: What approaches should be encouraged for forest carbon monitoring? Which should be explicitly discouraged?
• *Setting standards for measurements.* The international trading of commodities always requires some standards of accuracy and precision. If the commodity is wheat or rice, the weighing scale must be certified as accurate by an authorized agency. It is likely that over the next few years standards will be set for carbon forest trading to ensure that 1 Mg of C reported as stored in one project is the same as 1 Mg of C reported stored in another. Table 2 provides a draft set of measurement standards based on experience from Winrock's field testing and inventory experiences. These standards are defined as the maximum allowable non-sampling error in measurements. Measurements which exceed these standards are considered unacceptable.
Challenge: What standards can be recommended now to help guide the international process?
• *Qualifications for monitoring personnel and organizations.* Carbon sequestration projects are being implemented by a wide range of organizations and monitoring is being done by groups with varying levels of technical expertise. This increases the risk that projects will fail to produce credible carbon credits due to a lack of adequate monitoring. Sustainable forest management certification organizations have minimized that risk for certification organizations through "certification of the certifiers" by the Forest Stewardship Council. As a result, a wide range of technical personnel have been involved in the design and implementation of monitoring and verification systems. The risk in this approach is that monitoring involves a rigorous system of sampling and measurement that requires training and experience to do properly.
Challenge: Should there be a certifying body for forest carbon-monitoring organizations similar to the Forest Stewardship Council or standard business practice auditing? Are there other relevant approaches to minimize the risks of inadequate monitoring?
• *Monitoring post-harvest carbon storage.* Carbon remains stored in wood until oxidation occurs through the processes of decay or combustion. The storage period for carbon in high-value wood products such as decorative veneer, furniture, or trim is commonly hundreds of years. However, because most high-value hardwoods are slow-growing, the accumulation of carbon credits based on living biomass is also slow. A monitoring system to measure post-harvest carbon storage — particularly for medium to highly durable products — could allow reporting of additional carbon and improve the economics of projects that seek to grow higher value timbers.
Challenge: How can post-harvest carbon stored in durable wood products be measured?

Table 2. Measurement standards and allowable limits of error for a forest carbon inventory (Winrock, undated)

Measurement	Allowable error/standard
Tie lines	
Bearing	± of the true bearing
Distance	± of the true horizontal distance
Permanent plots	
Missed or extra trees	No error within the plot
Breast height	± 5 cm of the true height (1.3 m)
D.B.H.	± 0.1 cm or 1% whichever is greater
Circular plot radius	± 1% of horizontal
Statistical indicators	
Probability	p=0.05 (chance of 1 in 20 of random error in sampling) or p=0.01 (chance of 1 in 100 of random error in sampling)
Precision (size of the standard error as a proportion of the mean)	10 to 20%

• *Monitoring leakage.* Projects that remove land from a competing land use may cause "leakage," The risk of leakage is particularly high in preservation projects that stop harvests in production forests. It is very difficult to monitor leakage from wood product flows because the demand for wood products and land is not easy to predict in many countries — in part because the data often do not exist, and in part because there are many other factors that contribute to market prices and material flows (i.e., population, income, price of alternative materials, etc.). If leakage is to be monitored, a key issue is how far we look for evidence of leakage — to adjacent lands and sawmills, national markets, regional markets, etc. Certainly there is no simple answer to this question, but the question must be asked of project designers as leakage-monitoring systems are planned.
Challenge: Can the leakage impacts of a forestry project be monitored in a cost-effective way? Can guidelines be established for monitoring leakage of project benefits?
• *Verification organizations.* At present it appears no rules exist for what kinds of organizations will verify monitoring estimates. It would appear there are relatively few possibilities, including government agencies, private sector firms that specialize in verification, an intergovernmental body such as the UNFCCC, or groups of advisors established by the project implementors.
Challenge: Who should verify monitoring results?

3. Alternative approaches

Some of these challenges are being addressed by organizations already monitoring and verifying carbon offset projects. Four general types of approach have been taken to monitor carbon fixed through project activities.

3.1. LEAST COST — LEAST PRECISION

One approach is to spend little time or effort on monitoring and as a result produce gross estimates that are probably neither accurate nor precise. This approach makes sense when no serious interest in quantifying carbon exists or when there is no demand for information in which confidence is high. An example of this approach is the CARE Carbon Offset Project in Guatemala, funded by the U.S. utility company Applied Energy Services, which began in 1979. This innovative project was the first to utilize tree plantings to offset carbon emissions. The project used a series of "highly simplified assumptions" to estimate total carbon sequestration (Trexler *et al.*, 1992). These assumptions included the number of trees to be planted in either woodlots or agroforestry systems, initial stocking rates, mean annual stemwood volume increments, a biomass multiplier factor, and harvest rates. CARE presently reports basic statistics on tree planting and survival rates. All of the estimates of sequestered carbon are model-based (M. Trexler, personal communication). The World Resources Institute has developed the Land-use and Carbon Sequestration (LUCS) model to estimate CO_2 storage and has used it to estimate the carbon benefits of the CARE Carbon Offset Project.

3.2 REMOTE SENSING AND GROUND TRUTHING

Remotely sensed data from space or aircraft-based sensors can provide pixel-by-pixel measurements of energy reflected back from the earth's surface. Interest in space-based technology for natural resource monitoring continues to increase as imagery becomes cheaper, more readily available, and of higher resolution.

Satellite images have been used in forest carbon offset projects to monitor land area changes, to map vegetation types, and to delineate strata for sampling. Both the FACE Foundation in the Netherlands and Winrock International have used satellite imagery for these purposes. The FACE Foundation system is linked with a database called MONIS to produce maps and tabular data summaries on project activities (FACE Foundation, 1995). The Winrock system uses SPOT panchromatic images and a desktop mapping system with custom utilities for randomizing or systematically allocating plot locations. FUNDECOR in Costa Rica has successfully used Landsat data to monitor vegetation changes in national parks and plans to use a similar approach in the CARFIX carbon sequestration project.

Classification of vegetation using multispectral satellite images and indices such as the Normalized Difference Vegetation Index (NDVI) can, when coupled with adequate ground truthing, be a useful tool in delineating forest types. Panchromatic data provide generally higher resolution and are useful for boundary delimitation or edge detection. Space-borne radar systems such as AVHRR and RADARSAT provide active sensors that detect surface textures and can penetrate cloud cover and can be very useful tools for vegetation mapping.

However, attempts to estimate biomass from remote sensors have generally been costly and have had mixed results. Supervised classification is one important method of analysis and incorporates two stages of analysis (unsupervised classification using computer software and ground-based data), but is in practice most often used for vegetation mapping. Attempts to use remote sensed data to determine biomass have often relied on the relationship between NDVI and Leaf Area Index, although there are limitations in this relationship that misrepresent biomass changes over time (Brown, 1996). It should also be noted that very little of this kind of work has been done in tropical forests — forests that are often more diverse and spatially variable than their temperate counterparts. To date, no one has measured carbon using remote sensing, although classification of vegetation to identify carbon sinks has been done (Foody *et al.*, 1996).

3.3 INVENTORY-BASED

Periodic inventory of carbon in baseline and project cases[4] represents an approach to forest carbon monitoring that is analogous to the commercial assessment of timber volume or biomass.

In many countries timber is still measured prior to sale or other management purposes using sampling and mensuration methods that have evolved over many years. Such inventories can be tailored to a range of needs and constraints. A system that builds on standard forestry approaches to biomass measurement and analysis, and applies commonly accepted principles of forest inventory, soil science, and ecological surveys can be used to monitor carbon. Commercial-scale carbon inventories can be performed at virtually any level of precision desired by inventory sponsors and provide flexibility in the selection of methods, depending on the economic costs and benefits of monitoring. The Global Environmental Facility (GEF) has proposed an inventory-based approach for biomass production projects that may qualify for carbon offset credits (GEF, 1994).

Using permanent inventory plots, forest managers can efficiently assess changes in carbon fixation as long as the plots represent the larger area for which they serve as a gauge. This means that sample plots must be subjected to the same management as the rest of the project area. By involving the same vegetation over time, the use of permanent sample plots also permits the efficient study of trends over more than one rotation; temporary plots require a larger number of plots to detect the same difference reliably. Finally, permanent plots allow efficient verification of carbon monitoring efforts at relatively low cost. An outside organization can find and remeasure permanent plots to check the accuracy of a carbon-monitoring regimen in quantitative terms. To achieve the same level of verification with temporary sample plots or other inventory approaches would require substantially more time and expense.

One inventory-based system that has been extensively peer reviewed and field tested was developed by the Winrock International Institute for Agricultural Development and involves the following components (MacDicken, 1996):

- baseline determination of pre-project carbon pools in biomass, soils, and litter
- establishment of permanent sample plots for periodic measurement of changes in carbon pools

[4]The *baseline case* is defined as on-site conditions without project activities; the *project case* includes on- site changes in soil and biomass carbon that occur due to project activities.

- plotless vegetation survey methods (quarter point and quadrant sampling)[5] to measure carbon stored in non-project areas or areas with sparse vegetation
- calculation of the net difference in carbon accumulated in project and non-project land uses
- use of SPOT satellite images to monitor land-use changes, and as base maps for a microcomputer-based geographic information system
- software for calculating minimum plot size, assigning sample unit locations (either systematically or randomly), and determining the spacing between plots
- a database of allometric models for biomass production, by plant component (roots, wood, and foliage), for selected tree species

This system was designed to incorporate many of the characteristics listed in Table 1. It has been field tested on six sites located in Brazil, Belize, the Philippines, and the United States and is now in use, or planned for use on over 950,000 ha in six countries. Other values (such as commercial timber) and measures of sustainability (such as biodiversity and nutrient fluxes) can also be readily monitored with this permanent plot-based system.

In Costa Rica, the CARFIX Project plans to use LANDSAT imagery and IDRISI, coupled with annual measurements of growth to measure sequestration (FUNDECOR, undated). Lands included in the project will also be inspected in a minimum of two thorough inspections per year. The system planned for CARFIX was designed to work closely with a wood-certifying organization that will help integrate data collection procedures for carbon and for sustainable forest management.

3.4 RESEARCH

Carbon has been measured in many research projects for a variety of purposes. One program in particular has demonstrated the use of a research approach to carbon monitoring. The Reduced-Impact Logging Project was established in 1992 between the Innoprise Corporation in Sabah, Malaysia, and the New England Electric System, a coal burning utility in Massachusetts, USA. The objective of this project is to reduce logging damage and claim the carbon retained in the forest due to these practices as a carbon offset (Pinard and Putz, 1996). Monitoring on this site was done in an experiment with fixed area plots (1600 m^2) and the measurement of diameter at breast height and nested subplots for smaller stems and lianas. It includes inventory results using standard Malaysian forestry mensuration methods. Research was conducted by the silvicultural team from Innoprise, Malaysian forestry students, graduate studies in botany at the University of Florida, and post-graduate studies in economics at the University of Bangor. The research has included stand carbon stock measurements, determination of species composition, and a variety of sampling strategies for estimating below-ground biomass and necromass. This work both tested hypotheses and provided useful measurements of carbon savings due to the use of reduced impact logging. A

[5] In woody savannah areas, the quarter point method helps in laying out measurement units by using the distance between a systematic sampling point and the nearest tree or shrub. Quadrant sampling involves the use of a portable sampling frame to delimit an area for measurement.

committee-based verification scheme has helped incorporate a regular system of review.

Research has provided useful insights into the relative magnitude of forest carbon pools — but it is most often designed to ask sets of questions other than the "routine" query of how much carbon has been fixed by project activities. In cases where capable university programs are willing to make a long-term commitment to repetitive measurements, this approach can provide useful educational opportunities for students and at the same time result in detailed monitoring estimates. Research may often be a costly means of monitoring forest carbon when compared with other alternatives.

4. Verification

Verification of carbon offset projects is presently required by the U.S. Initiative on Joint Implementation and will likely be required in future JI programs. In many ways, the verification of carbon offset projects is equivalent to the use of audits in standard business practice. These practices include general standards such as (Arens and Loebbecke, 1988):

- Qualities the auditor should possess include formal education in forestry and mensuration, adequate practical experience for the work being performed, and continuing professional education.
- Care to ensure the independence of the auditing organization.
- Due care in the performance of all aspects of auditing.

The standards also include guidelines for field work, including evidence accumulation and the planning and conduct of the auditors' visits. Reporting must specify if statements are in accordance with generally accepted accounting principles and whether or not those principles have been consistently applied. There is also a detailed set of quality control elements that are relevant. If accounting is analogous to carbon monitoring, the principles of carbon monitoring (accounting) and verification (auditing) must be clearly defined and accepted by either a professional organization or by some level of government organization.

A general set of procedures for verifying carbon storage might include the following steps (Winrock, 1995):

1. Agreement on carbon monitoring methods at the outset. If the verifying agency and the project's carbon-monitoring team agree on a system of methods for measuring carbon before the project begins, the process can be evaluated efficiently, with little danger of problems that would call monitoring results into question. Such an agreement reduces the risk of voiding monitoring results due to inaccurate or inappropriate practices and will help avoid needless dispute or litigation over project benefits and credits.
2. Review of all monitoring records, including field data collection sheets, spreadsheet/database files, computer model outputs, maps, remote-sensing data, plans, analyses, and reports.

3. Inspection and calibration of measurement and analytical tools used by the monitoring team.
4. Relocation and measurement of a random sample of the permanent plots used in the inventory.
5. If satellite imagery is not used to calculate project area, obtain and process images to verify project area and changes in land-use between inventories.

5. Anticipated changes in technology to improve monitoring efficiency

Technological changes come rapidly and changes can have profound impacts on the technical arts. New technologies will likely be available that will simplify the processes of forest carbon monitoring and verification. The following are a few examples of developments likely to take place over the next several years.

5.1 IMPROVED MEASUREMENT TOOLS

Tools such as sonic distance measures and Global Positioning System (GPS) receivers are already used to reduce monitoring costs and improve the accuracy and precision of carbon measurement. However, several hardware and software tools, which are either not yet available or are prohibitively expensive, will help foresters improve the cost-effectiveness of forest carbon monitoring.

One example of technology that is presently available, but often not affordable, is hand-held laser measurement devices. These devices can be equipped with timber cruise functions, including diameter, height, and diameter at a given height, but presently cost more than US$ 10,000. It is highly likely that future generations of these devices will integrate GPS, data loggers, and computing functions and will become less expensive as they move into wider use in mainstream forestry applications.

Commercial imagery from improved satellite sensors is another example of rapidly changing technology. The new Indian IRS-1C satellite is anticipated to provide 5 m resolution panchromatic data (400% greater than SPOT) at substantially lower cost than current SPOT image prices, although global coverage is not yet available. Several additional satellites with 2 to 5m panchromatic resolution are scheduled for launch over the next few years. Greater competition among providers, enhanced availability of these products and the reduced unit cost of images will all contribute to improved forest carbon monitoring.

An example of remote sensing technology that is not currently available is 3-dimensional, high-resolution, remotely-sensed imagery. Advances in radar sensors such as RADARSAT suggest that 3D, high-resolution systems with accurate, practical forest mensuration applications will someday be a reality. The National Atmospheric and Space Administration (NASA) plans to launch such a system in the year 2000. Called the Vegetation Canopy Lidar (VCL) mission, this system will use a multi-beam laser ranging device to make direct measurements of tree heights and forest canopy structure. VCL should produce estimates of global forest biomass with ten times the accuracy of existing assessments (Isbell, 1997). When the VCL and other sensors are able to measure or allow accurate estimation of diameters and stem volume, we may be able to simplify the process of estimating above-ground woody biomass, although ground truthing, sampling for wood density, soil, litter, and herbaceous vegetation will still require substantial field work by trained crews.

Enhanced software tools will likely be developed that provide greater integration of functions from disparate sensor types (e.g., GPS receivers, calipers or lasers, moisture meters) and simplify data handling. If forest carbon becomes an important traded commodity, software will probably be developed specifically for these purposes.

6. Conclusions

Substantial progress has been made in defining and refining approaches and methods for monitoring forest carbon. Both experience with a small number of Joint Implementation projects and monitoring field tests suggest that some of the key challenges are being met and that forest carbon monitoring can be done at a reasonable cost with relatively high levels of precision.

A number of critical challenges remain — most of them related to the direction in which future development efforts should be placed and what standards should be set. If carbon sequestration forestry is to remain a viable means of reducing net greenhouse gas emissions, serious efforts must be continued to address these challenges. If we can collectively resolve the remaining issues, we will have helped push forward an approach that should both help mitigate global climate change and provide new investments in global forestry.

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SAMPLING GLOBAL DEFORESTATION DATABASES: THE ROLE OF PERSISTENCE

G. ARTURO SANCHEZ-AZOFEIFA
Research Center on Sustainable Development, University of Costa Rica
P.O Box 231-1200 Pavas, San Jose, Costa Rica

DAVID L. SKOLE
Complex Systems Research Center
Morse Hall, University of New Hampshire
Durham New Hampshire, USA

WALTER CHOMENTOWSKI
Ball State University, Department of Geology
Muncie, Indiana, USA

Abstract. One of the concerns regarding transformation of land cover in tropical areas has been the large degree of uncertainty associated with both rates of deforestation over time and total deforestation. Special monitoring mechanisms must be taken into consideration if a program toward deforestation control is going to be implemented at the national or regional scale. The premise of this paper is that any attempt to quantify tropical deforestation and deforestation rates — at regional level, by randomly selecting sites within a population of satellite scenes — would require an overwhelming number of samples. This paper suggests a methodological approach for sampling remote sensing databases to be uses as part of land use/cover change or joint implementation projects. This paper uses the concept of stratification and persistence as main tools.

Keywords: Amazon, deforestation, persistence, random sampling, remote sensing

1. Introduction

The worldwide lack of knowledge regarding total tropical deforestation and deforestation rates affects estimations of trace gas production and the impacts of global climate change (Foody, 1994; Myres, 1989; Shukla *et al.*, 1990). The dependency of current atmospheric and terrestrial models on the quality and quantity of information in tropical forest coverage is the main cause of uncertainty. Lack of information about forest coverage is also considered a major impediment to the development of regional and global budgets for a variety of nutrient species (Matson *et al.*, 1989). There is a need for methodologies to handle monitoring, verification, and certification of Joint Implementation (JI) projects as well as regional/global deforestation projects for decision makers and planners who must implement mitigation and adaptation strategies to global climate change. This lack of information is an important factor constraining the development of sound regional land-use/land-cover (LUCC) change policies in the tropics.

One of the concerns regarding transformation of land cover in tropical areas has been the large degree of uncertainty associated with both rates of deforestation over time and total area deforested. Questions include: What is the area of remaining tropical forests? Are existing estimates of national deforestation rates accurate? How can we use new technologies of remote sensing to get better estimates and monitor the newly developed forest restoration projects? How can we obtain representative samples that allow us to conduct an accurate assessment of total deforestation, and to define sound monitoring deforestation programs as part of national strategies for sustainable development? Recent studies, when they are conducted on a decade basis, have demonstrated that remote sensing data can help to answer the former questions (Skole and Tucker, 1993). But problems for annual appraisals, partial coverage, and high costs are still a limitation to the remote sensing technology.

The need for a statistical approach to sampling remote sensing databases is crucial for the LUCC research community. The importance and need for developing a methodology for monitoring tropical deforestation and other more comprehensive LUCC processes has been addressed in the last decade (Aselmann, 1989; Matson et al., 1989; Stewart, 1989). Even though a great deal of information exists regarding monitoring at the project level, there is still much uncertainty when there is a need to scale up from the JI project scale to regional, national, or global scales.

Special monitoring mechanisms must be taken into consideration if the program is going to be implemented at the national (country) or regional scale (i.e., the Amazon basin). When a program/project monitoring mechanism is going to be implemented with a wide scope of objectives, variables related to how, when, and which sampling screen must be selected as part of the project's monitoring/verification program play an important role during the decision-making process. Additional aspects such as sensor spatial and spectral resolution, frequency of acquisition of remote sensing information, and economic costs are key components of the monitoring program and its methodological development.

The premise of this paper is that any attempt to quantify tropical deforestation and deforestation rates — at regional levels, by randomly selecting sites within a population of satellite scenes — would require an overwhelming number of samples. Random sampling generally produces logistical problems and it has high economic costs. Any attempt for "fair sampling" will need to optimize both the performance of statistical analysis and the amount of information obtained when compared against the cost of the study (Hewitt *et al.,* 1993).

The following sections of this paper suggest a methodological approach for sampling remote sensing databases to be used as part of LUCC or JI monitoring projects. The proposed approach can be considered as a complementary approach to refine current sampling efforts carry on by the Food and Agriculture Organization (FAO, 1994) to monitor tropical deforestation.

This paper uses the concept of stratification and persistence as its main tools. Stratification is defined as the set of criteria used to select the lowest and most representative elements from a population of satellite scenes, minimizing the error, and producing less bias in estimation of a predictive variable. In this paper, it is suggested that stratification can be used for satellite scene selection for global databases. The proposed methodology is expected to contribute to better design and implementation of long-term deforestation-monitoring programs in the tropics. It is assumed that stratification will contribute to producing better designed sampling strategies for deforestation studies and JI monitoring projects at the regional and national scale.

2. Background: Global and Regional Monitoring Deforestation Projects

In global deforestation studies, sampling has often played an important role. Wall-to-wall interpretations of global deforestation can be time consuming and expensive. Though important, wall-to-wall inventories of tropical deforestation and forest cover have not been accomplished until recently. In most studies random sampling is used for scene selection. Because of the patchiness of the deforestation, random sampling can produce significant errors when the goal is to estimate total deforestation. Skole (1992) indicated that when random sampling of Landsat scenes was used for estimating deforestation in the Amazon basin, errors were between 48% and 252% of the actual deforestation value.

Sample construction must use procedures that yield the best results at the minimum cost (sub-sampling). It is possible to obtain sound statistical samples if stratification is used as a database developing tool. One attempt to develop a stratified database with the purpose of monitoring global deforestation in the tropics was implemented by the Food and Agriculture Organization (FAO) of the United Nations (FAO, 1996). The FAO sample covers all the tropical regions. A population consisting of Landsat Thematic Mapper satellite scenes was used. The original sampling population was formed by those scenes with a minimum land area of 1 million hectares and a forest cover of 10% or more. The area represented 62% of the total tropical land area and 87% of all tropical forest.

FAO's scenes were selected using a two-stage stratified random sampling:

Stage 1: Stratification was based on geographical continuity by dividing the survey area into sub-regions.

Stage 2: Stratification was based on forest cover and forest dominance.

The sampling selection was achieved by overlaying a sampling frame, vegetation data, and an eco-floristic zone map. FAO's survey consisted of a sample of 117 satellite Landsat TM scenes. These scenes represented 10% of the total remote sensing database. The distribution of the scenes by region was 47 in Africa, 30 in Asia, and 40 in Latin America. Sample size was selected to represent a standard error of less than ±5%. FAO's survey indicates that the former procedure "minimizes the sampling error by utilizing all the existing information and available knowledge on sampling techniques"" Selected scenes were visually classified for two different time periods. Forest/non-forest classes were the main attributes of this database. Total global deforestation and deforestation rates were then extrapolated between 1980 and 1990.

Other regional wall-to-wall studies have been developed for the Amazon Basin (Skole and Tucker, 1993). Skole and Tucker's (1993) assessment was performed for the legal Amazon basin. This area included the states of Acre, Amapá, Amazonas, Pará, Rondônia, and Roraima, plus parts of Mato Grosso, Maranhâo and Tocantis. A total of 228 Landsat scenes were used. The study area covered an area of ~5,000,000 km^2 (~4,090,000 km^2 forest, and ~850,000 km^2 cerrado or tropical savanna, and ~90,000 km^2 in water). Satellite and GIS techniques were used to stratify Amazonia on the basis of cover types. The study reports that total area deforested increased from 78,000 km^2 in 1978 to 230,000 km^2 in 1988. A deforestation rate of ~15,000 km^2 per year is also reported in the same study. Since this analysis includes two time periods with complete coverage by all 228 Landsat scenes for the Brazilian Amazon, it forms an ideal dataset from which it is possible to compare various sampling schemes against the entire population.

3. Methods

The Landsat tile system or World Reference System 2 (WRS-2) was used as a sampling frame. The WRS-2 is the standard reference system for Landsat Thematic Mapper (TM) and Multi-Spectral Scanner satellite scenes (MSS). The WRS-2 system codes the location of Landsat TM and MSS into path/row maps. The WRS-2 provides a convenient description of the geographical distribution of satellite scenes and is a ready-made sampling frame for the selection of remote sensing data (FAO, 1996). This reference system has been in place since the launch of the Landsat Mission Four in July 1982.

A remotely sensed data set, linked to the WRS-2 systems and developed at the Institute for Study of Earth, Ocean, and Space (EOS) of the University of New Hampshire was used as a sampling frame. The data set is the result of a wall-to-wall assessment of deforestation for the legal Amazon Basin (Skole and Tucker, 1993). Spatial location of scenes forming this database are coded using the WRS-2 reference system (Figure 1). The Amazon basin is the largest continuous tropical forest in the world (6,248,373 km^2). Deforestation of the Amazon basin accounts for a large fraction (12-20%) of the global estimate (~15,000 km^2/year).

The database used consists of land cover change information (i.e., deforestation) extracted from 228 satellite scenes for 1978 and 1988. Each scene represents (approximately) 185 ¥ 185 km. Deforestation, primary forest, clouds, and naturally occurring non-forest (know as cerrado or tropical savanna) are the main topological attributes. Results from these databases indicate a total deforestation of 78,271 km^2 and 230,324 km^2 for 1978 and 1988, respectively.

The methodology presented in this paper is based on stratified random sampling without replacement of a population of Landsat Thematic mapper satellite scenes from the Brazilian Amazon. Sampling without replacement means that each satellite scene in the database is not replaced after being selected. The first item is selected in "n" ways, the second in "n-1", and so on, until the rth is selected in "n-r+1" ways. In addition, the sampling process will be independent and the probability of selecting a sample unit from the population is the same for all the units in the population.

The former rules ensure that a random scene is one that is selected in such a way that any other scene could have resulted with equal likelihood. Non-random-

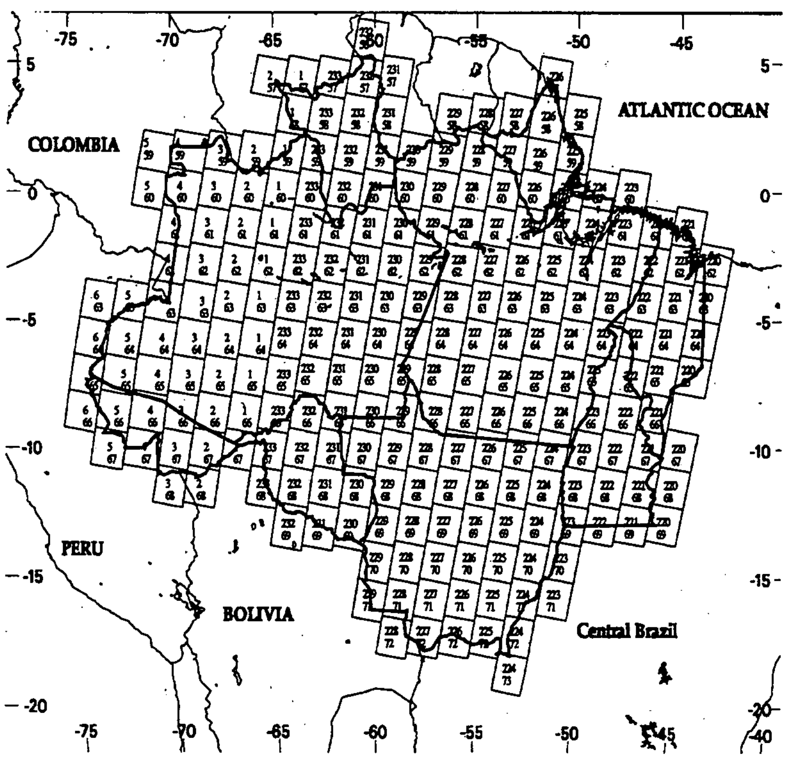


Figure 1. Tile system WRS-2 sampling systems for Landsat Thematic Mapper for the legal amazon basin. This area includes the states of Acre, Amapa, Amazonas, Para, Rondonia and Roraima, plus parts of Mato Grosso, Maranhao and Tocantis.

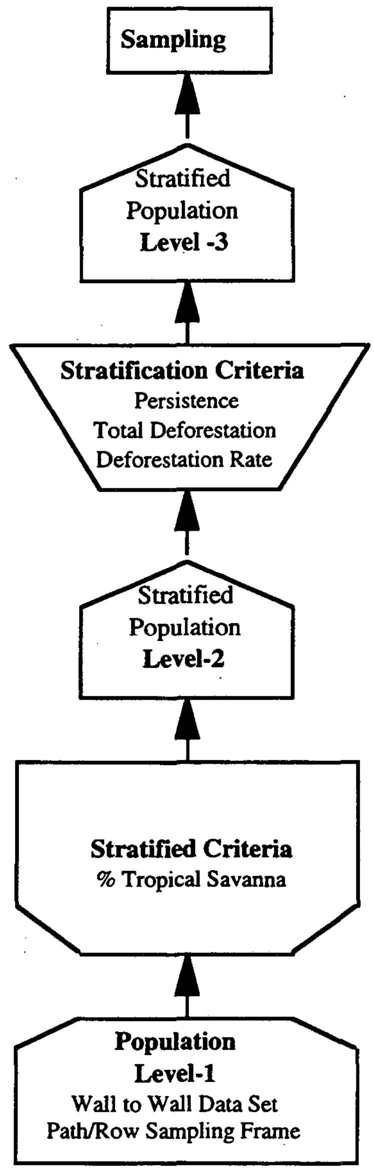


Figure 2. Generation of a stratified sampling population for the Amazon database using the concept of persistance.

ness of sample selection may well be reflected in a lack of independence of the items or in heterogeneity of variances. Moreover, the order of occurrence of the data is not important. Only the data value is important.

These studies follow a three-step procedure for selection of a stratified population for random sampling (Figure 2). During the process of creating a sampling population, the entire original population was defined as unstratified population (level 1). The application of a satellite scene selection criterion to generate a new sample from it produced a level 2 stratified population. Application of a additional criterion, over the population level 2, generated a stratified population — level 3. This last population was used for random sampling and estimation of total deforestation.

Stratification of a unstratified population (level 1) to level 2 used the percentage of tropical savanna as a basic criteria. Stratification from a level 2 to a level 3 sampling population used the concept of persistence. Two different sets of criteria for stratification and sampling — persistence and the rate of deforestation change — were used in this study. First, persistence was used as an indicator of deforestation dynamics at the scene level. Under the concept of persistence, scenes presenting some degree of deforestation on time Ti, will present more but no less deforestation on time Ti+1. Persistence was calculated as the correlation coefficient (r2) between time Ti and time Ti+1 of total deforestation. Secondly, the rate of change of total deforestation change (as a percentage) for each satellite scene between 1978 and 1988 was used as stratification criteria. Scenes with deforestation changes of 5% and 10% were used to create the sampling populations.

A graphical comparison of sample trial density against the normalized standard deviation was performed (Figure 3). Sampling from the level 3 stratified population was performed for several density classes in order to identify the optimum sample size. Density class was defined as the percentage of satellite scenes from the total stratified population level i used to generate a given sub-sample (i.e., a sample size of n = 20 scenes from a 202 population will represent 10% density class). Comparisons of results for each sample density were performed under standard conditions. In this specific case we have used a normalized standard deviation as a comparison between sampling densities. A decrease of the normalized variance increasing subsample size, n, is a function of an increase of information out of the finite population-level-i, N.

4. Results and Discussion

The original population was stratified by eliminating all scenes with an area of more than 30% of non-natural forest area (cerrado). A new stratified population level 2 consisting of 202 scenes was produced. Both 1978 and 1988 data sets accounted for 89% of the total Amazon basin area. Both data sets also accounted

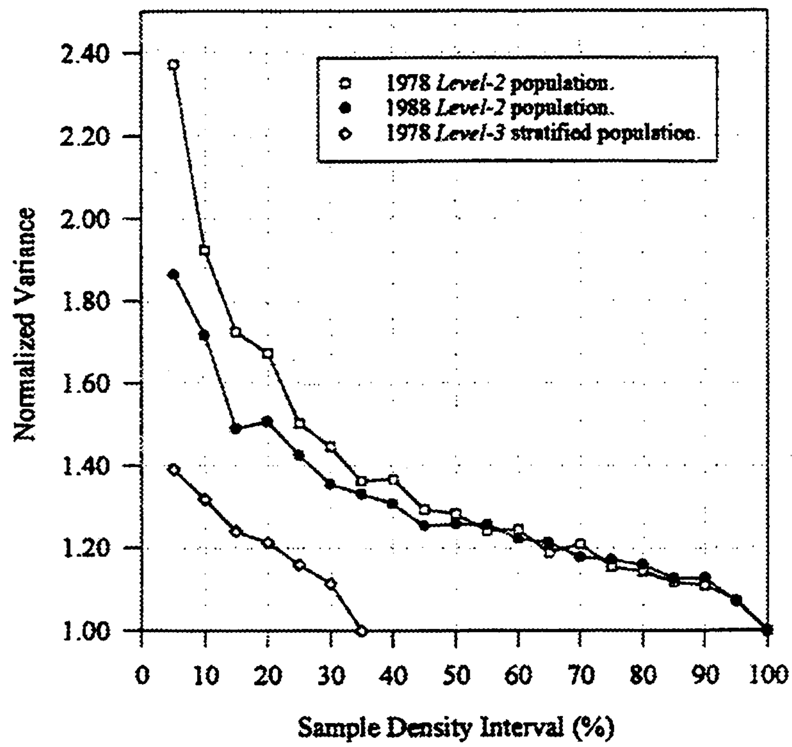
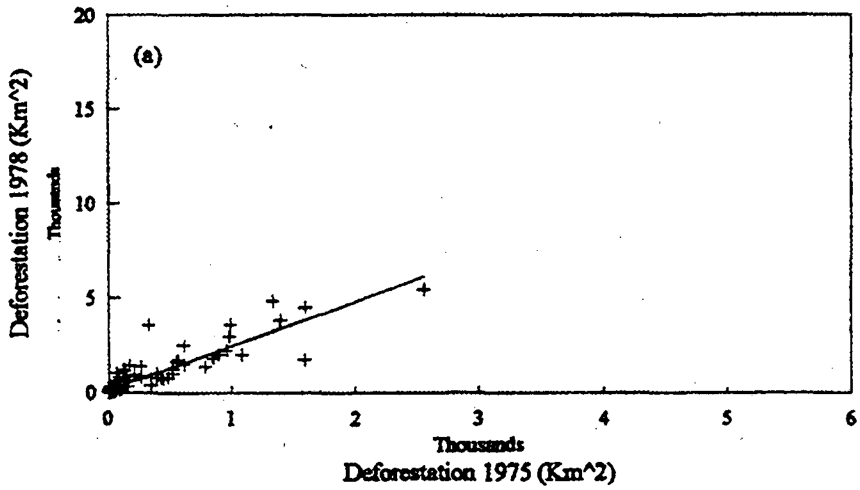


Figure 3. Comparison of results using a normalized standard deviation. For the stratified-population-level 2 there is no gain in precision by random sampling. A considerable gain is observed when

for 96% and 97% of the total reported deforestation, respectively. Most of the scenes eliminated from the original population had total deforestation ranging from 0 to 500 km2. None of the scenes with higher deforestation were eliminated from the data set.

A second stratified population level 3 was created by using the concept of persistence on the 202 scenes. Scenes presenting a departure from the 1978-88 regression line were selected (Figure 4). For the 1975-78 period, the correlation between the data is estimated to be 0.81. The high correlation for the 1975-78 data represents a less intense process of deforestation in the Amazon. Therefore, there is more clustering along the regression line. As deforestation increases during the 1980s, persistence also increases. A reduction in the correlation coefficient (r2) is a measure of a regional deforestation trend and therefore a reduction in persistence. The correlation for the 1978-88 data set is estimated to be 0.63. As deforestation becomes dominant as a spatial process over time, more dispersion and less clustering is observed around the regression line.



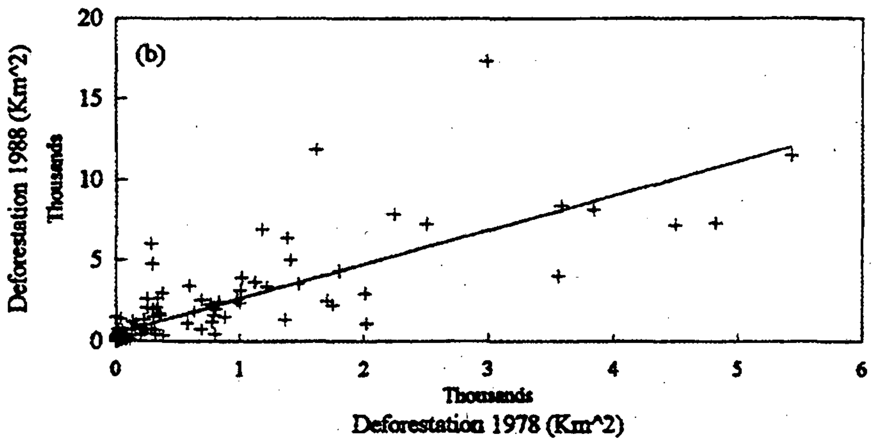


Figure 4. Persistance at the Amazon Basin wall-to-wall remote sensing derived data set. A reduction in the correlation coefficient (r2) is a measure of a regional deforestation trend.

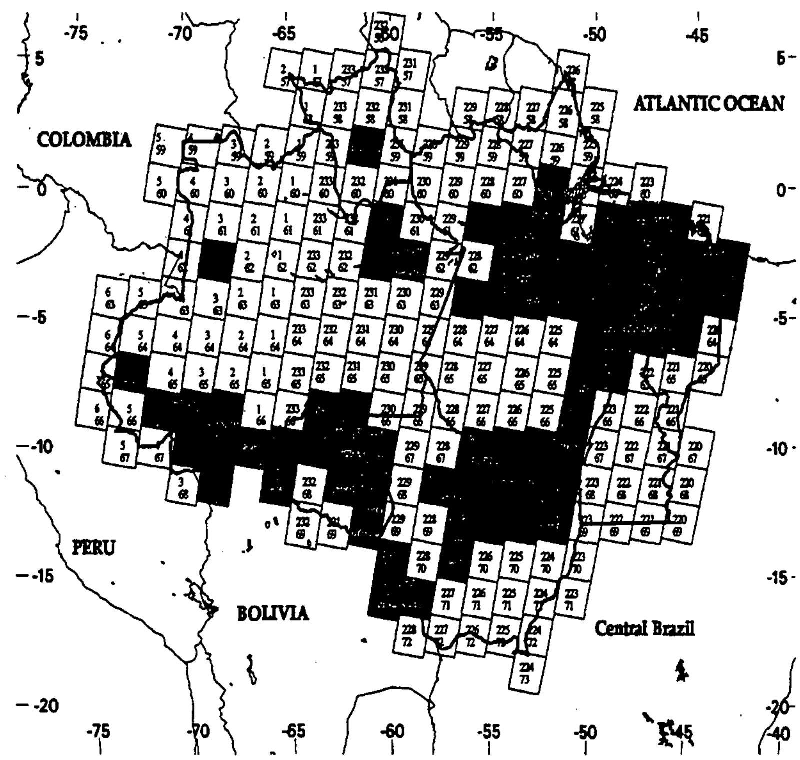


Figure 5. Location of 71 scenes selected using persistance. The selected scenes accounted for 31% of the total study area and 94% of all the 1978 total deforestation at the legal Amazon basin.

The use of persistence allowed for the identification of 71 of the 202 scenes (Figure 5). The selected 71 were identified from the 1978 data set in order to estimate total deforestation in 1988. The selected scenes accounted for 31% of the total study area and 94% of all the 1978 deforestation. A random sampling without replacement at 5% sample size density was applied to the two stratified data sets (Level 2 and 3) (*i.e.,* for 202 scenes, only 10 scenes will be sampled at 5% density). Sampling was performed 100 times for each sample density in order to ensure that no bias was present in the estimation of the average total deforestation. Comparisons of results for each sampling experiment were performed under standard conditions. Normalized standard deviations were calculated and compared (Figure 3).

Figure 3 indicates that for the stratified population level 2 there is no gain in precision by random sampling without replacement of the 202 original data set scenes. It is also concluded that there is no gain by increasing the sampling Figure

3. Comparison of results using a normalized standard deviation. For the stratified-population-level 2 there is no gain in precision by random sampling. A considerable gain is observed when persistence is used as a tool for stratification and scene selection. Minimum normalized standard deviation is reached when sample density drops from 2.38 (in 1978) to 1.35 (persistence 1978-88). In addition, minimum standard error is reached at a 35% sample density. When the minimum standard error is reached using the stratified population level 3, sampling from stratified population level 2 from the 1978 and 1988 data sets reports a ±40% level error. Our results indicated that random sampling from a stratified/persistence database can perform better than simple random sampling from a finite population.

The present study indicates that stratified random sampling, without replacement, using the concept of persistence has important consideration for regional monitoring of deforestation processes and therefore for the global change community. Implications of this finding permit us to design and refined current approaches for random sampling developed by FAO in order to monitor worldwide tropical deforestation. FAO's approach can be improved by using the concept of persistence avoiding current sampling problems.

In addition, the use of stratified sampling using persistence can play an important role in monitoring and verification of joint implementation (JI) projects on a regional and national scale. JI projects aimed at controlling tropical deforestation and estimating carbon fluxes and with a regional scope can take advantage of stratified sampling using persistence. Regional and nationwide projects in need of multi-scene/sub-scene monitoring analysis for verification and certification can utilize the concept of persistence in order to reduce monitoring costs and increase the frequency of their observation as part of measurement of carbon release and sinking rates.

5. Conclusions

1. Results of our study on the impacts of stratification as a scientific tool for estimation of global deforestation are encouraging. Our estimates indicate that stratification based on persistence contributes to the reduction of error regarding estimation of total deforestation when it is contrasted against stratified level one databases (random sampling without stratification). The results of this work also indicate that more accurate estimations of deforestation can be obtained if persistence is used to select sampling elements for deforestation studies. Use of persistence, for construction of sampling databases, could be possible only if current efforts to map tropical deforestation are a product of wall-to-wall reference data sets.
2. Results indicate that random sampling (from stratified populations level 2) has the potential for extreme over- or under-estimation of total deforestation. Reductions in error are achieved only when very high sampling den-

sities are attained. If a new level of stratification is applied, very accurate estimates of the total area deforested can be obtained using low sample densities.

3. Stratified sampling based on persistence can help develop sounder monitoring deforestation programs at the global or national scale in the future. Sound sampling methods are necessary to monitor current efforts regarding the effect of mitigation/adaptation policies and programs (*i.e.*, those new programs which are part of the Joint Implementation projects in the area of sustainable forest management).
4. The results from this research can be extrapolated from global deforestation estimates to more regional analysis. In those cases where there is a lack of good satellite imagery, the spatial dimension of the sample element can be reduced, so that multi-temporal aerial photography databases can be selected as a sampling element. This alternative could permit national governments and international organizations to implement regional or national LUCC programs based on inexpensive and available aerial photography data sets.
5. More accurate information on the current extension of tropical forests and the dynamics of deforestation processes can facilitate the refinement of global carbon budgets and models. The results of this study indicate that more accurate assessment of deforestation at global levels can be accomplished through the development of scientifically based monitoring methods based on stratification. The use of random sampling for original data sets is not encouraged.

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FOREST MANAGEMENT FOR MITIGATION OF CO_2 EMISSIONS: HOW MUCH MITIGATION AND WHO GETS THE CREDITS?

G. MARLAND
Oak Ridge National Laboratory, Oak Ridge, Tennessee 37831-6335, USA

B. SCHLAMADINGER and L. CANELLA
Joanneum Research, A-8010 Graz, Austria

Abstract. Forestry projects can mitigate the net flux of carbon (C) to the atmosphere in four ways: (1) C is stored in forest biomass — trees, litter and soil, (2) C is stored in durable wood products, (3) biomass fuels displace consumption of fossil fuels, and (4) wood products often require less fossil-fuel energy for their production and use than do alternate products that provide the same service. We use a mathematical model of C stocks and flows (GORCAM) to illustrate the inter-relationships among these impacts on the C cycle and the changing C balance over time. The model suggests that sustainable management for the harvest of forest products will yield more net C offset than will forest protection when forest productivity is high, forest products are produced and used efficiently, and longer time periods are considered. Yet it is very difficult to attribute all of the C offsets to the forestry projects. It is, at least in concept, straightforward to measure, verify, and attribute the C stored in the forests and in wood products. It is more challenging to measure the amount of fossil fuel saved directly because of the use of biomass fuels and to give proper attribution to a mitigation project. The amount of fossil fuel saved indirectly because biomass provides materials and services that are used in place of other materials and services may be very difficult to estimate and impossible to allocate to any project. Nonetheless, over the long run, these two aspects of fossil fuel saved may be the largest impacts of forestry projects on the global C cycle.

Keywords: Forestry, carbon balance, wood products, energy substitution, materials substitution

1. Introduction

In the search for approaches to mitigate the net flux of greenhouse gases to the atmosphere, there has been much interest in forestry-related measures to either reduce or offset net emissions of CO_2. Forest protection is widely recognized as a way to avoid CO_2 emissions (Dixon *et al.*, 1994; Harmon *et al.*, 1990; U.S. NAS, 1992) and afforestation is now appreciated as a possibility for offsetting some of the emissions from the consumption of fossil fuels (Houghton *et al.*, 1993; Sampson and Hair, 1992; Nilsson and Schopfhauser, 1995). The literature is increasingly cognizant that forest management also impacts the net flux of C through its influence on the flow of forest products, whether as fuels or as durable products, and their ability to substitute for alternate, fossil-fuel-intensive products (Hall *et al.*, 1991; Heath *et al.*, 1996; Matthews, 1996). The details of forest harvest, land preparation, product preparation and 2
use, and so on can make important differences.

An international agreement currently exists for countries to estimate and report their total emissions of greenhouse gases to the atmosphere (United Nations, 1992), and there is increasing impetus for communities and corporations to similarly be responsible for their emissions (U.S. Department of Energy, 1994). We want to know not only how much greenhouse gas is being discharged, but also where and by whom. We contemplate actions implemented jointly, where one party would produce reductions in emissions but would sell or trade those reductions either in the open market or in return for technical or economic assistance in realizing the reductions. We are evolving a regime where reductions in emissions have value, even if only public relations value. For alternate forest-management strategies this paper explores both the impact on the C cycle and the allocation of credits (or debits).

To examine the impact of land management alternatives on the global carbon cycle, we have developed a spreadsheet model of the system that is directly impacted by the choice of management regime. GORCAM (the Graz/Oak Ridge Carbon Accounting Model; see Schlamadinger and Marland, 1996) provides a simplified description of C stocks and flows associated with management of forests or agricultural land (see Figure 1). The model calculates C accumulation in plants, in long- and short-lived wood products, in fossil fuels not burned because biofuels are used instead, and in fossil fuels not burned because production and use of wood products requires less energy than does production and use of alternate materials that provide the same service. The model requires parameters to describe: the allocation of forest harvest to various product and waste streams, the mean lifetime of wood products and of soil and litter C, the efficiency with which wood products are used (and comparable values for the materials they displace), and the energy required for the management of the forestry system (and comparable values for production and delivery of alternate fuels or products). Wood materials can be recycled, placed in a landfill, or used to generate energy at the end of their useful lives.

The version of the model employed here uses a simple growth function for trees (Marland and Marland, 1992) and a dynamic model for the transfer of C to and from the litter and soil C pools (Schlamadinger *et al.*, 1997; Dewar and Cannell, 1992). The model represents in a simple way many parameters that have complex functional forms and that are variable in time and space. Our intent is to illustrate the functional relationships and the impact on the cycling of C by selecting parameters that are representative within the broad range of real-world situations. The scenarios described here should be taken as illustrative rather than demonstrative.

2. Two scenarios

We contrast two forestry projects that might be proposed for the mitigation of CO_2 emissions. The intent is to examine first the impact of the project on the global carbon cycle and then the carbon credits and debits that accrue to the potential participants in the mitigation project.

The two scenarios developed below both involve an existing second-growth forest stand. For the sake of illustration, we assume a standing, above-ground, biomass of 100 MgC ha^{-1} and a setting such that the mature stand will saturate over time and approach a steady-state standing stock of 160 MgC ha^{-1}, where it has no further net uptake of C. In the first scenario (Figure 2a) the strategy chosen is to protect the forest stand, to allow it to grow toward the steady state, and to

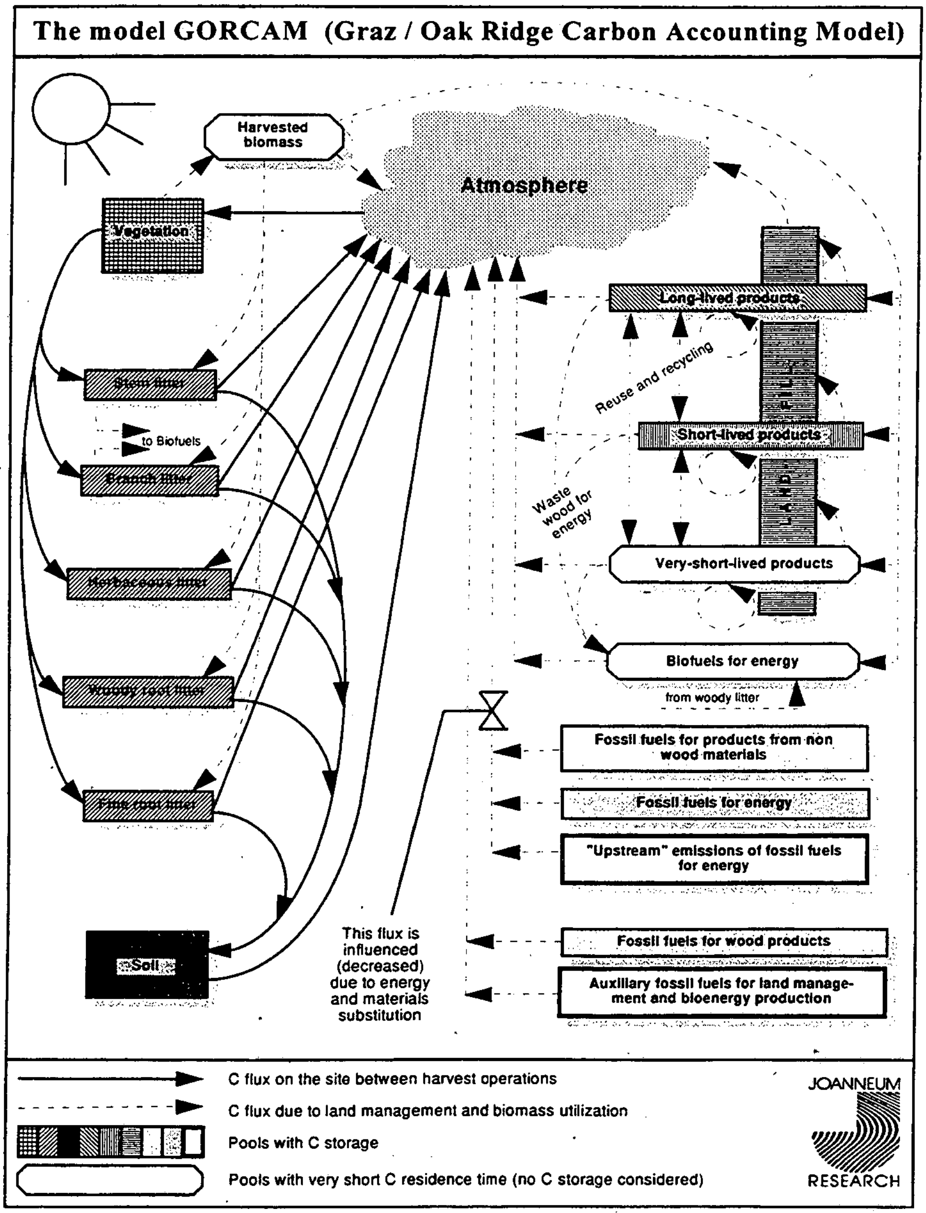

Figure 1. The Graz/Oak Ridge Carbon Accounting Model (GORCAM) describes changes in the amount of C stored in various biosphere, wood-product, and fossil-fuel pools over time for selected scenarios for managing land use. Details can be found in Schlamadinger and Marland, 1996.

accumulate and store C away from the atmosphere. The base productivity is defined at 1.72 MgC ha^{-1} yr^{-1} (this is the rate at which the young, vigorous stand will grow) and this declines as the stand approaches steady state. These parameters describe a forest that would be characterized as very productive but not extraordinary. The parameters are within the range of values reported by Nabuurs and Mohren (1993) for various forest types in temperate regions.

In scenario 2 (Figure 2b) the existing second-growth stand is harvested to produce a conventional mix of wood products and is then managed for continued, sustainable production of wood products on a 60-year harvest rotation cycle. The basic parameters of the scenario that drives the C flows are summarized in Table 1. Parameters used here to represent the efficiency with which forest products are harvested and used to displace other fuels or durable products can be characterized as efficient but within the range of current practice. We have assumed, for the sake of simplicity, that this scenario represents a continuation of the historic forest management strategy, does not result in a change in the mean age of the stand, and hence that there is no net change in the average amount, over time, of C stored in soils and forest litter. There will, of course, be a change in the soil and litter C dynamics following the harvest. All of the parameter values are derived in detail in Schlamadinger and Marland, 1996; those for the dynamic soil and litter C model are in Schlamadinger *et al.,* 1997.

3. Impact on the global carbon cycle

In Figure 2 we illustrate the changes in carbon stocks over time for the two scenarios. The diagram of the forest protection scenario (Figure 2a) shows increasing C stored on site in forest biomass. In the forest harvest scenario (Figure 2b), the bottom line in the figure is at -100 MgC ha^{-1} because there is a loss of 100 MgC ha^{-1} of on-site C during the initial harvest. From this baseline, the scenario shows the initial distribution of C from the standing forest to the array of forest products, with subsequent regrowth of the forest. The baseline drops slightly more as C is lost from soils, but eventually it rises again as the forest regrows. When we give credit for both direct and indirect displacement of fossil fuels and the forest is clear cut with efficient use of forest products, the net emission of C to the atmosphere for the forest harvest scenario is zero after about 30 years. After about 95 years the net impact on C emissions to the atmosphere is roughly the same for the two scenarios, forest protection and forest harvest with efficient conversion to, and use of, wood products.

It is important to appreciate that the relative impacts on the C cycle for the two scenarios shown are very sensitive to some of the input parameters. Also, note that if the results were reported for a specific end point, it would make a very large difference what time interval was chosen to define the end point. To illustrate the sensitivity to the input parameters, we show in a series of three-dimensional plots the "surface" of C emissions avoided for a range of values of forest productivity and of the efficiency with which forest products are harvested and used. To do this we have defined a new parameter, the "efficiency," that serves as a proxy for a number of parameters derived independently in the base case scenarios shown in Figure 2.

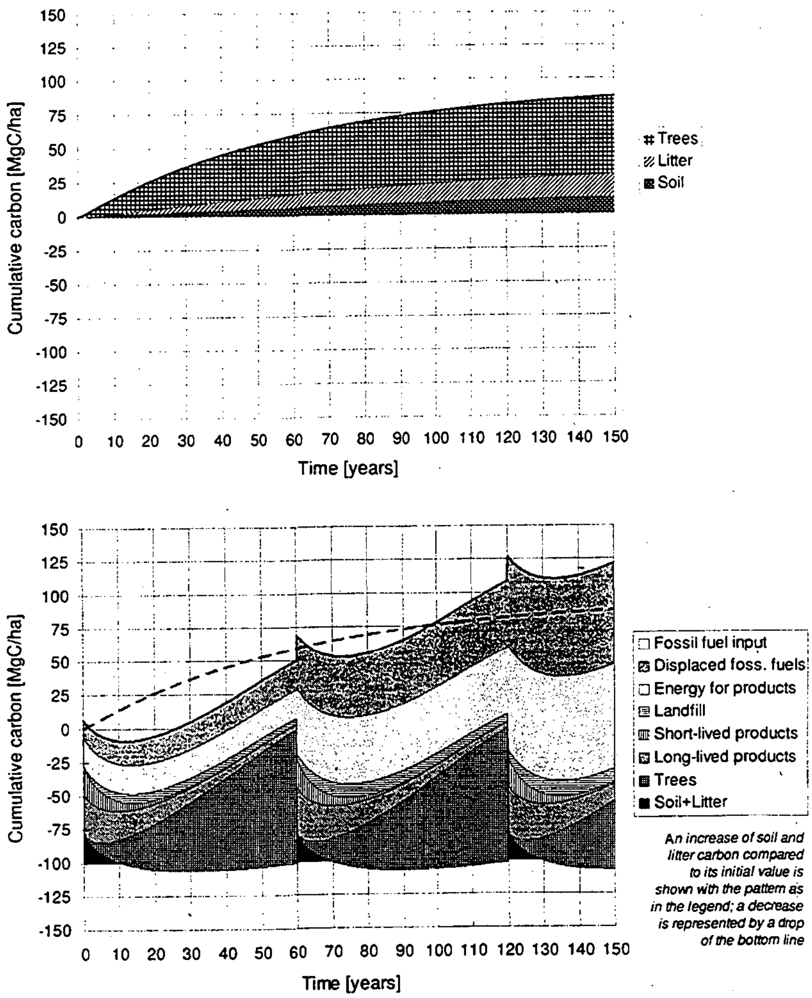

Figure 2. Comparison of the change in C stocks for two scenarios for forest management. The net change in the amount of C stored in the various reservoirs is represented as a function of time. In scenario 1 *(Figure 2a, upper diagram)*, growing forest with an initial 100 MgC ha^{-1} in above-ground biomass is protected and permitted to continue to grow and sequester carbon in trees and in forest litter and soils. In scenario 2 *(Figure 2b, lower diagram)*, growing forest with the same initial 100 MgC ha^{-1} is harvested for wood products with a 60-year harvest rotation cycle. For ease of comparison, Figure 2b includes the total cumulative C curve from Figure 2a (shown dashed in Figure 2b). Note that scenario 2 assumes that material harvested in all harvests after the first will be used with increased efficiency due to technological progress (compare parameters 25 to 28 with parameters 8 to 11 in Table 1). Because fossil fuel displacement is immediate but oxidation of wood products and litter occurs over time, there is a net increase in C sequestration immediately following each harvest.

Table 1. Values used in GORCAM (Graz/Oak Ridge Carbon Accounting Model) for the principal parameters in the two scenarios.

No.	Parameter		No harvest	Conventional forestry
	Initial harvest			
1	Initial above ground carbon	MgC ha^{-1}	100	100
2	Fossil C-emissions from harvesting	MgC MgC^{-1}	-	0.01
3	Share of harvest to biofuel	MgC MgC^{-1}	-	0.22
4	Share of harvest to long-lived products	MgC MgC^{-1}	-	0.30
5	Share of harvest to short-lived products	MgC MgC^{-1}	-	0.20
6	Share of harvest to very short-lived products	MgC MgC^{-1}	-	0.05
7	Share of harvest not used	MgC MgC^{-1}	-	0.23
8	Displacement factor fuel #	MgC MgC^{-1}	-	0.6
9	Displacement factor long-lived products #	MgC MgC^{-1}	-	0.5
10	Displacement factor short-lived products #	MgC MgC^{-1}	-	0.25
11	Displacement. factor very short-lived products #	MgC MgC^{-1}	-	0.25
12	Fossil C-emissions from bioenergy conversion	MgC MgC^{-1}	-	0.05
13	Upstream C-emissions of displaced fossil fuel	MgC MgC^{-1}	-	0.08
	Subsequent harvests			
14	Rotation length	yrs	-	60
15	Initial growth rate	MgC ha^{-1} yr^{-1}	1.72	1.72
16	Maximum standing stock	MgC ha^{-1}	160	160
17	Above ground carbon affected by harvest (calculated)	MgC ha^{-1}	-	100
18	Annual fossil C-emissions from cultivation	MgC ha^{-1} yr^{-1}	-	0
19	Fossil C-emissions from harvesting	MgC MgC^{-1}	-	0.01
20	Share of harvest to biofuel	MgC MgC^{-1}	-	0.22
21	Share of harvest to long-lived products	MgC MgC^{-1}	-	0.30
22	Share of harvest to short-lived products	MgC MgC^{-1}	-	0.20
23	Share of harvest to very short-lived products	MgC MgC^{-1}	-	0.05
24	Share of harvest not used	MgC MgC^{-1}	-	0.23
25	Displacement factor fuel #	MgC MgC^{-1}	-	0.8
26	Displacement factor long-lived products #	MgC MgC^{-1}	-	0.8
27	Displacement factor short-lived products #	MgC MgC^{-1}	-	0.4
28	Displacement factor very short-lived products #	MgC MgC^{-1}	-	0.4
29	Fossil C emissions from bioenergy conversion	MgC MgC^{-1}	-	0.05
30	Upstream C emissions of displaced fossil fuel	MgC MgC^{-1}	-	0.08
	Soil and litter parameters			
31	Initial soil carbon pool size	MgC ha^{-1}	140	140
32	Decay rate soil carbon	yr^{-1}	0.015	0.015
33	Initial litter carbon pool size	MgC ha^{-1}	26	26
34	Litter production of mature forest (incl. foliage and below ground)	MgC ha^{-1} yr^{-1}	5.4	5.4
35	Decay rate litter (stems+woody roots/branches/foliage+fine roots)	yr^{-1}	.01/.05/.85	.01/.05/.85
36	Share of litter entering soil pool (above/below ground litter)	MgC MgC^{-1}	0.2/0.5	0.2/0.5
	Wood products and landfill parameters			
37	Average lifetime long-lived products	yrs	-	30
38	Average lifetime short-lived products	yrs	-	10
39	Share of long-lived products for energy	MgC MgC^{-1}	-	0.30
40	Share of short-lived products for energy	MgC MgC^{-1}	-	0.30
41	Share of very short-lived products for energy	MgC MgC^{-1}	-	0.30
42	Displacement factor products for energy (long) #	MgC MgC^{-1}	-	0.6
43	Displacement factor products for energy (short) #	MgC MgC^{-1}	-	0.6
44	Displacement factor products for energy (very short) #	MgC MgC^{-1}	-	0.6
45	Share of long-lived products into landfills	MgC MgC^{-1}	-	0.40
46	Share of short-lived products into landfills	MgC MgC^{-1}	-	0.40
47	Share of very short-lived products into landfills	MgC MgC^{-1}	-	0.40
48	Average lifetime long-lived products in landfills	MgC MgC^{-1}	-	40
49	Average lifetime short-lived products in landfills	MgC MgC^{-1}	-	10
50	Average lifetime very short-lived products in landfills	MgC MgC^{-1}	-	5

Notes to Table 1:

\# Displacement factors describe (1) the amount of C emission from fossil fuels that is avoided when biofuels are used and (2) the amount of fossil C not oxidized because wood products are used instead of products from other, more energy-intensive materials like concrete and steel (indirect energy substitution). Both of these displacement factors have units of MgC $(MgC)^{-1}$ and represent the net amount of fossil fuel C not oxidized because 1 Mg of biomass C is used for energy or is stored in wood products.

The efficiency is scaled from 0 to 2 where 1 represents the base case values, used above, for the displacement of fossil fuels and of products from alternate materials. On the efficiency scale, e = 0 to 2, the values of e are multipliers for all of the efficiency-related parameters in the model. Thus, an efficiency of 2.0 represents a doubling of the mean lifetime of durable products, a doubling of the effectiveness of wood products in displacing other products, and a doubling in the efficiency with which biofuels displace fossil fuels. Similarly, an efficiency of 0.0 represents a scenario with the mean lifetime of wood products, the effectiveness in displacing non-wood products, and the efficiency with which biofuels replace fossil fuels all reduced to zero.

Figure 3a shows the cumulative change in C stocks, C sequestration, after 100 years for the forest protection scenario. Since there is no harvest, the change in C stocks does not depend on the efficiency factor. We do see that after 100 years the forests with high growth rates have reached the point where they are taking up little additional C, with a net increase of just over 80 MgC ha^{-1} (including C accumulation in litter and soils), and that only for low growth rates will there be continued, significant, net C uptake beyond 100 years. Note that the scenario illustrated permits some accumulation of C in the soil and litter even when there is no increase in above-ground standing biomass (i.e., when the growth rate is 0.0). The surface for net cumulative C mitigation is more complex in Figure 3b, where forest is harvested initially, and again at a defined harvest-rotation age, for the production of forest products. Figure 3c shows the difference between these two scenarios, i.e., each value in Figure 3a is subtracted from the corresponding value in Figure 3b, and we see the net advantage of the forest harvest scenario with respect to the forest protection scenario. The wave structure seen in Figures 3b and 3c occurs because the scenarios all assume that forests will be harvested in the year that they reach 100 MgC ha^{-1}. Consequently the 100 year end-point for the scenarios illustrated occurs at different points in the rotation cycle, depending on the defined growth rate. The wave is dampened at high growth rates because 100 years represents several harvest cycles whereas for a growth rate of 1 MgC ha^{-1} yr^{-1}, the end of the 100-year scenario corresponds with the end of the first harvest cycle.

Figure 3c shows that when productivity is high and when the forest can be harvested and the products used efficiently, there is a net C benefit, over time, of harvesting and using wood products, i.e., the net cumulative C values in Figure 3c are positive. On the other hand, where productivity is low and the harvest is used inefficiently, the maximum carbon benefit is achieved by protecting the forest to accumulate and store C, i.e., the net cumulative C sequestration values in Figure 3c are negative. The intersect between the surface describing scenario output and the 0-carbon-accumulation plane defines the boundary at which higher growth rates and higher efficiencies favor sustainable harvest scenarios over forest protection scenarios as the more effective way to maximize the net mitigation impact on C emissions to the atmosphere.

As shown in Figures 2a and 2b, as the time frame of the analysis is extended, C sequestration saturates in the forest protection scenario while the forest products scenario continues to provide an offset for fossil fuel emissions. The difference between the two scenarios decreases with time until, after about 95 years in the base case scenarios, the sustainable forest products scenario provides the larger net impact on CO_2 emissions to the atmosphere. The same impact of time on the forest products scenario can be observed by comparing Figure 4 with Figure 3c. Figure 4 is, as in Figure 3c, the difference between the sustainable forest harvest scenario and the forest protection scenario, except that Figure 4 represents the difference 20 years after project initiation whereas Figure 3c is the difference after 100 years. Comparison of the two figures shows that, in general, as the time horizon is increased, the intersect at which sustainable harvest represents the more attractive choice with respect to impact on the C cycle, moves toward lower values of efficiency and growth rate. This general conclusion breaks down at very low growth rates where the oxidation of forest products continues to release C over time but regrowth of the forest takes up very little C. This general conclusion also breaks down at very low efficiencies (compare again Figures 3c and 4) where forest is harvested but the products are used so inefficiently that little fossil fuel use is displaced and little C is stored in products. Hence, at very low values of growth rate or efficiency, the value of cumulative C difference is more negative after 100 years than after 20 years.

Another observation is that for high growth rates and efficient harvest use the advantage of the forest harvest scenario over the protection scenario is much greater after 100 years (650 MgC ha^{-1} for growth rate equal 5 and efficiency equal 2) than after 20 years (70 MgC ha^{-1} for growth rate equal 5 and efficiency equal 2. Note that this number increases faster than linearly). This difference can be explained by the large amount of fossil fuel that is substituted when fast growing forests are used efficiently for materials and energy substitution.

4. Credits and debits

Having represented the net impact of two potential mitigation projects on the flux of C to the atmosphere; and having seen how the relative merits of the two approaches vary with the specifics of growth rate and efficiency, we look back at the base case scenarios and examine the implications for monitoring, verifying, and attributing the impacts on the global C cycle that result from mitigation projects. Recall that the two base case scenarios yield nearly identical results for the net impact on C emissions to the atmosphere at the end of 100 years (see Figure 2b).

In the forest protection scenario (Figure 2a), the monitoring and verification is conceptually straight-forward. The forest has been allowed to grow and accumulate C and we envision that we could measure the additional amount of C accumulated in the plants, litter, and soil on site and attribute the C mitigation to the site manager/owner. It can be verified that C has been removed from the atmosphere and we know where it is.

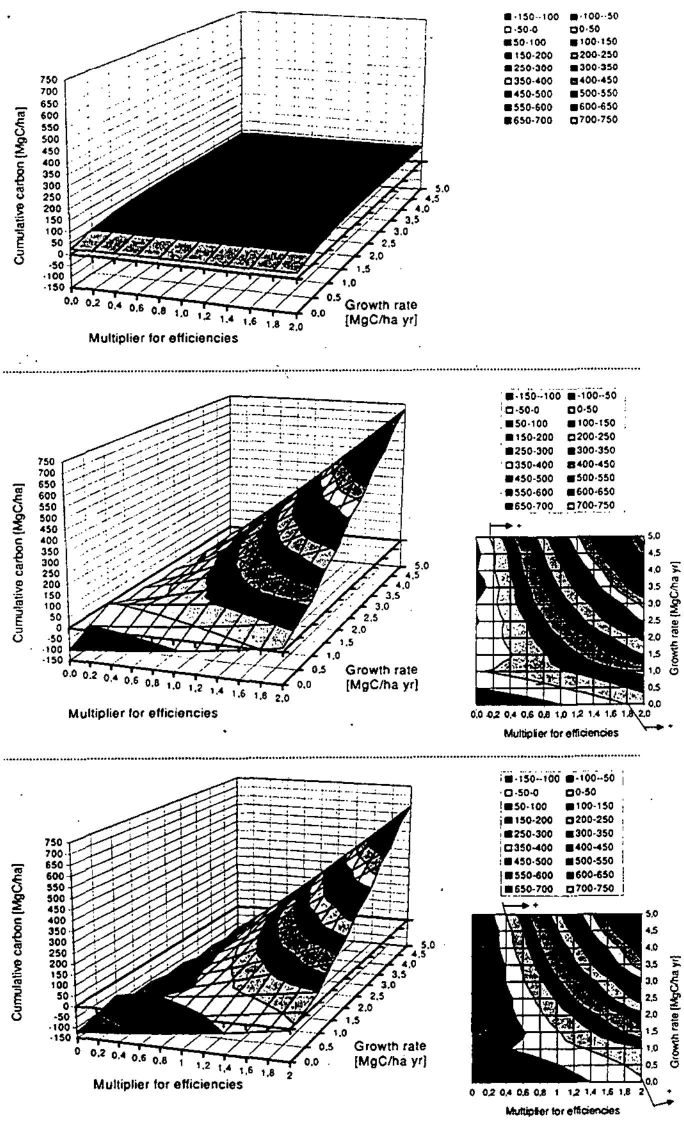

Figure 3. Sensitivity of the results to changes in growth rate and efficiencies. Figure 3a (upper diagram) shows the net cumulative C mitigation after 100 years for the forest protection scenarios. Values of net cumulative C mitigation are shown as a function of the forest growth rate and the "efficiency" with which forest products are harvested and used, as defined in the text. The accumulation of C in soil and litter is taken from the base-case scenario and is not dependent on the forest growth rate. Figure 3b (middle diagram) shows the net cumulative C mitigation after 100 years for a sustainable, forest-harvest scenario. The insert shows a contoured, two-dimensional representation of net cumulative carbon mitigation to make it easier to see the location of the zero contour. Figure 3c (lower diagram) shows the difference between the scenarios of Figure 3a and 3b. Values for net cumulative C mitigation for scenario 1 (Figure 3a) are subtracted from corresponding values for scenario 2 (Figure 3b). As in Figure 3b, an inset is provided to help characterize the location of the zero intercept. The zero contour line separates regions where mitigation is greater for the forest protection scenario (negative values in the figure) from those in which sustainable harvest yields greater mitigation (positive values of cumulative C).

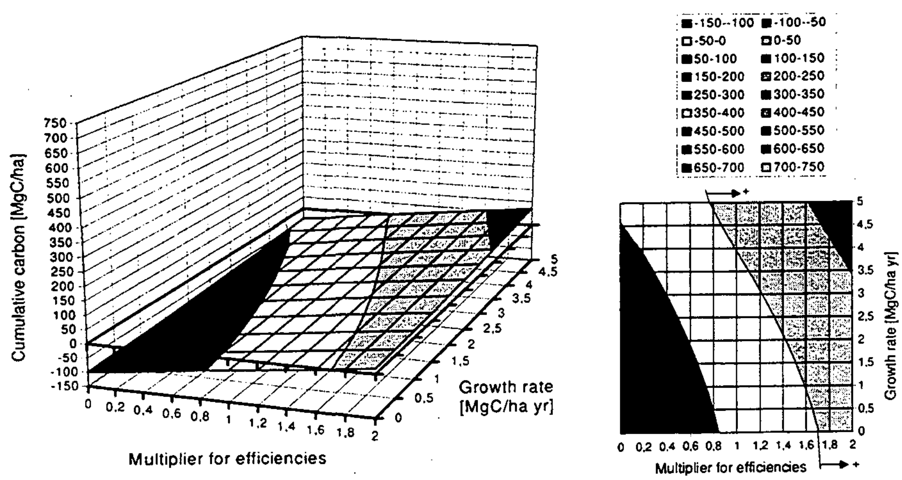

Figure 4. The same as in Figure 3c, except after 20 years.

For a scenario involving forest harvest, we can still put our arms around the C stored on site in trees and in the soil and litter; but it is clear that the site manager/owner will observe a decrease in mean C stocks on site. Figure 5a shows the amount of C that can be accounted for on the original land. With a bit more effort, we can track and monitor the amount of C stored in wood products. As Figure 5b illustrates, these wood products have a finite lifetime and the C will be released to the atmosphere slowly over time. Storage of C in wood products is real and, in theory, measurable, even if the wood products are no longer in the possession of the forest manager/owner. In our scenario, some wood products are placed in landfills and some are used for energy at the end of their useful lives.

At this point we introduce two candidate approaches for evaluating the impact of scenario 2 (Figure 2b) on C emissions to the atmosphere: we can monitor the flows of C to and from the atmosphere or we can monitor the changes in C stocks. Our diagrams show the changes in stocks and carry the premise that to the extent C stocks increase (or are depleted less than in a reference case) in the biosphere, wood products, and unmined fossil fuels, C flows to the atmosphere are correspondingly reduced. On a global scale a flow methodology would produce the same result for the net flux of C to or from the atmosphere. A methodology based on C flows would also yield the identical result for the forest protection project described in Figure 2a; the net flow of C from the atmosphere can be accounted for by the increase in C stocks on the site. However, the two approaches have significantly different implications for the allocation of debits and credits when used to evaluate the sustainable harvest scenario. It is clear in Figures 2b and 5a that the site owner has, on site, for many years, much less C than just prior to the forest

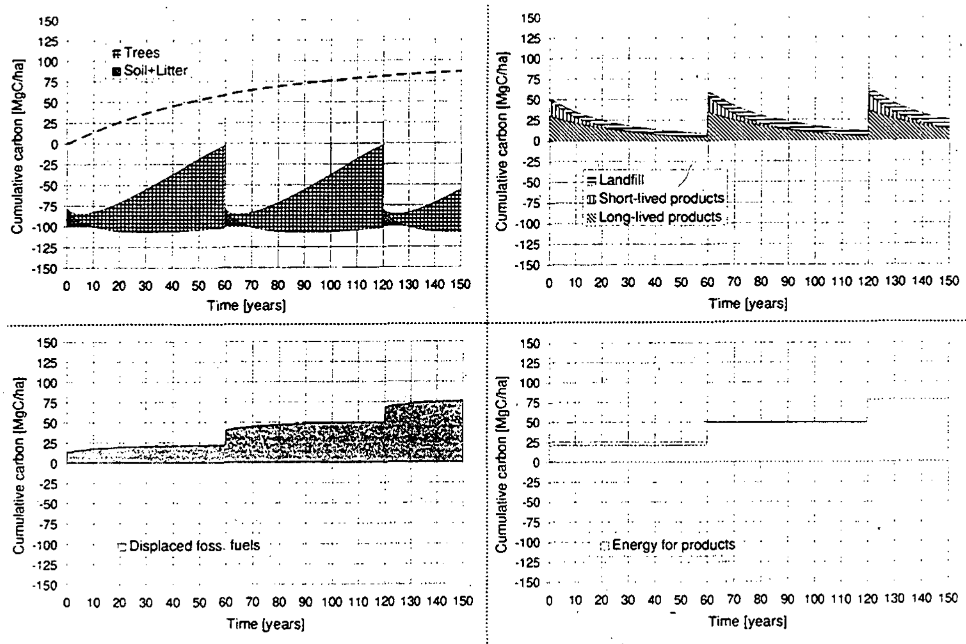

Figure 5. The components of the carbon balance in Figure 2b (sustainable harvest scenario) are depicted separately. Figure 5a (upper left) shows change in on-site C storage. The baseline of the plot is at -100 MgC ha^{-1} because of the initial loss of on-site C during harvest. As in Figure 2b, the dashed line shows, for contrast, the path of on-site C accumulation for scenario 1. Figure 5b (upper right) shows changes over time in the amount of C stored in wood products and in landfills. Figure 5c (lower left) shows the amount of fossil-fuel C not discharged to the atmosphere because of the direct substitution of biofuel for fossil fuel. Figure 5d (lower right) shows the amount of fossil-fuel C not discharged to the atmosphere because wood products are used in construction to displace concrete, steel, and glass. The credit shown is the difference in emissions between producing products of steel, concrete, and glass and producing products from wood that provide the same service.

harvest. On the other hand, the site owner has not actually discharged most of the lost C to the atmosphere (the scenario assumes that 23% of the harvest is lost during harvest and haul or is otherwise left as harvest slash to oxidize to CO_2 over a short period of time). The regrowing forest provides a continuing sink for C and someone else has taken possession of the C in the harvested wood. Even if the new owner chose to convert the land to pasture and not to allow natural revegetation orto replant, the forest manager would still physically discharge little CO_2 to the atmosphere so long as the harvested wood were transferred to another owner (perhaps another country). In a stock-change approach the site owner would be responsible for the change in on-site C (Figure 5a). A flow approach to accounting for emissions of C to the atmosphere would show in the land owner's account only the fraction of the harvest actually oxidized under the land owner's stewardship. The main part of the emissions would show up in the account of the wood-product user, perhaps even in another country.

Monitoring, verification, and attribution of C emissions become more complex for cases where wood fuels or wood products displace consumption of fossil fuels. The second scenario described here (Figure 2b) assumes that logging and sawmill residues equivalent to 22% of the initial harvest and 30% of waste-wood products are burned for useful energy (Figure 5c). This material is assumed here to be used for power generation with an efficiency such that 1 kg of C in biomass displaces 0.6 kg of C in fossil fuel — a value that seems to be typical of wood burned to displace coal in US power plants (Marland and Marland, 1992). Monitoring and verification of fuel displacement may be straightforward when wood chips are co-fired with coal in a boiler. For a dedicated facility fired with biofuels, it is less clear what fuel is displaced and with what efficiency the displaced fuel would have been used. Demonstration of fossil-fuel displacement carries an additional burden in economies where energy consumption is supply-limited, a newly available source of biomass fuel may simply increase overall energy consumption. We have made the assumption in our scenarios that the marginal fuel in current markets is a fossil fuel and that any biomass fuel used thus displaces a fossil fuel. The scenarios shown here assume that this will be coal. On a project-specific level, the project will have the burden of demonstrating the amount of fossil fuel saved. A careful and credible "base case" is required to demonstrate what fossil fuel is saved and with what efficiency.

Assuming we can estimate the amount of fossil fuel saved, there is still the question of allocating the credits. It is on the matter of fossil-fuel displacement that we encounter the most graphic illustration of the consequences of flow vs. stock-change accounting methods; that is, who gets the credits. If we adopt a stock-change methodology, the net C responsibility of the forest manager would be as illustrated in Figure 5a while the net C account for the fuel user would be as in Figure 5c. The forest manager would have net C debits until the forest was replanted or allowed to regrow naturally to its initial state, and the fuel user would get net C credits to the extent that fossil fuel use was reduced. In a flow methodology, the forest manager would show no C debit (to the atmosphere) for the C in wood fuel transferred to the fuel user. On the other hand, the fuel user would show increased C emissions because CO_2 from 1 unit of C in biofuels was discharged in place of 0.6 unit of C in coal.

The situation described above is for a 1 ha forest stand. The C balance over time appears a bit different when we consider the C balance for a sustainable forest plantation (a normal forest with a constant age structure); see Schlamadinger and Marland, 1996. In this case the forest manager would observe no change in the C storage under an accounting that measured the change in stocks of biomass, whereas the fuel user would get C credits to the extent that fossil fuel use was reduced (as above). Using the flow methodology, the forest manager would report a continuing C sink and the fuel user would, as above, show increased C emissions because CO_2 from 1 unit of C in biofuels was discharged in place of 0.6 units of C in coal.

Note also that Figure 5c shows the amount of fossil fuel actually displaced, it does not include the amount of energy used upstream to mine, refine, or deliver that fossil fuel (which would increase the benefit) nor the amount of energy required to manage, harvest, and deliver the biofuel (which would result in a decrease in the benefit). These two factors often nearly cancel out on the global scale (see Schlamadinger and Marland, 1996) and are not shown here, but they do play an important role in the accounting if we are interested in the allocation of credits and debits. A forest management project, for example, would show the energy (and CO_2 emissions) costs of forest management, harvest, and delivery but would not get the credit for reduced emissions at petroleum refineries or coal mines. Those benefits to the global C cycle probably could not be claimed by a forest mitigation project.

Finally, our scenario assumes that wood products are used to displace some mix of concrete, steel, and glass in construction. The details are in Schlamadinger and Marland, 1996, and the result is that the same service is rendered in the economy but that energy use is decreased (Figure 5d). Note that the assumption made here is similar to that made for biomass fuels. The assumption here is that wood products produced in a mitigation project add to the supply of wood available in markets and displace products made from energy-intensive materials such as glass, concrete and, steel. The C mitigation benefits will be less if wood from a mitigation project is used less efficiently or if it displaces wood from another sustainable source or some other material less energy intensive than glass, concrete, and steel. The C benefit can still be substantial if wood from a sustainable mitigation project displaces wood from an unsustainable source, e.g., deforestation. Clearly the quantity of CO_2 emissions saved depends on the mix of forest products and on precisely how forest products are used and how that service would be provided in their absence. The point here is that the C benefit may be very large on this account but that, first of all, it is very difficult to estimate what the global CO_2 savings are and, second, the savings in fossil fuel burned may be in economic sectors far from the forest and forest products sectors. And, what Figure 5d actually shows is the estimated net savings in C emissions, i.e., it is the C emissions that would be required to produce non-wood products less the C emissions that would be required to produce the wood products that would provide the same service. Consequently, the forest products sector, or a CO_2 mitigation project, would expect to see increased fossil fuel emissions for increased wood production, but would have difficulty claiming the decrease in emissions that occurred as fossil fuel use was reduced in the steel or cement industry.

5. Discussion

Forestry projects are being considered as a possibility for mitigating the increase in atmospheric CO_2. Reductions in emissions of CO_2 to the atmosphere bring public relations benefits now and may gain market value if the USA and other countries agree to binding targets for CO_2 emissions reductions. In this context, two important questions for any proposed mitigation project arise: What is the net impact of the project on CO_2 emissions to the atmosphere? Who gets credit for any emissions reductions or increases?

We have developed a mathematical model of the changes in C storage which might be expected to result from forest management choices. The model shows that, if we take a comprehensive view, there are many circumstances where it may be more advantageous to harvest forests in a sustainable manner to produce energy and other forest products and services than to simply protect standing forests to sequester C. Although any given project has to be examined for its particular details, sustainable forest harvest is favored when the forest growth rate is high and when forest products can be harvested and used efficiently. Efficient use of forest products to displace fossil fuels or energy-intensive products like steel, concrete, and glass leads to large net carbon benefits. Forest protection is favored when the rate of forest regrowth is very slow, there is a high energy cost for forest management and harvest, or the forest harvest does not efficiently displace fossil fuels or energy-intensive products.

Part of the problem in evaluating a mitigation project, however, is that the global-scale effect on net emissions to the atmosphere may not be reflected in the local-scale C balance. Much of the C mitigation benefit may accrue beyond the traditional boundaries of a forestry project. In this case it may be impossible for project participants to claim emissions credits for all of the emissions reductions that occur as a consequence of a particular project. Because of the challenges of monitoring, verification, and attribution, those responsible for a mitigation project might obtain higher emissions-reduction benefits for a forest-protection scenario than for a sustainable forest-harvest scenario; even though the latter produced, over time, larger net C benefits at the global or national scale. In many cases a forestry project could show net C debits on site in spite of net C benefits on a larger scale.

If we want to evaluate the full global impact on net CO_2 emissions to the atmosphere, we have to recognize that some of the significant impacts will be essentially impossible to capture within even carefully defined and expansive project boundaries and despite a well-conceived project baseline. These impacts will appear variously throughout the regional, national, and even global accounts as other fuel users report lower-than-baseline product output and hence lower-than-baseline fossil fuel consumption. This "leakage" into the concrete, steel, cement, petroleum refining, and other sectors may be an important part of the net impact of forest management projects on the global C cycle.

The distribution of credits and debits among participants in a biomass-based mitigation project can also depend on the choice of the accounting scheme (for example, whether a C-stock or a C-flow methodology is adopted). As described in preceding paragraphs, we think that a stock-change method — accounting for changes of C stocks not only in the forest but in wood products pools — does the better job of recognizing desired forest management practices, sustainable forest management and efficient production and use of forest products.

Another factor that becomes very prominent in our analyses is time. Figure 2b shows graphically that the net C benefit of sustainable forest harvest increases with time because the harvested products continue to displace fossil fuel use at every harvest cycle whereas a protected forest eventually achieves a steady state with respect to net C uptake. This is true, of course, only if we focus entirely on masses of C and have no preference between current and future C emissions. There is interest, then, not only in who gets credit for emissions reductions, but in their value as a function of time. It is likely that current emissions reductions will be perceived to have greater value than future reductions and that some discounting of future emissions reductions is appropriate (see, for example, Marland *et al.,* 1997).

Thus the forest manager has a near term incentive to avoid current C emissions — or to allow C uptake — by protecting C storage in the forest, while the economic incentive is to harvest standing trees for merchantable wood products now with C emissions offsets in the future as the forest regrows.

Monitoring and verification of the full impact of forestry projects on the net emissions of C to the atmosphere is a challenging task. Attribution of who gets the credits, and how credits now and later are compared, compounds the challenge.

Acknowledgments

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GLOBAL CLIMATE CHANGE MITIGATION AND SUSTAINABLE FOREST MANAGEMENT — THE CHALLENGE OF MONITORING AND VERIFICATION

WILLY R. MAKUNDI
Lawrence Berkeley National Laboratory
University of California, Berkeley, USA

Abstract. In this paper, sustainable forest management is discussed within the historical and theoretical framework of the sustainable development debate. The various criteria and indicators for sustainable forest management put forth by different institutions are critically explored. Specific types of climate change mitigation policies/projects in the forest sector are identified and examined in the light of the general criteria for sustainable forest management. Areas of compatibility and contradiction between the climate mitigation objectives and the minimum criteria for sustainable forest management are identified and discussed. Emphasis is put on the problems of monitoring and verifying carbon benefits associated with such projects given their impacts on pre-existing policy objectives on sustainable forest management. The implications of such policy interactions on assignment of carbon credits from forest projects under Joint Implementation/Activities Implemented Jointly initiatives are discussed. The paper concludes that a comprehensive monitoring and verification regime must include an impact assessment on the criteria covered under other agreements such as the Biodiversity and/or Desertification Conventions. The actual carbon credit assigned to a specific project should at least take into account the negative impacts on the criteria for sustainable forest management. The value of the impacts and/or the procedure to evaluate them need to be established by interested parties such as the Councils of the respective Conventions.

Key words: sustainable forest management, climate mitigation, criteria and indicators, carbon offset projects

1. Introduction

The forest sector plays a significant role in the accumulation of greenhouse gases (GHG) in the earth's atmosphere, and has a potential to play an even bigger role through GHG emission reduction and/or increasing carbon dioxide (CO_2) sequestration in vegetation, detritus, soils, and biomass-based products. In the IPCC Climate Change Report (1995a), it is estimated that if various measures are implemented in the forestry sector, it is possible to sequester between 1.2 and 1.8 billion tonnes of carbon (Pg C) annually for the next 50 years.

Despite the high profile accorded to forests in the climate change debate, the state of global forests and their rate of depletion had been of concern in the international community for some time. The impact of humans on the world forests has led to a decline of about a third of the original expanse estimated at 6.2 billion hectares (Lanly, 1982). The problem is more critical in the tropical regions, where an estimated 154 million hectares were lost in the decade ending 1990 alone (FAO, 1993a). As such there have been numerous efforts at national and international levels which emphasize the need to manage forest resources sustainably, with the tropical forests receiving much of the attention.

Some of the most notable initiatives include the Tropical Forestry Action Plan (TFAP) (WRI, 1987), the International Tropical Timber Agreement (ITTA, 1984) which sought to achieve a sustainable use of tropical forests, as well as the

Noordwijk Declaration (Noordwijk Report, 1989), which called for a net increase of global forest cover by 12 million hectares annually. More recently, linked to the United Nations Conference on Environment and Development (UNCED, 1992) the "Forest Principles" issued under Agenda 21 urge the global community to pursue sustainable management and conservation of all types of forests.

The twin objectives of using forestry to mitigate climate change and managing forests sustainably do pose a challenge in monitoring and verifying benefits from carbon offset projects in the sector. The purpose of this paper is to explore the concept and practice of sustainable forest management and its compatibility with global climate change mitigation. The likely impacts of various types of mitigation policies on a minimum set of criteria for sustainable forest management are identified and discussed. Issues associated with assigning credits from such carbon-offset policies/projects and the implications on a credible monitoring and verification regime are high-lighted.

2. Background

Forests have always been a primary resource in human sustenance and development. They have been the main source of agricultural and pasture land, wood fuel, solid wood, fibre, environmental services, and a host of valuable non-timber products. The dependence on forests for these and other goods and services has led to depletion of large portions of the global forests, with tropical forests being the most vulnerable due to high growth rate of land-dependent population and fast increase in the demand for tropical forest products. The severity of the problem varies across regions, but it is most critical in Asia and central and south America.

In southeast Asia, only a third of the land area is currently covered with forests (D'Silva and Apannah, 1993) and it is estimated that the rate of deforestation in India, Nepal, Philippines, Sri Lanka, Thailand, Malaysia, and Indonesia is approaching 2 million hectares per year. At this rate, the original forest cover in the region, which exceeded 725 million hectares, will be halved by the turn of the century. Furthermore, in a region which is home to about half the world's population, it is estimated that agriculture needs an additional 20-25 million ha by year 2000. This trend seems to be incongruent with the goals to increase the land area currently under forests, for example: (a) India to 30% from 23% (b) China to 20% from 13% (c) Thailand to 40% from 28% (Makundi *et al.*, 1992).

The fast growth of many economies has been driving the excessive demand for tropical forest products. About 5.5 million hectares of undisturbed tropical forests are logged every year , and another 7.5 million hectares of logged-over forests are annually re-logged (Lanly, 1982; Myers, 1984). The disappearance of forests is linked to their economic value under the existing modes of utilization. Logging is responsible for the deforestation of about 1.5 million hectares annually (FHB, 1994), which is about 10 percent of the world's deforestation. Timber is the second foreign currency earner after oil, earning $4.2 billion for Indonesia in 1991, and $3.8 for Malaysia in 1992. To make matters worse, the Asian region, which has the fastest growing economies in the world, is rapidly becoming wood-deficit and the World Bank (1992) projects that by the year 2000, the region will import forest products to the tune of $20 billion a year. For example, India has seen its import bill for industrial roundwood expand from $1.8 million in 1981 to $124 million in 1991. Such trends are at the root of the various efforts intended to manage forest resources sustainably.

Associated with the deforestation and consumption of forest products are emissions of GHG to the atmosphere. The world's forests store large quantities of carbon, estimated at 340 Pg C in vegetation and 620 Pg C in soils. Changes in land use in lower latitudes are estimated to contribute between 1.1 to 2.1 Pg C of net emissions annually into the atmosphere (IPCC, 1995b), mostly from south and central America and Asia. This trend is projected to worsen to varying degrees in each region. For example, in the absence of effective mitigation policies, the Asian forests, which are currently responsible for about 6% of the rise in atmospheric CO_2, are projected to contribute much more because they are uniquely close to centers of rapid economic and population growth, and so they are more vulnerable than comparable expanse of forests in other regions (World Bank, 1992). The deforestation of the Amazon continues to dominate emissions from land-use changes (Fearnside, 1996).

However, forests can also play a major role in absorbing atmospheric carbon. There is a large capacity for forest ecosystems to sequester carbon by increasing biomass density in existing forest lands through natural and enhanced regeneration, as well as expanding carbon stocks by conversion of non-forest lands to forests. The mid- and high-latitude forests are estimated to be a net sink of between 0.5 and 0.9 Pg C annually (Brown *et al.*, 1996). Although there is some controversy over biomass equilibrium in mature forests, a few recent studies seem to suggest that some apparently mature tropical forests sequester up to 2 tC per hectare annually (Grace *et al.*, 1995; Lugo and Brown, 1992).

Measures to reduce emissions from land-use changes, as well as a combination of carbon sequestration in existing forests and in new forests, offer a real opportunity to reduce the amount of CO_2 in the atmosphere, most of which comes from burning fossil fuels. The United Nations Framework Convention on Climate Change (UNFCCC) as indicated in paragraph 1 (d) of Article 4 of the Convention commits signatories to:

> promote sustainable management and cooperate in the conservation and enhancement of sinks and reservoirs of all greenhouse gases not controlled by the Montreal Protocol, including biomass, forests and oceans as well as other terrestrial, coastal and marine ecosystems (United Nations, 1992).

Other sections of the UNFCCC specifically require systematic observation of pertinent areas related to the climate system, including inventory of GHG and the impact of response strategies.

Pursuant to the commitment to manage forest resources sustainably, the United Nations Council for Sustainable Development (UNCSD) established the Inter-governmental Panel on Forests (IPF) in 1995, with a mandate to formulate relevant policies for meeting the challenges of sustainable forest management. Other related instruments resulting from the UNCED process that have a direct bearing on the management of global forests include the Convention on Biological Diversity and Convention to Combat Desertification. These policy instruments must be taken into account when addressing the role of forests in the global climate system.

Reconciling the two objectives of managing forest resources for climate-change mitigation and achieving sustainable forest management pose some interesting challenges arising from the ambiguous definition(s) and the existence of diverse multiple objectives for sustainable management of forests within the context of sustainable development.

2.1 DEFINITIONS OF SUSTAINABILITY

The verb sustain originates from the Latin word *sustenere*, meaning to maintain at an elevated position. In practice, the concept of sustainability alludes to an unending state, be it of a static entity or of a dynamic process such as the use of resources. In its theoretical form, sustainability involves a perpetual time frame, but in practice the time horizon implied is that period within which the level of the static or dynamic "state" is desired. Whereas sustainable supply of oxygen refers to infinite time horizon, the sustainable supply of coal may only refer to a few decades needed to phase out the use of such an energy source.

In the conventional resource-utilization context, the concept has often been used to refer to a physical concept of either a single resource or of an intertwined group of resources such as an ecosystem. The emergence of a more comprehensive school of thought, which approaches sustainability as a socio-economic concept associated with the management and use of physical resources (Dixon and Falcon, 1989), has broadened the debate and made the practical application of the concept much more complex.

Sustainable development was defined in the World Commission on Environment and Development Report, commonly known as "The Brundtland Commission," using very general but compelling language. The term was defined as:

> development that meets the needs of the present without compromising the ability of future generations to meet their needs (WEC, 1987).

In order to translate this general definition to specific applicable policies, a myriad of definitions have sprouted everywhere (Michael, 1992), serving different interest groups, at times with diametrically opposed objectives (O'Riordan, 1988). Different countries have tried to formulate relevant policies of varying degrees of sophistication to achieve sustainable development. One of the more comprehensive coverage of the term is contained in Costa Rica's Sustainable Development Strategy (Quesada, 1990), where sustainability is defined as:

> ...a dynamic process in which management of natural resources, the empowerment of human beings, the focus of scientific and technological development, the formulation of new legal and administrative schemes, and the orientation of the economy fortify the options to satisfy the basic necessities of the current generation

without destroying the ecological base or the life support systems on which future development and environmental quality depend.

The concept of sustainable development is historically related to sustainability of a natural resource in use. In resource management such as forestry, fishing, and wildlife, the concept is commonly referred to as sustained yield, which has been used to imply "*a harvesting regime for a reproducible natural resource that could be maintained over time.*" In forestry, the concept has its formal roots from the 19th century German forester Faustmann (Gane, 1968) who advanced a framework for determining the economic rent for land used for perpetual forest management.

In ecology the concept of sustainability is used more broadly, and in general carries the meaning of "*preserving the status and function of entire ecological systems.*" On the other hand, in economics, the concept is used with emphasis on the "*maintenance and improvement of human living standards,*" in which natural resources and the environment are only a part of the story. In other fields such as geography and anthropology, the term is used with emphasis on "*maintaining social and cultural systems*" such as the preservation of indigenous peoples' knowledge (O'Riordan, 1998, *op.cit.*)

To effectively be translated to natural resource management, the concept of sustainability must be construed to include the preservation and maintenance of a reproducible resource or the capacity to produce the goods and/or services obtainable from it by current and future generations. This would tend to include the emission reduction role of the forest. However, the additional sequestration role does not automatically derive from the conventional sustainability concept, but is here treated so since climate mitigation is one of the contemporary roles of global forests. To discern the ecosystem's ability and potential to provide these functions, one needs to know the initial state of the resource, which tends to lead to different sustainable stream of outputs, each requiring different set and amounts of inputs to achieve. Such initial states may include: (i) equilibrium forest ecosystems — mature forest, (ii) growing forest, *e.g.*, secondary forest or a young plantation or (iii) non-forested land, *e.g.*, grasslands, exhausted and abandoned agricultural land, and other land uses convertible to forestry.

Under an equilibrium forest ecosystem, sustainability alludes to conservation of the ecosystem, such that it maintains its ecosystem functions. Such measures may include protection against natural disturbances such as catastrophic crown forest fires or epidemics, which may significantly alter the ecosystem. However, since most ecosystems are degraded by human activities such as conversion to agriculture, pasture and harvesting, the most effective measures to conserve such areas should be those geared towards eliminating human encroachment, including rural development policies, harvesting of non-timber forest products, land tenure, tax disincentives, gazetting, and surveillance of protected areas .

Sustainability of an ecosystem, which initially constitutes a growing forest such as a plantation or secondary forest, must be consistent with the desired future use of the forest area. If the area needs to be reverted to an equilibrium ecosystem, then the case becomes the same as that discussed above. If the area is slotted for production forestry, then sustainability of this ecosystem implies the ability of the forest to recover from disturbance(s) and produce the desired goods and services repeatedly. Measures to make this possible may include active management of the area, enhanced regeneration, and even altering the species composition through partial or complete introduction of other desired species. A monocultural forest plantation constitutes an extreme form of this regime and will be referred to as sustained yield management as described below.

The third type of initial state involves non-forested land such as grasslands and abandoned pastures or agricultural lands. Sustainability of such areas must also be consistent with the desired transitional and final state. In some cases, the land needs to be left as open grassland or rangeland to play its necessary role. In other cases, these areas are amenable to conversion to other land uses through afforestation, natural or enhanced regeneration, eventually turning to a desired ecosystem like production forest, catchment area, soil stabilization forest, etc. It is obvious that sustainable forest management can only be defined within the parameters of the initial state of the ecosystem, as well as the desired transitional and final state of the area. Managing forests to meet specific or general human needs has been practiced to a degree for some time.

In the context of this paper, we will use a definition of sustainable forestry as *that management regime which produces forest products and services at a level compatible with the maintenance of the ecological processes that sustain the forests* (Johnson *et al.,* 1993). Although this is applied more frequently to natural forest management, the idea is just as valid for human-grown or modified forests. The sustainability aspect covered here does not address the "deep ecology" point of view, which tends to discount the superiority of human needs over other species.

This definition of sustainable forest management is still deficient since it mainly focuses on streamlining the supply of goods and services from the resource, without paying any attention to the demand structure which dictates the levels of consumption. Taking the demand and prices as exogenous to the management regime will force the examination of sustainability to be mainly concentrated on physical flows of goods and services from the forest, and pay little attention to the social and economic factors surrounding the use of forest resources.

2.2 SUSTAINED YIELD IN FORESTRY

The apparent change in paradigm between conventional *sustained yield* and that of *forest conservation and sustainable development* is now finding more and more coverage in the literature (Damodaran, 1992; D'Silva and Appanah, 1993 *op. cit.*; FAO, 1993b; Aplet, 1993; Maser, 1994). As mentioned earlier, sustained yield management has been used in forestry to imply the production of steady and perpetual flow of timber. The extreme idealization of this is what is referred to as a "normal forest", which constitutes a forest with an age structure which allows for production of equal annual volume of wood in perpetuity (Brasnett, 1953).

Although the concept of sustained yield was initially conceived for even-aged forests (Gane, 1968 *op. cit.*), various technical approaches have been tried to apparently achieve what has often been referred to as sustainable forestry in natural forests. Such practices typically involve some silvicultural operations such as liberation of desirable species by cutting climbers and opening canopy, as well as transplanting desirable species (often commercial timber spp.) to increase their density, and light pruning to enhance vertical growth and merchantibility of desired species. The regime has also discouraged clear-cutting and emphasized less destructive harvesting methods commonly known as selective harvesting *e.g.*, patch and strip-felling, shelterwood selection system, single tree extraction, etc. Although there are relatively few natural forests managed this way (Poore *et al.*, 1989), there is no good evidence that this regime constitutes sustainable management, even for timber production (WRI, 1991).

It is argued that the system has not been in use long enough in diverse enough ecosystems to allow a comprehensive evaluation of its performance under the stated objectives. Furthermore, some evidence exists to show that selective harvesting has been associated with substantial damage to non-target vegetation (Johnson and Carbale, 1993). The manipulation of species structure tends to favor those species which are more valuable under current utilization technologies and consumer preferences, thus reducing the sustainability of the other timber species which have potential uses given technological and market changes. It would therefore seem that sustained yield forestry is but a subset of sustainable forest management which focuses on timber production, while the latter covers a wider array of goods and services.

2.3 NATURAL FOREST MANAGEMENT

Although the concept of sustainable forest management has its roots in sustained yield forestry, it involves a broader scope and more complex spectrum of goods and services. However, the case for sustainable management of natural forests has mostly been based on showing that the economically useful species regenerate naturally after initial harvesting, and in a few cases, after the second rotation (Keto *et al.*, 1990; Poore *et al.*, *op. cit.*). The case against this claim is based on the fact that natural regeneration covers only a few species and it has not been shown that the pre-harvesting species and biomass density is ever achieved in successive rotations (Moad, 1989). This historical caveat not withstanding, most policies on sustainable management of natural forests seem to imply a desire for restoration of the ecosystem to its pre-utilization condition, involving regeneration of the original species mix, restoration of soil conditions and re-constitution of the ecological functions of the area (Freezailah, 1994). However, a deeper examination of this widely held view on sustainability of natural forests reveals a more complex reality.

For a production forest, a complete re-constitution of the prior ecosystem may not be feasible, neither desirable — given the management objectives. Once the forest is sufficiently disturbed, some of the macro and micro ecosystems are altered in very profound ways, unleashing a mosaic of dynamic processes at species and substrate level. Such changes may include the edaphic and microbial conditions, hydrological and temperature regimes, extent and duration of exposure to light, structure of the residual vegetation, and a different regenerative mixture of seeds, seedlings, saplings, and coppices. These conditions dictate the dynamic processes which will eventually lead to a new equilibrium. Under an irrevocably degraded ecosystem, possibly from unsustainable forest resource utilization, the new eco-equilibrium is significantly different from the pre-utilization equilibrium.

There are other important transitional-state issues which need to be addressed when dealing with ecosystems which have been disturbed by human activity or natural causes. Even if the utilization was conducted in such a way that it would ensure a re-constitution of the original ecosystem, such a process takes a long period of time. Different utilization regimes lead to different recovery paths each with different time horizons, and none with a 100 percent chance of total re-constitution. Each path has a different probability of recovery, depending on *inter alia,* the initial conditions, the disturbance intensity, the likelihood of seeding (*e.g.,* from surrounding vegetation), and most important of all, the nature of intervening events after the disturbance, whether natural or anthropogenic.

It is also important to note that the disturbed ecosystem was not a static system, but rather a dynamic mosaic of biota, substrate and ambiance. Although the forest may be seen as a stable equilibrium, there are processes and micro ecosystems which are constantly changing. Indeed, the whole forest may actually be in a particular stage of change, except that most of the natural and normal change is quite slow, thus giving an impression of an equilibrium at the macro-ecosystem level. It is not obvious that the entire ecosystem can ever be re-constituted, neither is it obvious that this is necessary for sustainability to be realized. Strict interpretation of re-constitution would require one to predict the ecosystem structure and function at the future date, upon which the recovering forest area can be evaluated and compared. This is a difficult task that can be approximated through comparison with undisturbed ecosystems of same/similar structure prior to the disturbance.

On the other hand, one has to acknowledge that the ecosystem function is a continuum which has various utility to humans at different time periods. Timber may be the product which is harvested 30 years after the initial disturbance, but other annual and shorter-term products may actually be available prior to full recovery. Water catchment capacity is one such service, as well as herbs and fruits. There exists other transitional functions which would not otherwise have been obtained under the initial equilibrium. A good example is the fact that the pioneer vegetation after harvesting (especially clear cutting) precedes a climax vegetation and some of the functions of the pioneer ecosystem are different from the climax ecosystem. Herbs, fruits, pollen, and habitat provided during the transition is a different set of goods and services, some of which can not be provided by mature climax vegetation.

Transitional goods and services from recovering deforested areas which meet Brundtland Commission definition of sustainable development with regard to satisfaction of inter-generational needs, tend to lend credence to the more liberal definition of sustainable forest management. Such a view must consider recovering natural forest as an integral part of a natural forest sustainable management system, which provides various goods and services as secondary forests compared to climax forests. If transitional forest products and services are included in the examination of sustainable forest management, the issues of monitoring and verification must then include measuring the production adequacy during these transitional states, and not only the production capacity of the equilibrium states.

To the extent that forestry policies or projects are intended to mitigate climate change — such as those falling under JI/AIJ iniatives, their impact on sustainable natural forest management should be assessed in light of the issues of re-constitution, transition, and equilibrium states of the ecosystem. Monitoring equilibrium-state goods and services can be undertaken using standard biometrical and productivity tracking methods. Surveys and biomass studies are the most common methods to estimate timber output and other products. Transitional products and services such as fruits and hydrological control, can be monitored periodically as they come on stream. These products and services will vary from one project to another, and over the lifetime of the project, and as such, accounting for them should be based on established methods for measuring the ecosystem's yield at various times. However, the climate mitigation benefits should be evaluated against some clearly defined criteria for sustainable forest management, paying specific attention on the impacts of such projects/policies on the criteria.

3. Criteria for Sustainable Forest Management (SFM)

In policy analysis, a *criterion* is defined as a distinguishing characteristic of an instrument that provides policy framework, while an *indicator* refers to a measurable variable in relation to a criterion (Maini, 1993). More specifically, FAO (1995) defined a criteria in this context as "identified elements of sustainability against which forest management can be assessed." Ecologists have identified a set of minimum ecosystem health indicators which should be used to monitor the state of a forest which has been disturbed in comparison with the preceding virgin ecosystem (Johnson and Carbale, 1993).

3.1 ECOSYSTEM HEALTH INDICATORS

Assessment of the following list of indicators provides a good basis for evaluating the health of a given ecosystem, which in turn forms one of the tenants of determining whether an ecosystem is being managed sustainably given the social objectives.

(i) *Biodiversity*

The status of fauna and flora at various intervals, especially those responsible for seed dispersal and pollination of plants on-site and off-site is important for biodiversity assessment. A healthy ecosystem with biologically diverse populations should have the capacity for natural regeneration of important pioneer and climax species and to accommodate a natural balance of animal, insect, and bird populations. In its broader definition, biodiversity does subsume most of the other ecosystem health indicators since it includes landscape patterns, habitat and guild structure, taxic composition, hydrological characteristics, etc. However, for the purpose of assessing SFM criteria, these indicators need to be addressed separately.

(ii) *Nutrient status*

Availability of mineral and organic nutrients, including the rate of depletion or accumulation provide information about the capacity of the ecosystem to support vegetation.

(iii) *Microbial and soil fauna*

Density and activity levels of soil modifying microbes and micro/macro fauna.

(iv) *Hydrological characteristics*

Thawing, water quality, flow, retention, and evapo-transpiration rates.

(v) *Edaphic and landscape stability*

Soil erosion and translocation of litter and organic matter to other areas, including downstream water bodies.

(vi) *Microclimate*

Soil temperature, moisture, and humidity govern germination and seedling/sapling survival.

(vii) *Natural disturbances*

Propensity of fires, epidemics, wind impact should be monitored over time.

Unsustainable forest management has adverse impacts on each one of these indicators. Although the indicators tell us the health of the ecosystem, sustainable forest management is not always defined or interpreted from this point of view. Various institutions such as the International Tropical Timber Organization (ITTO) and the United Nation's Food and Agricultural Organization (FAO) have attempted to identify the essential elements of a sustainable forest management policy. Since 1990, but more so after UNCED summit in Rio, there have been a number of efforts to identify the relevant criteria and indicators for sustainable forest management. The conclusions of each of these initiatives reflect the forces driving the effort, although some common elements appear in each set of criteria and indicators. The three levels of interest, that is global, national and management-unit, necessitate identification of criteria which address each level's concerns.

The ITTO, responding to timber market pressures, came up with five national criteria with 27 associated indicators and six site-level criteria with 23 indicators. The most important criteria are summarized in Section 3.2. In 1994, the European Union through the Helsinki process arrived at a combination of six criteria and 27 indicators for sustainable forest management, while a non-European group concerned with temperate and boreal forests under the so called Santiago Declaration in 1995 identified six criteria and 67 indicators (ISCS, 1996). Both the Helsinki and Santiago initiatives were responding to pressures from environmental groups concerned with respective forest ecosystem management. On the tropical front, the eight countries which are signatories of the Amazonian Cooperation Treaty advanced the Tarapoto proposal, listing 12 criteria with 77 indicators, with the emphasis being on the sustainable utilization of the Amazon resources for their national socio-economic development, while paying some attention to environmental concerns. The last major effort was a proposal with seven criteria and 47 indicators for Dry-Zones in Africa which was spearheaded by the UN as an outgrowth of the UNCED process. Since our main interest lies in the compatibility of sustainable forest management with climate mitigation policies and/or projects, we will use the ITTO and FAO criteria to highlight the areas of compatibility and contradiction which must be addressed in the course of monitoring and verification of such projects.

3.2 ITTO'S CRITERIA FOR SFM

One of the first institutions to put forth criteria upon which sustainable forest management should be based was the ITTO. Article 1(H) of the International Tropical Timber Agreement (ITTA, 1983), the legal instrument which instituted ITTO, clearly states that the objective of the organization is "to encourage the development of national policies aimed at sustainable utilization and conservation of tropical forests and their genetic resources, and at maintaining the ecological balance in the regions concerned" (ITTA, 1983, 1994). Pursuant to a 1988 survey (Poore *et al.*, 1989) of sustainable management in tropical timber producing countries which found that only a negligible amount (less than 1 million hectares) of the world's moist tropical forests were managed sustainably, and consistent with the agreement's preamble and article 1(H), the ITTO issued a working definition of sustainable forest management in 1990. This definition emphasizes *production of a continuous flow of desired forest products and services without undue reduction of the forest's inherent values and future productivity, and without undue undesirable effects on the social environment* (ITTO, 1992). In an attempt to translate this principle into a policy framework, the organization issued a list of 41 guidelines intended to move countries towards the goal of sustainable forest management (ITTO, 1990).The following criteria constitute the key elements addressed by the guidelines:

(i) *Establishing a permanent forest estate.* A need to establish a permanent forest estate (PFE), whether public or private, in order to secure optimal contribution of forests to national development. The main categories to be set aside include land for nature conservation, protection forestry, timber production, and other forest products, or a combination of these objectives. The guidelines recommended that in establishing the PFE, the area should be surveyed and clearly demarcated in consultation with surrounding populations, taking into account their present and future needs for agricultural land and their customary use of the forest.

(ii) *Conservative harvesting levels.* A need to set conservative harvesting levels (annual allowable cut) bearing in mind current limited understanding of tropical forest dynamics. In practice, this will mean conservative setting of rotation age, felling cycles, girth limits, and selection intensity, parameters which will be amended as permanent sample plots begin to yield more reliable information about the forest dynamics. Environmental impact assessment should be carried out prior to harvesting, and logging damage to residual vegetation minimized.

(iii) *Involvement of local people.* In recognition of the importance of social issues, the guidelines state that the success of forest management for sustained timber production depends to a degree on its compatibility with the interests of local populations, and they should be consulted prior to planning and implementing forestry operations.

(iv) *Strong political commitment.* A need for a strong political commitment to a national forest policy on sustainability, supported by legislation and in harmony with other sectors. The interests of all players should be considered, with the concessionaires ensured of long-term viable concessions. Benefits of local population must be taken into consideration while management and governments receive sufficient revenues from the operations, since forest management for timber production can only be sustained in the long term if it is economically viable.

The ITTO hopes that if such criteria are adhered to, the tropical timber-producing countries will move closer to a more sustainable forest management, with a strong emphasis on timber production, without blatant disregard for the other products and services from the forest estate. There is still some skepticism on the effectiveness of this policy because the criteria are seen as too narrow with the timber production aspect dominating the other aspects (Goodland, *et al.*, 1990).

A recent study by Rice and Gullison (McRae, 1997) on the effect of applying the ITTO criteria to the Chimanes Permanent Timber Production Forest in the Bolivian Amazon indicates that this criteria tends to lead to a serious loss of biodiversity, mainly due to the silvicultural requirements for regeneration of the targeted timber species; in this case the shade intolerance for mahogany. Under certain circumstances such as the remoteness of the forest, prevailing interest rates, enforcement regimes, etc., even the commercial timber trees for which these criteria of sustainability is focused get severely depleted. Such concerns have made the development of a more comprehensive set of criteria for sustainable forest management very imperative. In response to this need, the UN FAO (1995) proposed a short list of basic objectives which would form the foundation for a sustainable forest management policy.

3.3 FAO'S CRITERIA FOR SFM

The FAO's criteria incorporate most of the ecosystem health indicators, but also address some of the key services of tropical forests, including climate change. The following is the summary of the criteria and the corresponding indicators:

(i) *Protection of biodiversity.* This will involve setting aside areas deemed necessary for biodiversity and protecting from encroachment those already conserved for this purpose.

(ii) *Maintenance of forest productivity,* which will ensure a sustained flow of forest products for human consumption, from both natural and human-grown forests.

(iii) *Maintenance of forest vitality* to ensure and/or increase the capacity of the forest to support life. Also maintain and improve the resilience of the ecosystem.

(iv) *Protection of soil and water,* specifically for reducing soil erosion and improving water catchment role of the forest. Soil protection will also reduce emissions of soil carbon and enhance soil carbon storage.

(v) *Contribution in carbon cycling*. Under this item, emphasis should be on:
- utilizing biomass to substitute fossil fuels e.g. biomass-based power plants to replace fossil fuel electricity generation,
- sustainable harvesting of timber from natural forests.
- plantation timber substituting for emission intensive materials such as steel, cement and plastics in construction, industrial packaging and in furniture,
- plantation timber production to substitute for natural forest timber,

(vi) *Enhancing social and economic benefits* through:
- sustainable harvest of timber and non-timber products
- matching demand and supply of forest products and services (both short and long term)
- by generating incomes, employment, taxes, foreign exchange, and improvement of rural infrastructure.

The theme of this criteria for sustainable forest management is to run the forest estate for provision of goods and services while maintaining the integrity of the ecosystem. However, some of the objectives may prove to be contradictory when applied in small ecological units. For example, economically viable timber harvesting may not be reconcilable with maximization of biological diversity on the same forest tract. It is unlikely that timber harvesting can be reconciled with biodiversity of rare insects, epiphytes, microbial organisms, or avi fauna. Another objective which contradicts some of the sustainability criteria is reduction of net carbon emissions. While the objective for contribution to carbon cycling deals with climate change issues directly, each of the other objectives have an indirect impact on GHG emissions and/or carbon sequestration in the forest sector. In the next section, we examine the relevance of sustainability criteria from the various foci to climate change mitigation.

4. Sustainable forest management and climate change mitigation

As mentioned earlier, sustainable forestry has often been explored using the physical resource approach, where sustainability consists of managing the forest resource without reducing the stock, which in turn is determined by site factors such as nutrient availability, climate, precipitation, species composition, etc. If the ecosystem is in equilibrium in terms of biomass, any harvesting involves drawing down the stock, albeit temporarily. Biomass harvesting for sustainable forest management involves the removal of biomass not exceeding the periodic growth (usually mean annual increment). For this to be consistent with the broader definition of sustainable development, such harvesting has to observe the SFM criteria as well as fall within the legitimate human needs. Since it is difficult to determine the appropriate level which is required by society, the minimum one could do is to utilize as much of the biomass extracted as possible and assume that in the absence of major distortions in the economy, prices will arbitrate the optimal level of consumption.

Different practices in forest management may be construed to be sustainable, and yet they have distinctively different implications to biodiversity as well as carbon cycling. The classical examples often quoted are those involving the conversion of natural forests to rubber plantations (*e.g.,* Malaysia, Thailand, Indonesia, etc.), versus latex tapping from rubber trees in natural forests (*e.g.,* Brazil, Bolivia, etc.). The former constitutes an economically sustainable regime, although it has a very low biodiversity index, while the latter is economically unsustainable (due to competition from rubber plantations) but is environmentally sustainable with a high biodiversity index. The two options have very different GHG implications. Determining the criteria which carries more weight is at the core of the problems of reconciling the SFM objectives to those of climate mitigation.

In this section, we attempt to link the issues associated with climate change mitigation in forestry to the specific standing policies under sustainable forest management. The problem is first examined at general policy level to see how sector-wide mitigation policies interact with sustainability criteria. Then we discuss the likely impact of specific types of mitigation projects on the SFM criteria.

4.1 SECTOR-WIDE MITIGATION POLICIES

At general level, mitigation policies must address the areas where significant reduction of emissions and/or carbon sequestration are possible. The most effective mitigation policies should reduce emissions through reduction of deforestation. Sustainability at the forest management unit level must take place within a conducive framework of sustainable management of the forest sector, preferably as a part of a sustainable development policy. An area of priority would be to formulate policies which address the core causes of tropical deforestation.

By and large, tropical forests are lost through clearing for farming and pasture, extraction of woodfuel and fodder, and excessive commercial logging. In general, the process is driven by socio-economic policies governing land use, development strategies, trade, and other macro-economic policies. However, at the sector level, the three major failures which underlie the tropical deforestation crisis include those related to *economic policy in forestry, institutional inadequacies,* and *lack of technological improvements.*

In the policy area, there has been a divergence between private and social costs, that is, those who derive private benefits from the public forests do not compensate society the full costs associated with their actions which is borne by others. The symptoms of these failures include setting stumpage prices lower than the cost of replacing the removed trees under various guises such as supporting forest-based industrialization in the country by using cheap local inputs.

The institutions which are in place were established decades ago, in most cases during colonial era, with structures which served the mandates of the time, mainly to administer harvesting of timber resources for the metropolis, and protect the forests from "encroachment" by local communities. For historical reasons, these institutions lack community support, and they operate in an environment with ambiguous property rights. As such, they can not adequately serve the contemporary purposes of social forestry and multiple-use management for local and global environmental services.

The technical factors contributing to deforestation include lack of adequate information on the dynamics of the ecosystem, *e.g.*, species structure, growth rates, interdependence of members of the ecosystem, poor understanding of impacts of various harvesting schemes, use of old vintage technologies for converting timber to products, etc.

Changes at the level of forest policy, institutions, and technological improvements which reduce deforestation are most likely going to be consistent with the SFM criteria. However, in the short term, there may be some dislocations as may happen in the case of laid-off workers who were dependent on a logging company which was operating unsustainably. The intertwined nature of the economy and the critical position of forestry as a primary sector makes it difficult to monitor and verify the impacts of sector-wide mitigation measures.

Modifications in stumpage-pricing policy, increases in concession fees, or establishment of decentralized and more responsive institutions, and increased research efforts can be monitored and their implementation be verified at various times. The impact of such policies cannot be easily assigned to each individual aspect, but a change in the trend of deforestation should be considered as an indicator of their effectiveness. However, due to intersectoral effects and linkages between policies, the verification regime should carefully include assessment of new or other policies in the sector and related sectors which reverse and/or contravene the intent of the mitigation policies. Monitoring the deforestation trend by itself is not adequate to evaluate the impact of these general level measures.

4.2 IMPACT OF MITIGATION PROJECTS

Climate change mitigation projects in forestry involve three types of actions. The most effective in the short term are the GHG emission-reduction measures such as forest conservation and efficiency improvement in biomass extraction and utilization. The second type involves sequestering carbon in existing and expanded ecosystems such as in reforestation, afforestation, and agroforestry. The last projects are those intended to substitute non-renewable carbon-intensive products such as fossil fuels, chemicals, construction material, and unsustainably harvested wood with sustainably grown biomass and its derivatives. Each one of these mitigation policies is related to sustainable forest management in some form. To examine the interaction of these two major objectives, we will use the FAO criteria which seem to offer potentially good stewardship of forests and possibly a good chance for sustainable forest management.

In the criteria listed under Section 3.3, carbon cycling is explicitly mentioned as an objective of SFM. However, each one of the sustainable forest management objectives is collaterally related to climate change via GHG emission reduction or by carbon sequestration. Also, the feedback effects from climatic change such as CO_2 fertilization, succession and migration of ecosystems, etc. will impact each one of the SFM criteria (Solomon and Cramer, 1993). It should be borne in mind that any assessment of the interaction between carbon offset projects and SFM criteria is complicated by the uncertainty in the dynamics of natural forests and the long production periods involved. In natural forest management, cause and effect can not easily be predicted (Maser, 1994).

Assessing the performance of a management regime given a set of criteria may pose some difficulties due to lack of comparable indicators (Prabhu, 1994). Criteria such as preservation of biodiversity or degree of social acceptance may not be easily measured and trade-offs between criteria are even more difficult. The complex dynamics of forestry make any action or policy implemented in the sector have multiple inter-related effects, many of them being incidental to the main objective of the policy. In this section we will attempt to discuss the collateral impacts of mitigation projects on sustainable forest management.

In previous sections we alluded to the various types of indicators and criteria which have been put forth by different sources. To illustrate the pertinent issues of SFM and climate mitigation in forestry, we have listed the FAO criteria in Table 1 against the various types of mitigation projects in forestry. We try to score in each case the likelihood of impact of a typical project in each category on the SFM criteria, showing whether the criteria will be affected positively (enhanced), negatively (harmed), or whether the project has no impact (neutral). The usefulness of such information is to indicate how each project will influence SFM criteria. The mitigation criteria, *i.e.,* emission reduction or carbon sequestration, should be considered in light of the impact the project has on other standing commitments towards sustainable forest stewardship.

The country in which the project is to be implemented may already be committed to the SFM criteria in prior international agreements such as the biodiversity convention. SFM may be vital to existing national aspirations as indicated by plans on resource management. To the extent that the effect of a given project is non-neutral, the monitoring and verification regime must include thorough assessment of the impacts on SFM criteria over and above the emission reduction or C-uptake goals of the project. The impacts that enhance other standing criteria may not be as contentious as those which negatively affect the criteria. In any case, the inclusion of such impacts in cost-effectiveness indicators of a given mitigation project will depend on the evaluation of the collateral impacts. The final value may require some level of bargaining between interested parties, for example, between the Secretariats for CBD and FCCC or their functionaries.

4.2.1 Protection and conservation projects

As shown in Table 1, there are a variety of possible mitigation projects which are likely going to reduce emissions through protection of the ecosystem. Such projects may be undertaken specifically for climate mitigation purpose, or for conservation objective, with carbon as a collateral effect. Each project type will be examined assuming that its primary objective is climate change mitigation.

Projects for wildlife protection (flora and fauna) are more likely going to enhance carbon cycling. Those which are intended for forest protection will

Table 1. Impacts of Climate Mitigation Projects on Sustainable Forest Management

Types of Mitigation Projects	Projects	Sustainable Forest Management Criteria					
		Protect Biodiversity	Maintain Forest Productivity	Maintain Forest Vitality	Protect Soil & Water	Contribute to carbon cycling	Enhance socio-economic benefits
Protection and conservation	Wildlife protection	+ + + 0	+ 0 - -	+ + 0 -	+ + + 0	+ + 0 -	+ 0 - -
	Recreational reserves	+ 0 0 -	+ 0 - -	+ 0 0 -	+ 0 0 -	+ + 0 -	+ + 0 -
	Water catchment	+ + + 0	+ 0 - -	+ + 0 0	+ + + +	+ + 0 0	+ + + -
	Soil conservation	+ + + 0	+ 0 0 -	+ + 0 0	+ + + +	+ + 0 0	+ + + -
	Fire protection	+ 0 0 -	+ + 0 -	+ 0 0 -	+ 0 0 -	+ 0 0 -	+ + 0 -
	Protection against natural disturbances	+ + 0 -	+ + + 0	+ + 0 0	+ 0 0 0	+ 0 0 0	+ + 0 0
Efficiency improvements in harvesting and biomass use	Reduced Impact logging	+ + 0 0	+ + + -	+ 0 - -	+ + 0 -	+ + + 0	+ + + 0
	Improved biomass conversion efficiency	+ 0 0 0	+ + 0 -	+ 0 0 -	+ 0 0 0	+ + 0 -	+ + + +
	Residue utilization for tertiary products	0 0 0 0	+ + 0 0	0 0 0 -	0 0 0 -	+ + + 0	+ + + +
	Pre-conversion salvage operations	0 0 - -	+ 0 0 -	+ 0 0 0	0 0 0 -	+ + 0 -	+ + 0 0
Substitution for fossil fuels, and high-emission goods, and unsustainably grown wood	Short rotation forestry for biofuels	+ 0 - -	+ + + 0	+ 0 - -	+ 0 - -	+ + + +	+ + 0 -
	Substitute unsustainably grown biomass	+ + 0 0	+ + 0 0	+ 0 0 0	+ + 0 -	+ + + +	+ + + 0
	Waste use for energy	0 0 0 0	+ 0 0 0	0 0 0 -	0 0 0 0	+ + + 0	+ + + 0
Carbon sequestration	Afforestation	+ 0 - -	+ + + -	+ 0 - -	+ 0 - -	+ + + +	+ + + -
	Reforestation	+ + + +	+ + 0 -	+ + + 0	+ + + 0	+ + + +	+ + 0 -
	Rehabilitation	+ + + +	+ + 0 -	+ + + 0	+ + + 0	+ + + +	+ + + -
	Agroforestry	+ + 0 -	+ + 0 0	+ + 0 -	+ + 0 -	+ + + 0	+ + + +
	Non-timber tree farms	+ 0 - -	+ + 0 -	+ 0 - -	+ 0 - -	+ + + +	+ + + 0
	Urban & community forestry	+ + 0 -	+ + 0 -	+ 0 - -	+ 0 - -	+ + + 0	+ + + 0

Key: + = enhances the SFM criterion; - = negatively affects criterion; 0 = No impact on criterion. Score in each category shows the likely impact of such projects to the SFM criterion, e.g., +++- mostly enhances criterion with a minority of projects which can contravene the criterion. 00++ implies the project will most likely impact the criterion negatively.

conserve carbon, and if the ecosystem was not in biomass equilibrium, there is an opportunity to sequester carbon. If the project is geared toward protection of wild animals, the contribution to carbon cycling will depend on the wildlife management regime. In the extreme, the project may loose carbon if the animal population grows to exceed the carrying capacity of the reserve. Evidence of habitat destruction by elephants has been shown in some wildlife reserves in east and southern Africa.

Protection and conservation tends to enhance biodiversity as well as protecting soil and water, with a slight chance of neutral impact on these two attributes depending on the initial state of the ecosystem. Such a project is likely going to reduce the flow of products such as timber, which may have been procured prior from the reserved area, and consequently they may reduce direct socio-economic benefits. However, since the area will be preserved, there is a possibility of producing other types of benefits such as ecotourism, scientific knowledge, and possibly micro-climate modifications which may enhance other socio-economic benefits.

The impacts of recreational reserves are similar to those of forest and wildlife reserves, except that they have a bigger chance of having a negative impact on biodiversity if over-used by visitors. Also, the negative impact on socio-economic benefits is reduced since recreational activities tend to generate more income and has a general positive impact to the society.

Water catchment reserves and soil conservation projects have either a neutral impact or most likely enhance carbon cycling. They are more likely to enhance biodiversity and maintain forest vitality on top of protecting soil and water. These projects will tend to enhance the socio-economic criteria by stabilizing water flow, providing irrigation and household water down stream while reducing erosion and siltation. There may be a reduction in benefits associated with products which were previously obtained from the catchment area.

The impacts of fire protection projects on the various criteria are quite uncertain. If the area has been subject to regular human-caused fires, such a project will reduce emissions from oxidized woody biomass, as well as reducing emissions of methane, nitrous oxides, and oxides of nitrogen in the short-term. However, the extent of these reductions will depend on the type of fire protection, with prescribed burning leading to the least reduction in non-CO_2 emissions. In the longer term, the fuel loading resulting from averted fires may lead to major crown fires which will lead to more emissions than prior to the project. The impact on the other criteria follows a similar trend, except that the project may enhance socio-economic benefits by reducing the frequent destruction of biomass.

Strictly speaking, protection against natural disturbances such as windfalls, natural fires, and botanical epidemics, should not be considered a mitigation measure, but it can be so interpreted if one considers that resulting emissions are anthropogenic by way of omission of preventive action. Given the nature of disturbance, such action is likely going to reduce carbon emission and enhance each of the other criteria or leave them neutral. The only negative impact could be on biodiversity, where the pests are eradicated, or where the dead wood would have served as a substrate for many new lower forms of life in the ecosystem.

So, in conclusion, the GHG benefits from conservation and protection projects are most likely going to be positive, and in many cases they enhance the other criteria on SFM. However, there are possibilities of some negative impacts on carbon cycling but more so on the other criteria. These impacts need to be evaluated together with the GHG benefits so as to provide a basis for weighing the trade-offs.

4.2.2 Efficiency improvements

Any increase in the amount of usable biomass extracted and/or reduction in collateral damage during harvesting reduces associated carbon emissions. Projects like reduced impact logging enhance carbon cycling criteria by reducing the vegetation which is turned to necromass during logging (Pinard and Putz, 1997). This harvesting method will more than likely improve the social economic benefits by reducing the destructive effects of conventional logging. Applying reduced impact logging will enhance biodiversity or leave it unchanged, although there is a chance of reducing biodiversity compared to un-logged forest. Forest productivity is also improved since the method reduces the damage on the remaining ecosystem, and the directional felling and better skid management reduces the deleterious effect on soil. Since any harvesting reduces crown cover and opens up patches for water runoff, the impact on water catchment can be negative depending on the harvesting method practiced before. Although the technique attempts to maintain the integrity of the ecosystem, the capacity of the forest to support life may not be increased by this method.

To increase the biomass conversion efficiency and the use of biomass residues for producing tertiary products will reduce the emissions from waste and reduces the forest area which needs to be harvested to meet a given level of product demand. Increasing recovery of timber, charcoal, or firewood reduces carbon emissions and clearly would seem to enhance socio-economic benefits. There is a slight possibility of a project of this nature leading to increased emissions by making the use of unsustainably produced biomass more economically attractive and as such delay the consumers' movement to cleaner fuels. These types of projects have little or no impact on biodiversity or water and soil protection, except perhaps enhancing it by reducing pressure on new forest land.

Pre-conversion salvage operations increase the use of the biomass from a forest area instead of leaving it on-site for decomposition. To the extent that the biomass is used for products, then the socio-economic benefits are enhanced, and mostly no impact on soil and water protection. However, if most of the biomass is removed, the area may be exposed to erosion and also depleted of organic matter-derived nutrients, thus reducing its productivity. Depending on the fauna and flora of the area, such operations will most likely lead to a reduction of biodiversity.

4.2.3 Substitution

Using sustainably produced biomass to substitute for fossil fuels either by producing biofuels, producing power or direct burning unambiguously reduces emissions. The same thing applies when we use sustainable procured biomass-based products e.g. wood instead of cement for construction, or chemicals.

Utilizing wood waste for energy generation also reduces emissions from decomposition and may reduce emissions from "dirty fuels" used for producing energy.

Short rotation forestry may reduce biodiversity if it replaces a rich natural ecosystem, but it could be neutral or even enhance the criteria if it is practiced in a farmland or degraded land. Replacing unsustainably produced wood with sustainably-grown biomass will most likely enhance biodiversity, whereas waste use for energy has little or no impact on biodiversity. Forest productivity and socio-economic benefits are enhanced by the substitution projects, although forest vitality and protection of soil and water may be diminished by short rotation forestry for biofuels with waste utilization for energy having no impact at all.

4.2.4 Carbon sequestration

Carbon sequestration projects seem to have the most direct positive impact on carbon cycling, with agroforestry and community forestry having a slight chance of neutral effect depending on the farming practices and possible emissions from soil disturbance. Reforestation and rehabilitation clearly enhance biodiversity and afforestation and non-timber tree farms may contribute negatively simply because they are usually monocultures or at most consist of a few species.

Afforestation increases forest production most, but the other types of projects also enhance productivity or have little impact. Depending on the type of vegetation replaced by non-timber tree farms, urban community forests, and afforestation, there is a likelihood to reduce forest productivity, especially if the area's prior use was multiple-use forestry. Reforestation and rehabilitation projects largely enhance forest vitality and protection of water and soil, while the projects with few species are likely to reduce both soil and water protection and forest vitality. By and large, all the sequestration type of projects enhance socio-economic benefits by producing forest goods and services in areas which were being used for other purposes.

5. Discussion and conclusion

Sustainable management of forests does not necessarily imply constant or smooth flow of goods and services. The interaction between a dynamic ecological and socio-economic system is likely going to lead to fluctuating flows. The main concern of a sustainable system is to ensure that there is no major sustained imbalance between demand and supply for the goods and services, given the constraints imposed on the system such as maintenance of biodiversity, protection of soil and water, etc.

Monitoring all indicators for each project requires technical expertise as well as financial resources. The cost per unit of climate mitigation indicator, e.g., tonnes of sequestered carbon, will be increased by the cost of monitoring and verifying the state of, and changes in the other indicators for sustainable forestry.

There are three types of indicators, management unit (on-site), national, and global. The relevant indicators will vary between projects and countries. It is essential to identify core indicators for each project, consistent with national criteria and indicators, and possibly with some regional correspondence. For a JI/AIJ project, these core indicators will be a part of the negotiation between the host country and the investor. In some cases, wherever a global criteria is core to the project, *e.g.*, biodiversity, but disregarded or lightly weighted by the host and/or investor, a global arbitrator may need to be involved in the trade-off negotiations. Such players whose interest may need to be balanced with the interest on the FCCC include The Biodiversity Council, Intergovernmental Panel on Forests, Desertification Convention, etc.

The assignment of a monetary value to the carbon sequestered or on avoided emissions constitutes an effort to internalize an environmental externality in a monetized economy. However, using the carbon benefit yardstick leaves out other related externalities such as those represented by the criteria for sustainable forest management, while the host country and/or the international community may want to include them while evaluating the cost-effectiveness of climate-mitigation projects and policies.

Furthermore, mitigation project may create a new set of externalities which were non-existent prior to the project. For example, a new forest project may hinder seasonal migration of wildlife or introduce crop vermin (negative externality), while a forest rehabilitation project may increase proximal crop pollination (positive externality). Such leakages, which have a monetary value, can directly be included in the cost-benefit schedule of the project, but those which are non-market spillovers will need to be qualitatively monitored and evaluated, balanced against the GHG benefits of the mitigation project.

We therefore conclude that the task of monitoring and verifying climate mitigation policies and projects requires a comprehensive monitoring regime which will include the impacts of such policies/projects on the existing commitments covered under non-FCCC standing agreements or policies such as those governing sustainable forest management. The final assignment of credits and determination of cost-effectiveness may require some level of arbitration with other interested parties.

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CERTIFICATION OF TROPICAL TIMBER AND DEFORESTATION: MICRO MONITORING WITHOUT MACRO CONDITIONS?

DAAN P. VAN SOEST
University of Groningen, Department of Economics, P.O. Box 800, 9700 AV Groningen, The Netherlands

CATRINUS J. JEPMA
Professor of Economics, Department of Economics, University of Groningen Open University and at the University of Amsterdam, The Netherlands

Abstract. Due to external effects associated with rainforest conservation, it is likely that the preferred size of rainforests is larger from the point of view of the international community than from the point of view of those who directly exploit the forests. As trade in tropical timber is the main direct link between forest exploitation and the international community, trade policy instruments have been proposed to promote sustainable forest exploitation. One such instrument is certification of internationally traded tropical timber: sustainably produced timber is labelled so that it becomes distinguishable from unsustainably produced timber. One of the aspects of the current debate is the level at which monitoring of compliance to the certification criteria should take place, *i.e.*, at the macro (country) level or at the micro (concession) level. There seems to be a consensus that in order to be acceptable for industrialised countries' consumers, monitoring and certification should in any case take place at a micro level. However, we argue that in terms of maintaining tropical forests a firm level certification regime may be counter-effective in the short and medium run if no macro conditions are included in the certification process as well.

Key words: Sustainable forestry, certification, sustainable production techniques, decision processes

1. Introduction

During the last two decades, the international community has become increasingly aware of the problems associated with the destruction of tropical rainforests. On a global level, disappearance of rainforests inflicts negative external effects in terms of reduced retention of greenhouse gasses (mainly carbon dioxide) and loss of biodiversity. In tropical countries, governments that own rainforests do not always take these external effects into account in their land-use decisions because their prime interest is in the economic benefits from forest exploitation accruing to the country. They base their policies on the comparison between the economic benefits of forest conservation (mainly the possibility to produce timber not only today, but also in the future) and the economic benefits of clearing forested land for alternative uses (mainly agriculture). As a result, the optimal size of a country's rainforest area will typically be lower from the point of view of governments of tropical countries than from the point of view of the international community, because governments of tropical countries are concerned only with the local (economic) benefits of rainforest conservation while the international community also takes the global benefits into account.

This dichotomy has led to an intense debate on the proper use and exploitation of the tropical forest as well as other boreal forests. On the one hand, it has been argued that concern about the loss of biodiversity would lead to the conclusion that the exploitation of tropical forests should be largely restrained to prevent these forests from degrading further. On the other hand, the reasoning has been raised that there is no convincing argument why one would not continue exploiting the forests for timber production and for the production of non-timber products, as long as the exploitation is sustainable. Although the latter concept can still be interpreted in a wide variety of ways, most interpretations boil down to the argument that the exploitation should be such that the interests of future generations are consistently taken into account. An additional argument in favour of sustainable exploitation of the forests, next to the point that it will produce economic returns for the producers and take environmental concerns into account, is that many alternatives for timber, such as aluminium and plastics, require a large amount of energy for their production, and are therefore themselves to be considered significant sources of pollution of different kinds.

One instrument now seriously considered to be implemented in order to stimulate forest conservation is tropical hardwood certification for internationally traded volumes. For these purposes sustainably produced timber is labelled — after a careful monitoring and certification process which also includes the various chains of custody after harvesting — so that it can be distinguished from non-sustainably produced timber. Assuming consumer preferences exist for sustainably produced timber based on environmentalism in at least some of the markets in the world, it can be argued that a positive price gap (a "green premium") will arise between certified and non-labelled timber on the international market. This would then create an incentive for timber logging and trading firms to introduce or maintain sustainable forest management techniques and processes.

In the discussion about the various details of such a certification regime for internationally traded timber, several arguments have been put forward as to the level of aggregation at which the sustainability required for the certification should be assessed. Some would argue that an assessment at the level of the timber exporting country or state or province or district would be sufficient to decide about whether or not to allocate a certificate to the individual timber producers in the area. After all, so they argue, it is the overall forest context including land use planning and legal and institutional structure that matters most. Others, instead, argue that if the certificates are to be convincing for the final consumers, monitoring would be required at the level of individual concessions. Indeed, a consumer would like to know if he/she can be sure that a particular piece of timber bought is actually produced in a sustainable manner or not; generalities such as that the timber is originating from an area where broadly speaking the sustainability criteria would be satisfied may not be convincing enough. As a matter of fact, there seems to be a broad consensus that awarding of the certificates and the associated monitoring should primarily take place at the micro level, *i.e.* at the level of concessions, if the procedure is to generate sufficient confidence with the final timber consumers.

The general perception in the consuming countries of the impact on the forests of the introduction of such certification schemes at the micro level is rather positive. It is believed that if (part of) the concessions are now being managed sustainably, the quality of the forests will - if all other aspects remain the same - improve unambiguously, especially because of the conviction that a considerable part of the present, non-sustainable logging practices causes serious damage to the forests. It is argued that even if many of the current logging techniques are based on selective logging - only a few trees of high commercial value are extracted per hectare - the ecological damage can still be substantial given the vulnerability of the tropical forests ecosystem (Grut, 1990; Lamprecht, 1992; Myers, 1991 and 1994).

However, if a certification system is introduced which only assesses sustainability of tropical forest management at the micro level, this is not to say that the overall condition of the tropical forests will thus improve if considered from a macro, national or global perspective. The reason is that either a certification regime alters the incentive system at the micro level and therefore various aspects of both sustainable and non-sustainable forest management, or because a certification regime has an adverse impact on the overall macro conditions relevant for the forest condition. To illustrate, if various timber producers consider it not to be profitable for them to start sustainably managed timber production because the investment required to satisfy sustainability conditions outweighs the extra return expected from the green premium, they will basically opt out and concentrate on selling on the non-certified markets only. Given that the price on these markets may tend to decline as the certified products are likely to be sold at the luxury part of the market, the final impact of a certification regime may well be that the suppliers on the non-certified timber markets will increase their volumes of non-sustainable supply in order to at least keep up with the traditional level of foreign exchange received by selling their timber abroad. Precisely because they opted out, there is no incentive for them to produce sustainably, so that the overall impact of a certification regime is a more rapid decline of the tropical forest then would otherwise have occurred. Note that the chances that a serious part of the timber producers would opt out will increase the faster a certification regime including a full blown and tough interpretation of the sustainability concept will be introduced; if one would intend to keep "aboard" a substantially large fraction of the potential producers on a sustainable basis, one might therefore consider to introduce the certification regime via a phased approach which is to say, that the conditions set are gradually tightened on an individual basis and via a regime which enables feed back between the certifying entity and the various concessionaires during at least a number of years.

Another reason why a certification regime, although successful at the level of individual concessions, may well produce a more rapid decline of the forests from an overall macro perspective has to do with the role of the government with regard to land use planning. Governments of tropical forested countries typically indicate which areas are to be converted to alternative use, such as agriculture. The government's land use decision process may be affected by the introduction of a firm level certification regime, insofar as this induces the governments to clear larger parts of the forests because they have the feeling that the need for environmentalism with regard to the forests has already been satisfied by the introduction of sustainable timber management practices, or as a mere bargaining tactic vis-à-vis the donor community that may consider to help the countries to preserve their forests.

In this paper we aim to explore through a theoretical analysis whether and under what circumstances the adoption of a firm level certification regime will have beneficial effects in terms of forest conservation. In addition, we will analyse if it is necessary to impose macro conditions next to the sustainability conditions at the micro level in order to give the right incentives to the government. The approach will be to analyse the land use decision process of a tropical forested country's government, assuming that all individual firms have decided to switch to sustainable techniques and that micro monitoring effectively prevents cheating. We will consider both the long-run and short-run consequences of certification on forest cover because the larger the rainforest area in each period, the better the forests are able to perform their ecological functions.[1] It will be shown theoretically that a certification regime may indeed lead to some counterintuitive results insofar as its impact may be more rapid forest conversion rather than conservation. In fact our analysis shows that introducing a firm level certification regime will indeed induce the government of a tropical forested country to improve long-run forest conservation, but that in addition in the short run, the government through the newly established certification regime may actually be induced to increase rather than to decrease the *current* rate of deforestation. Through this a depletion trade-off may arise: improved long-run forest protection through certification may go together with increased instantaneous rates of deforestation.

The set-up of this paper is as follows. In the second section, the consequences of the introduction of a certification regime at the concession level will be considered. It will be argued that the situation at the country level is important as well. In order to analyse how both concessionaires' decisions and government policy interact, in the third section a model will be presented of the decision process of a government that aims to maximise national income that is derived from different uses of the rainforest area. In the fourth section the long-run consequences of introducing a certification regime and the resulting short-run depletion paths will be derived. This analysis will make clear that in the short-run deforestation *rates* may increase after the implementation of a certification regime, although in the long run *cumulative* deforestation will decrease. In the fifth section, the likelihood of this depletion trade-off will be explored. Finally, conclusions will be drawn and policy recommendations will be proposed to avoid the trade-off.

2. The decision processes

The international community (both governments and non-governmental organisations) considers alternative ways of implementing a certification regime. One of the most crucial decisions to be taken is at what level certificates must be awarded. The consensus seems to be that monitoring should take place at the level of the individual management unit, *i.e.* at the level of individual logging firms: there should be appropriate incentives to induce individual firms to apply environmentally friendly production techniques. Furthermore consensus seems to emerge about the sustainability requirements that have to be fulfilled. These requirements go beyond strict guidelines about actual logging techniques: there are ecological, economic and social conditions to be satisfied as well.

[1] That is, given the (limited) information we currently have on the functions rainforests fulfill on Earth. Mainly because of the uncertainty associated with the benefits of forest preservation, a conservative approach seems justified: the higher the long term size of the forest area and the lower the instantaneous rate of deforestation, the better it is.

Basically, individual firms that are confronted with a certification regime compare the net present value of sustainable logging to the net present value of unsustainable logging. The firm faces the following maximisation problem:

$$\max\,[NPV(P_S,C_S,I_S),NPV(P_U,C_U,I_U)] \qquad (1)$$

The firm's choice whether or not to apply sustainable production techniques depends on variables such as the difference between the per unit price at which certified timber can be sold (P_S) and the price of unlabelled timber (P_U), and the extra per unit costs involved in sustainable logging (that is, the difference between the extraction costs applying sustainable techniques C_S and the per unit costs of unsustainable harvesting C_U). Furthermore, the decision has investment characteristics to it: for example, meeting certain criteria (such as minimum stem size requirements) implies that some harvesting must be postponed and that there are also some genuine investment expenditures (for example to meet the social criteria) to be made which are smaller (or even absent) if logging is undertaken unsustainably (I_S exceeds I_U). This implies that also the firm's time horizon plays a role: variables such as the firm's discount rate, the duration of the concession contract and expectations about the likelihood of renewal are important to the outcome as well.

Thus, if the costs of meeting the sustainability requirements are more than compensated by the difference between revenues of certified and non-labelled tropical timber (given the time horizon of the logging firm), individual firms will have a distinct incentive to apply sustainable production techniques.

Although compliance to certification conditions by individual forestry firms is crucial to the success of a certification regime, other parties play an important role as well. Typically, governments of tropical forested countries award concessions to logging firms and hence they influence whether or not logging will be undertaken sustainably. Governments may be expected to have a broader view on the desirability of forest conservation than individual firms. The main reason is that the government generally remains the owner of the forests: logging rights are usually awarded only for limited periods of time and thus, unlike governments, forestry firms do not take alternative uses of forested land into account. The government of a tropical country essentially compares the economic benefits of conserving an additional unit of forested land to the economic benefits of clearing that extra unit, including the benefits of alternative use. Based on such a comparison, the government may consider conversion of part of the forested land to alternative uses to be desirable even if sustainable logging is much more profitable than unsustainable logging from the perspective of individual firms. Indeed, most tropical countries have land use plans indicating which rainforest areas should remain forested (either as production forests in which logging activities are undertaken on a sustainable basis, or as nature reserves) and which parts of the rainforest base should be allocated to alternative land uses (see also Myers, 1994).

3. The model

To analyse the effects of the introduction of a certification regime at the level of individual logging firms, we construct a model which derives the optimal rate of deforestation from the point of view of the government of a tropical forested country, taking into account the decision process of individual firms. Concerning the desirability of sustainable logging for individual firms, we assume that the resulting market situation after the introduction of a certification regime is such that all firms would like to switch to sustainable production techniques. So basically as an extreme starting point, we assume that the firm level certification regime is highly effective. Each firm applies sustainable production techniques up to the moment that the government decides that its concession will not be renewed, thus inducing the firm to switch to unsustainable techniques. Furthermore, we assume that the government has full control over the exploitation of its forest base: individual firms may be induced by the introduction of a certification regime to apply sustainable logging techniques, but the ultimate decision which concessions should be cleared for alternative uses is made by the government which is also able to put its land allocation decisions into practice.[2] Concerning the government's land allocation decision process, we assume that it is based solely on economic considerations[3].

The model used in this paper captures the most important economic benefits of both deforestation and forest conservation. It is an extended version of the model of Ehui, Hertel and Preckel (1990). In their model it is assumed that the government of a country endowed with rainforests maximises the net present value of forest exploitation, choosing the optimal rate of deforestation in each period and assuming perfect government control. Apart from some simplifications, we have modified their model by taking into account that revenues can be earned by selling unsustainably produced timber (*i.e.* the timber extracted from conversion forests), by acknowledging that the tropical timber market can be segmented in a market for sustainably produced timber and a market for unsustainably produced timber and by explicitly specifying all equations.

The land use decision process of the government is modelled as follows:

$$\Pi = \max_D \int_0^\infty \pi(t)\, e^{-rt} dt \tag{2}$$

$$\text{s.t. } \dot{F}(t) = -D(t) \tag{3}$$

$$p(t) = P_S\,[g_S\, F(t)] + P_U\,[(1-g_S)\, D(t)] + P_A\, Z(t)\,[F_0 - F(t)] \tag{4}$$

[2] This assumption is clearly violated in reality: rainforests can more appropriately be characterized as open access resources than as privately owned resources. However, it can be argued that if forestry firms have invested in sustainable logging techniques, the incentive to prevent encroachment by shifting cultivators is increased and hence government control over the rainforest area is increased as well.

[3] Of course, the reasons for stimulating forest conversion are not always strictly economic: for example, sometimes governments stimulate agricultural colonisation of their rainforests to relieve social pressures elsewhere in the country (Amelung and Diehl, 1992; Repetto and Gillis, 1988). These considerations can easily be incorporated in the model, but will be ignored because they would only complicate the analysis without changing the results.

$$Z(t) = \bar{Z} + \alpha D(t) - \beta [F_0 - F(t)] \tag{5}$$

Equation (2) reflects the assumption that the government maximises total discounted profits of forest exploitation Π by choosing the optimal rate of deforestation (D, measured in units of land) in each period; profits in each period (denoted by $\pi(t)$) are discounted at rate r. Depletion of the forest stock is represented by equation (3), the equation of motion: the size of the forest stock (F, measured in units of land) falls over time at the rate of deforestation D. As can be derived from equation (4), profits in each period arise because of three activities.[4] In the first place, profits are earned by logging sustainably the entire forest area ($F(t)$), P_S denoting the price at which this type of timber can be sold at the international markets and γ_S is the fraction of trees which can (on average) be harvested sustainably per unit of land in each period.[5] In the second place, profits are earned by logging excessively on land which is to be converted into agricultural land in the same period ($D(t)$); this 'conversion' timber can be sold at the international markets at price P_U. The quantity of timber still present on such a hectare is the fraction which has not yet been removed under the sustainable logging regime ($1-\gamma_S$). Finally, agricultural production also contributes to national income: agricultural revenues can be calculated by multiplying the monetary yield per unit of land (the price of agricultural products P_A times the average per unit land productivity Z) by the area of land allocated to agriculture (F_0-$F(t)$). As is reflected in equation (5), land productivity is not fixed. On the one hand, deforestation contributes to average soil productivity as burning of the forest cover increases average soil productivity because of the release of nutrients (Hecht, 1985). A freshly deforested area is very fertile in the short run, but it can be cultivated for only a limited period of time as soil productivity falls quickly during cultivation because of nutrients depletion (Herrera, Jordan, Medina and Klinge, 1981; López and Niklitschek, 1991; OTA, 1984); therefore only *current* deforestation contributes to average soil productivity. On the other hand, the proximity of forest cover increases average soil productivity because it prevents erosion and accelerates soil formation by shedding organic material onto the fallow land (Ehui, Hertel and Preckel, 1990; Ruthenberg, 1980, p. 45); cumulative deforestation has a negative effect on average soil productivity.[6]

The prices at which each type of timber is sold need some extra clarification: the model differs between the situation with and without certification. In a situation without certification, *all* timber can be sold at the same international timber market. Of course, no actual *sustainable* logging takes place: the current harvesting is *selective* logging, in which only the most valuable trees are extracted so that the number of trees harvested per hectare is quite limited too. Hence, in the situation without certification the entire forest

[4] We ignore production costs and thus profit maximisation coincides with revenue maximisation.
[5] This does not imply that an area is logged every year: the *average* quantity of trees which is harvested per year can be calculated as the total quantity of timber removed in a rotation cycle divided by the length of the rotation.
[6] Note that we ignore revenues of other economic benefits from forest conservation, such as revenues of gathering non-wood products (bush-meat, nuts etceteras). The importance of these non-wood revenues is difficult to establish, but they can be substantial (see for example Meijerink, 1995). By ignoring them, the subsequent mathematics are facilitated but the resulting optimal size of the rainforest area will be underestimated.

area is assumed to be logged *selectively* until the government decides not to renew the concession contracts; from the area to be allocated to agricultural land, all (commercially valuable) timber is removed and sold at the international timber market. In the absence of a market segmentation, we assume that the demand function is downward sloping:[7]

$$P_M = \overline{P}_M - \theta_M \left[\gamma_M F + (1 - \gamma_M) D \right] \tag{6}$$

In this demand function, $\overline{P}_M$ is the maximum price at which tropical timber can be sold (in other words, it is the vertical intercept of the inverse demand function) and θ_M is the coefficient which reflects the amount with which the price falls if quantity supplied is increased by one unit. Furthermore, γ_M is the average fraction of timber which is extracted per hectare in each period under a selective logging regime.[8] Therefore, in the absence of market segmentation the model should be modified by replacing in equation (4) the inverse demand functions P_S and P_U by P_M and also γ_S should be replaced with γ_M.

However, under a certification regime the tropical timber market is segmented into markets for sustainably and unsustainably produced timber.[9] The tropical country's forestry sector will therefore be confronted with two different inverse demand equations:

$$P_S(F) = \overline{P}_S - \theta_S(\gamma_S F) \tag{7}$$

$$P_U(D) = \overline{P}_U - \theta_U (1 - \gamma_S) D \tag{8}$$

Again, we assume the inverse demand functions to be linear and downward sloping.[10] Again, in these two equations is $\overline{P}_i$ the maximum price and θ_i is the coefficient which reflects the amount with which the price falls if quantity supplied is increased by one unit (for $i = S, U$).

Finally, we assume that the agricultural sector is confronted with a fixed price for the agricultural yield per unit of land ($\overline{P}_A$).[11]

In order to derive the optimal long-run (equilibrium) size of the forest area and the path towards that equilibrium, the model must be solved by taking the appropriate first derivatives of the Hamiltonian of this model:

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[7] Barbier, Burgess, Bishop and Aylward (1994, p. 43) present evidence that the own price elasticity of demand for tropical timber is quite low, so that the demand function can be assumed to be downward sloping.

[8] Typically, the fraction of timber extracted under selective logging will be higher than the fraction of timber which can be harvested sustainably. Therefore, $\gamma_M > \gamma_S$. However, the fraction extracted under selective logging will not exceed the fraction extracted under sustainable logging by much: current logging practices are already highly selective (see for example Grut, 1990; Lamprecht, 1992; Myers, 1991 and 1994).

[9] See also Mattoo and Singh (1994) and Varangis, Crossley and Braga (1995).

[10] This specification does not rule out that the two demand functions are interdependent. The resulting location and slope of the demand functions depend on the degree in which the two types of tropical timber are considered to be substitutes by the consumers, just as other materials such as temperate timber, aluminum and plastics are (to a certain extent) substitutes for tropical timber

[11] This assumption does not affect the conclusions of the paper, but facilitates the mathematics.

$$H(D, F, \lambda) = [\, P_S [\gamma_S F] + P_U [(1) - \gamma_S \; D] + P_A Z [F_0 - F] - \lambda D \tag{9}$$

In this equation, λ is the co-state variable associated with the equation of motion: it reflects the marginal value of the state variable (F) at each moment t (see for example Kamien and Schwartz, 1981, pp. 151-153). This variable is akin to the Lagrange multiplier in a static optimisation problem, and can be interpreted as the shadow price of an extra unit of forested land.

Maximising this Hamiltonian yields the following first order conditions:

$$\lambda(t) = (1 - \gamma_S) P_U(t) + \alpha \overline{P}_A [F_0 - F(t)] - \theta_U (1 - \gamma_S)^2 D(t) \tag{10}$$

$$\lambda(t) = r\lambda(t) - \gamma_S P_S(t) - \beta \overline{P}_A [F_0 - F(t)] + \overline{P}_A Z(t) + \theta_S \gamma^2 \gamma_S F(t) \tag{11}$$

The interpretation of equation (10) is as follows. The marginal benefits of deforesting a unit of forested land (measured as the sum of the direct revenues of deforestation in terms of timber sold and the plus the increase in agricultural productivity arising from that extra unit of land deforested minus the resulting decrease in price at which non-labelled timber can be sold because the demand function is assumed to be downward sloping) are equal to the marginal costs of deforesting that unit now rather than in the future. Equation (11) is nothing but an extended version of the intertemporal non-arbitrage condition as stated by Hotelling (1931). In order to be indifferent between deforesting a unit of land now or in the future, the shadow price of the forest stock should increase at rate r, reduced by the decision maker's marginal return on forest conservation and increased with the marginal benefits of actual deforestation. The marginal returns on forested land are equal to the revenues which can be earned by logging a unit of land sustainably ($\gamma_S P_S$) and the forests' contribution to average soil productivity ($\beta \overline{P}_A(F_0 - F)$). The benefits of deforesting an extra unit of land are the revenues earned by having an additional unit of land under cultivation ($\overline{P}_A Z$) and the increase in revenues of sustainably produced timber (because of the increase in its price resulting from the decrease in supply; $\theta_S \gamma_s^2 F$).[12]

4. Results

On the basis of the equation of motion (3) and the first order conditions (10) and (11), together with the inverse demand functions for timber (equations 7 and 8 in the case of certification, equation 6 in the absence of a certification regime), the model can be solved. The equilibrium size of the rainforest area can be found by setting the time derivatives ($\dot{F}$ and $\dot{\lambda}$) equal to zero. The resulting equilibrium forest size under a certification regime (F_C^*) is presented in equation (12):

$$F_C^* = F_0 - \left(\frac{\overline{P}_A \overline{Z} + 2(1 - \gamma_s)\overline{P}_u + \gamma_s^2 \theta_s F_0 + \gamma_s P_s(0)}{\overline{P}_A [2\beta - r\alpha] + 2\gamma^2 \theta_S} \right) \tag{12}$$

[12] See also Ehui and Hertel (1989).

By analysing equation (12), it becomes clear whether or not a certification regime will have a positive influence on the equilibrium size of the rainforest area.[13] It is likely that the denominator of the second term on the right hand side of the equation is positive: even if β is very low relative to α (that is, if the negative effect of *cumulative* deforestation on average soil productivity is very small relative to the positive influence of *current* deforestation on average soil productivity), the fact that the demand function for sustainably produced timber is downward sloping implies that the denominator is likely to be positive (θ_S is positive). Also, the higher β relative to α, the more likely it is that the optimal forest size is close to the initial forest size.

The numerator of the second term on the RHS of equation (12) reflects the weighing of the benefits of deforesting the first unit of land and the benefits of managing it sustainably. Concerning the decision of an individual firm, we have assumed that it finds it advantageous to switch to sustainable forest management. This means that initially the current value of sustainable logging ($\gamma_S P_S(0)/r$) exceeds the one-shot revenues of unsustainable logging, $(1-\gamma_S)\,\overline{P}_U$. However, the government also takes the current value of alternative uses of land into account ($\overline{P}_A Z^- /r$) and the effect of deforesting the first unit of land on the price of sustainably produced timber as a result of the downward sloping demand function ($\gamma_S^2 \theta_S F_0/r$). It is likely that the addition of these two terms results in a positive value of the numerator of the term and thus at least some deforestation is desirable: the equilibrium size of the rainforest area (F_C^*) is less than the initial size (F_0), even though switching to sustainable production techniques is profitable for all individual firms.[14]

It is generally argued that a necessary condition for rainforest conservation is that the economic benefits of tropical rainforest conservation should be increased relative to the economic benefit of deforestation (see for example Barbier, Burgess, Bishop, and Aylward, 1994; Burgess, 1994; Vincent, 1990). Equation (12) suggests that this argument is indeed valid: a decrease of the vertical intercept of the inverse demand function for unsustainably produced tropical timber ($\overline{P}_U$) or an increase of the vertical price intercept of sustainably produced timber ($\overline{P}_S$) leads to a larger long-run forest base.

Having derived that it is likely that at least some deforestation is desirable, the question now is how the government should deplete the forest base up to its long-run equilibrium size in an optimal way. The depletion paths can be calculated by taking the time derivative of the co-state variable λ (equation 10), inserting the result together with the equation of motion (5) into equation (11) and solving the resulting second order differential equation (Apostol, 1967, pp. 322-328):[15]

[13] Solving the maximisation problem in the absence of a certification regime yields an expression of the equilibrium size similar to equation (12); the resulting equation is presented in Appendix 1.

[14] Ehui and Hertel (1989) have applied the original Ehui, Hertel and Preckel (1990) model to estimate the optimal size of the rainforest area of Ivory Coast. For reasonable values of the different parameters, they find that some deforestation is desirable from the point of view of governments of tropical countries. Since we modified their model by explicitly including the revenues earned by selling conversion timber, it can safely be assumed that in our model the initial size of the forests is suboptimally large from the point of view of governments of tropical countries. Ehui and Hertel (1989) also find that because of the contribution of forests to agricultural productivity, rainforests are not likely to disappear entirely.

[15] The depletion path in the absence of a certification regime is similar to equation (13); see

$$F_C(t) = \left(F_0 - F_C^*\right)e - \left[\sqrt{\left(\frac{1}{4}Z^2 + \frac{\overline{P}_A(2\beta - 2\alpha) + 2\gamma_s^2\theta_s}{2(1 = \gamma_s)^2\theta_u}\right)} - \frac{1}{2}r\right]t + F_C^* \tag{13}$$

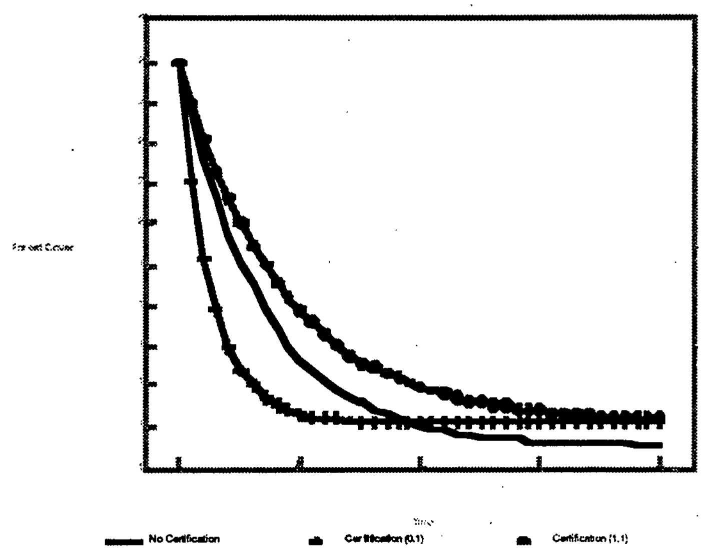
Depending on the parameter values of the resulting inverse demand functions under certification relative to the parameter values of the inverse demand function in the absence of a certification regime (the current situation), the *rate* of deforestation can increase or decrease. Although it does not play a role in determining the long-run equilibrium size of the rainforest area under a certification regime, the price elasticity of the demand function for unsustainably produced timber does affect the rate at which forests are depleted. Taking the first derivative of equation (13) with respect to θ_U, a positive relationship is found: the lower θ_U (that is, the *higher* the price elasticity of demand),[16] the lower the forest stock in each period ($F_C(t)$). The intuition behind this result is that if the elasticity is high, a sharp increase in the quantity of timber sold does not lead to a large fall in its price. In other words, the cost of increasing the supply of unsustainably produced timber in terms of the decrease in the price at which the entire stock of that type of timber can be sold, falls if the demand elasticity increases. Thus, if the price elasticity of demand for unsustainably produced timber turns out to be high enough after the introduction of a certification regime relative to the elasticity before the adoption of the certification regime (that is, if θ_U is small enough relative to θ_M), it becomes profitable for governments of tropical countries to increase the instantaneous rate of deforestation. This can also be shown graphically; see Figure 1.

In this figure three depletion paths are depicted. Apart from the depletion path in the absence of a certification regime, two depletion paths are drawn for different values of the price elasticity of demand. As is clear from this figure, if the price elasticity of the demand for conversion timber turns out to be lower than in the absence of a certification regime ($\theta_U > \theta_M$),[17] a certification regime is unambiguously preferable: in each period the size of the forest area is larger under a certification regime than without such a regime. However, if the elasticity of the demand for unsustainably produced timber is high enough ($\theta_U << \theta_M$), the long-run equilibrium forest area under a certification regime still exceeds the equilibrium forest size without such a regime, but in the short and medium run deforestation rates may be higher.

Appendix 2.

[16] The price elasticity of demand is $\frac{dy}{dP}\frac{P}{y}$ (see for example Varian, 1992, p. 253). Hence, the lower θ, the higher the price elasticity of the demand function.

[17] Note that as a benchmark θ_M is set equal to 1.



Parameter values: $\overline{P}_S$=60, θ_S=1.1, $\overline{P}_U$=35, $\overline{P}_M$=50, θ_M=1, $\overline{P}_A$=22.5, γ_S=0.4, γ_M=0.5, r=0.15, α=0.3, β=0.04, $\overline{Z}$ =1, F_0=24.

Figure 1. Comparison between the optimal depletion paths with and without certification, for θ_U=0.1 and θ_U=1.1

The adoption of a certification regime thus ensures that the size of the rainforest area is increased in the long run relative to the case in which no segmentation is introduced, but that in the short and medium term instantaneous rates of deforestation may increase. Of course, whether the depletion trade-off will actually occur depends on the demand functions after the introduction of the regime: both the relative magnitudes of the price elasticities (θ_M, θ_S and θ_U) and the size of the 'green premium' prove to be important.

First we consider the influence of the relative sizes of the price elasticity of the original demand function (that is, the demand function for tropical timber before certification) and the price elasticities of demand for sustainably and unsustainably produced timber. Table 1 gives the number of periods after which the forest size under a certification scheme is larger than in the absence of certification, for different values of θ_S and θ_U. In other words, the number of periods are calculated at which the depletion path under a certification regime intersects the depletion path which occurs without such a regime, as depicted in Figure 1.

As is clear from this table, an adverse short-term result will only occur if the demand function for unsustainably produced timber turns out to be more elastic than the demand function in the absence of a certification regime. The higher the elasticity of demand for non-labelled timber (*i.e.* the lower θ_U), the larger the benefits of current deforestation because an increase in D leads only to a small fall in P_U. But the price elasticity of the demand function for sustainably produced timber also plays a role: the more inelastic the demand function for sustainably produced timber (the higher θ_S), the more the benefits of current deforestation increase because the resulting decrease in supply of sustainably produced timber leads to a sharp increase in P_S, and hence the more likely it is that the depletion trade-off will occur.

Table 1. Number of periods for which $F_C(t)$ is less than $F_M(t)$, for different combinations of the price elasticity of demand for sustainably produced and unsustainably produced timber

θ_U	θ_S=0.9	θ_S=1.0	θ_S=1.1
0.1	1.22	1.49	1.88
0.3	0.79	1.17	1.67
0.5	0	0.1	0.89
0.7	0	0	0

Parameter values: $\overline{P}_S$=60,P $_U$=35, $\overline{P}_M$=50, θ_M=1, $\overline{P}_A$=22.5, γ_S=0.4, γ_M=0.5, r=0.15, α=0.3, β=0.04, $\overline{Z}$ =1, F_0=24.

The second important precondition for the occurrence of the depletion trade-off is that the 'green premium' should not be too high. Basically, two premia can be discerned (see also Varangis, Crossley and Braga, 1995). In the first place, there is the difference between the price at which sustainably produced timber can be sold and the price of unsustainably produced timber ($\overline{P}_S$- $\overline{P}_U$). In the second place, there is the difference between the price of sustainably produced timber and the price at which timber was sold before the adoption of certification ($\overline{P}_S$- $\overline{P}_M$). Table 2 gives the number of periods for which short term deforestation is higher under certification than in the absence of a certification regime for different values of the vertical intercepts of the inverse demand functions of certified and non-certified timber (note that the analysis is undertaken keeping the location of the original inverse demand function P_M fixed at $\overline{P}_M$=50).

Table 2. Number of periods for which $F_C(t)$ is less than $F_M(t)$ for different combinations of $\overline{P}_S$ and $\overline{P}_U$, for a given $\overline{P}_M$

$\overline{P}_U$	$\overline{P}_S$=60	$\overline{P}_S$=65	$\overline{P}_S$=70
40	2.65	1.02	0.50
35	1.88	0.88	0.41
30	1.52	0.76	0.31

Parameter values: θ_S=1.1, θ_U=0.1,P $_M$=50, θ_M=1,P $_A$=22.5, γ_S=0.4, θ_M=0.5, r=0.15, a=0.3, b=0.04,Z =1, F_0=24.

The results presented in this table show that for both definitions of the 'green premium', an increase in the premium will reduce the likelihood that the trade-off will occur. The reason is that an increase in both price gaps increases the optimal long-run size of the rainforest area by increasing the benefits of forest conservation relative to deforestation. If this increase is large enough, desired *cumulative* deforestation is reduced and the resulting *rate* of deforestation in each period will necessarily be smaller. In sum, the higher the price of sustainably produced timber relative to the price before certification and also the higher the price of sustainably produced timber relative to the price of unsustainably produced timber, the shorter the period in which short-run deforestation rates will be higher with certification than in the absence of certification.

Thus, it can be concluded that if the 'green premium' is not too large and if the elasticity of the demand function for non-certified timber is large enough, the international community should be cautious with introducing a micro level certification regime because it may speed up rather than retard deforestation in the short and medium run.

5. The likelihood of the depletion trade-off

The main stimulus for sustainability created by the introduction of a certification regime is the positive price gap which will arise after the introduction of a certification regime. The extent of this gap will be limited by the possibilities of substitution (Varangis, Crossley and Braga, 1995, Annex 1). If for a particular type of use there are many alternatives for tropical timber (such as temperate timber, plastics or aluminium), a significant price increase is not likely to occur after the introduction of a certification regime because demand will shift to alternative materials; unsustainably produced tropical timber will generally be sold in markets with a high elasticity of demand. A survey conducted by Barbier, Burgess, Bishop and Aylward (1994, pp. 52-53) confirms this hypothesis: manufacturers believe that there is scope for a price premium only in the high quality product markets (such as the markets for quality joinery and furniture) while in markets where there are many close substitutes for tropical timber (such as the construction industry where temperate timber and non-wood products can be used) they do not see much room for a premium.

There is also some evidence on the size of the price gap resulting from the introduction of a certification regime. Surveys of the research as presented by Barbier, Burgess, Bishop and Aylward (1994, pp. 55-56) and Varangis, Crossley and Braga (1995) indicate that there is no unambiguous evidence that the price gap between the price of sustainably produced timber and the price of timber before the adoption of a certification regime (that is, $\overline{P}_S - \overline{P}_M$) will be sizeable. Several surveys[18] indicate that consumers will only be prepared to pay a moderate premium for sustainably produced timber: in most cases this premium is less than 10% while the majority of the respondents would be prepared to pay a premium between 1 and 5%.[19] However, there is some evidence that consumers in Western countries may be willing to abstain from purchasing non-certified timber, thus leading to an increase in the difference between the price of sustainably and unsustainably produced timber ($\overline{P}_S - \overline{P}_U$).

[18] FOE (1992), Milland Fine Timber Ltd. (1990), MORI and WWF (1991), Winterhatter and Cassens (1993). See also ESE (1992) and Haji Gazali and Simula (1994).
[19] Varangis, Crossley and Braga (1995).

6. Conclusions and policy recommendations

In this paper we have analysed the consequences of the introduction of a firm level certification regime on the resulting long-term size of the rainforest base and on the depletion path. Assuming that loggers cannot autonomously choose to apply sustainable forestry techniques (the government decides whether the concession area is designated as permanent forest or as conversion forest), we find that in the long run such a certification regime will lead to more overall forest conservation but that the depletion path along which this higher equilibrium forest size is reached can become steeper, thus leading to faster deforestation in the short run. This depletion trade-off may occur if the price elasticity of demand for unsustainably produced timber turns out to be high relative to the price elasticity of the original demand function and if the 'green premium' turns out to be small.

Surveys among consumers and producers indicate that there is indeed reason for concern. Although the price of sustainably produced timber is likely to exceed the price of unsustainably produced timber so that certification will have a positive long-run effect on forest conservation, on empirical grounds the possibility of an increase in short-run rates of deforestation cannot be excluded: the price elasticity of demand for unsustainably produced timber is likely to exceed the price elasticity of demand for certified timber, and the gap between the price of certified timber and the original timber price is not likely to be substantial.

To conclude there is indeed reason for a careful introduction of certification. The policy implication is that apart from monitoring the activities of individual firms, also the decisions of the government of a tropical forested country should be included in the certification regime. For instance, the price received by individual logging firms for sustainable timber might be made dependent on the overall rate of deforestation occurring in that country, thus inducing its government to decrease the rate at which forested land is allocated to alternative use. Another instrument may be to set a minimum price for sustainably produced timber. The incentives given to the government of a tropical forested country are then as follows. Given the fact that under a minimum price system in the certified timber market a decrease in the supply of certified timber (resulting from increased deforestation) would not lead to an increase in the sales price of certified timber as long as the market price would be lower than the minimum price, an important stimulus to increase the instantaneous rate of land conversion is reduced: the extra benefit of deforestation in terms of the increase in the price of sustainably produced timber is removed.

The applicability of this model in terms of policy advise is hampered by the fact that in order to be able to solve the model, strong assumptions are needed: especially the assumption of full land use control by the governments of tropical forested countries is violated in reality. However, the insights this model gives remain valid: governments of tropical forested countries should be given appropriate incentives to pursue forest conservation because otherwise market incentives can be thus that deforestation rates increase rather than decrease in the short and medium run.

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Appendix 1

The equilibrium size of the rainforest area in the absence of certification is derived by combining the equation of motion (3), the first order conditions (10 and 11), the inverse demand function (6) and by setting the time derivatives equal to zero. The resulting size of the rainforest area without certification (F_M^*) is:

$$F_M^* = F_0 - \left(\frac{P_A Z - \left(\gamma_M - 2(1-\gamma_M)\left[P_M 0 - \theta_M\right]\right)}{\overline{P}_A(\beta - 2\alpha) - 2\theta_M \gamma_M (\gamma_M = 2)} \right) \qquad \textbf{(A1)}$$

The similarities with the equilibrium size of the rainforest area under certification (F_C^* , equation 12) are that again in the numerator of the second term on the RHS the net present value of the benefits of deforesting the first unit of land are weighed against the net present value of the benefits of logging it selectively. The discounted benefits of selective logging are $\gamma_M P_M(0)/r$; the discounted benefits of deforesting it are the one-shot timber revenues $(1-\gamma_M)P_M(0)$ plus the present value of the agricultural revenues $P_A \overline{Z}/r$ plus the effect on the price (the movement along the demand equation). This last component is more complicated than in equation (12) as both changes in the supply of selectively logged timber and conversion timber affect the price in the future. Deforesting the first unit of forest implies that in the future there is less supply of sustainably logged timber, resulting in an increase in its price: the discounted benefits of deforesting the first unit of land arising from the price increase are $\gamma_M^2 \theta_M F_0/r$. On the other hand, the additional timber extracted from a hectare which is to be converted to agricultural use results in a decrease in the price at which total timber supply can be sold: the price falls with $(1-\gamma_M)\gamma_M \theta_M F_0$. The denominator again acts as a multiplier.

Numerical simulations show that if the inverse demand function for sustainably produced timber is not too different from the original inverse demand function, F_C^* is larger than F_M^*: this holds for a very wide range of parameter values.

Appendix 2

The depletion path in the absence of a certification regime is as follows:

$$F_0 - F_M^* e - \left[\sqrt{\frac{1}{4}Z^2 + \frac{\overline{P}_A(2\beta - 2\alpha) + 2\gamma_M\theta_M(\gamma_M - 2\gamma_M)}{2(1-\gamma_M)2\theta_M}} - \frac{1}{2}Z \right] t + F_M^* \qquad \textbf{(A2)}$$

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MONITORING NEEDS TO TRANSFORM AMAZONIAN FOREST MAINTENANCE INTO A GLOBAL WARMING-MITIGATION OPTION

PHILIP M. FEARNSIDE
National Institute for Research in the Amazon (INPA)
C.P. 478, 69011-970, Manaus, Amazonas, Brazil

Abstract. Two approaches are frequently mentioned in proposals to use tropical forest maintenance as a carbon offset. One is to set up specific reserves, funding the establishment, demarcation, and guarding of these units. Monitoring, in this case, consists of the relatively straightforward process of confirming that the forest stands in question continue to exist. In Amazonia, where large expanses of tropical forest still exist, the reserve approach has the logical weakness of being completely open to "leakage": with the implantation of any given reserve, the people who would have been deforesting in the reserve area will probably continue to clear the same amount of forest somewhere else in the region. The second approach is through policy changes aimed at reducing the rate of clearing, but not limited to specific reserves or areas of forest. This second approach addresses more fundamental aspects of the tropical deforestation problem, but has the disadvantages of not assuring the permanence of forest and of not resulting in a visible product that can be convincingly credited to the existence of the project. In order for credit to be assigned to policy change projects, functioning models of the deforestation process must be developed that are capable of producing scenarios with and without different policy changes. This requires understanding the process of deforestation, which depends on monitoring in order to have information as a time series. Information is needed both from satellite imagery and from on-the-ground observations on who occupies the land and why the observed changes occur. Monitoring must be done by individual property if causal factors are to be identified reliably; this is best achieved using a database in a Geographical Information System (GIS) that includes property boundaries. Once policy changes are made in practice, not only deforestation but also the policies themselves must be monitored. Decrees and laws are not the same as changes in practice; the initiation and continued application of changes must therefore be confirmed regularly. The value of carbon benefits from Amazonia depends directly on the credibility and transparency of monitoring. The great potential value of carbon maintenance in Amazonia should provide ample reason for Amazonian countries to strengthen and increase the transparency of their monitoring efforts.

Key Words: Amazonia, carbon, deforestation, environmental services, greenhouse effect, greenhouse gases, global warming, mitigation, rainforest, tropical forest

1. Introduction

1.1. Carbon Value

Maintenance of tropical forests such as those in Brazilian Amazonia represents a significant benefit to all countries in the world because of the high potential costs of damage from climatic change should these forests be replaced with low-biomass land uses. The way in which credit is calculated for this environmental service strongly influences both the value assigned to the service and the kind of monitoring needed.

The following sections will examine different types of carbon value and their implications for mitigation and monitoring. The opportunity presented by Brazilian deforestation will then be assessed, together with the challenges of increasing the effectiveness and credibility of monitoring in order to allow the value of the carbon services provided by the forests to be tapped.

1.2. AVOIDED EMISSIONS

Net Incremental Costs have been adopted by the Scientific and Technical Advisory Panel (STAP) of the Global Environment Facility (GEF) as the guiding criteria for awarding carbon credits in the evaluation of projects competing for funding as global-warming response options. This implies that forest only has a climatic benefit if it would have been cut in the absence of a given mitigation project. If this remains the criterion, then receiving credit for carbon benefits requires demonstrating that a given amount would be cut in a "no project" or "business as usual" scenario.

While the logic of this approach is clear in setting priorities for scarce financial resources, it also has disturbing implications as a means of rewarding bad behavior, especially with regard to tropical deforestation. If a country is rapidly clearing its forests and subsequently stops as a result of policy changes, then the difference between continuation of the old behavior and the new scenario represents forest "saved" and represents a credit for avoided emissions. A country that has not been destroying its forest gets no credit for its good behavior (Fearnside, 1995a). While incremental cost is the criterion used by the GEF, neither this criterion nor any other has yet been adopted as a universal one for projects under the Actions Implemented Jointly (AIJ, formerly Joint Implementation, JI) regime.

1.3. STOCK MAINTENANCE

If carbon stock maintenance were recognized as a form of mitigation, as distinguished from avoided deforestation, then monitoring needs would be much simpler from the point of view of countries contributing funds as carbon credits: only accompaniment of the forest stock remaining each year would be necessary. Brazil, as a recipient of credits, would still find that its national interests are best served by having more detailed information, such as that at the property level, in order to understand the deforestation process and to control or influence it effectively to maximize the benefits of retaining forest, including its carbon credit benefits. Recognition of the value of the forest carbon stock would greatly increase the value credited to areas with large stocks relative to annual losses to deforestation, as is the case in Brazilian Amazonia. This would increase the need for effective monitoring of forest areas, biomass stocks, and the processes of forest loss and degradation.

Any deforestation avoidance project in Brazil has the potential of affecting the fate of one of the Earth's major carbon stocks. This contrasts with the situation in many of the smaller tropical countries. For example, the ultimate impact of a project in Costa Rica is the possibility of saving the tiny remnants of forest left within that small country, plus a tenuous indirect connection to the remaining tropical forests of the world through any lessons learned or demonstration effect that may be gained from the projects.

One of the difficulties in gaining recognition of forest carbon stock maintenance as a benefit is the fear that the same arguments might be used with regard to fossil fuel carbon stocks, thereby making any form of credit inviable in practice. The world's "available" fossil fuel carbon stocks total approximately 5000 × 10^9 t C (calculated by Bolin *et al.*, 1979, p. 33, based on Perry and Landsberg, 1977), whereas carbon stocks in the biosphere total approximately 2190 × 10^9 t C, of which 610 × 10^9 t C is live vegetation and 1580 × 10^9 t C is detritus and soils (Schimel *et al.*, 1996, p. 77). Much of the soils portion of this is not at risk of release: only 6.9 × 10^9 t C would be released from the top 20 cm of soil if all tropical forests were converted to other land uses and Brazilian soil carbon parameters are assumed (Table 1). The tropical forest portion of the global carbon stocks is estimated at 265.3 × 10^9 t C, which, together with the 6.9 × 10^9 t C of at risk soil carbon, less 22.5 × 10^9 t C in the landscape that would replace tropical forests, would bring the total tropical forest carbon stock requiring maintenance to 249.7 × 10^9 t C (Table 1). Conversion of Brazil's Amazon forest to a replacement landscape reflecting current trends would release an estimated 90.0 × 10^9 t C, or 36% of the total potential net release from the world's tropical forests. The other tropical regions of the world also have substantial carbon stocks (Table 1), which translate into correspondingly large potential financial values if carbon stock maintenance were regarded as a global benefit worthy of financial reward.

One of the relevant differences between carbon stocks in forests versus fossil fuels is that population growth and technology for effecting land-use change have advanced to the point where all biosphere carbon stocks are effectively at risk of clearing within a century, whereas only the tip of the vast iceberg of deposits of fossil fuels, especially coal, could realistically be burned over the same time horizon. In addition, active defense of forests is needed to keep them standing, whereas fossil fuel use rates are more easily influenced through economic policy instruments such as taxes and tariffs.

1.4. WILLINGNESS TO PAY

The carbon stored in Amazonian forest has a substantial value as a result of the damage that would be caused by global warming should that carbon be released to the atmosphere as carbon dioxide, together with other carbon and non-carbon greenhouse gases. What developed countries are willing to pay to avoid the impacts of global warming is perhaps a good measure of the volume of funds that could be tapped to maintain the carbon storage services of Amazonian forest. Since this reflects only impacts on the rich, it is grossly unfair as a measure of the real damage that would be done by global warming, which would also fall on people who cannot afford to pay anything to avoid impacts. Nordhaus (1991) derived values based on willingness to pay, which, along with other indicators of this willingness, have been used by Schneider (1994) to estimate per-hectare values for carbon storage in Amazonian forests. Additional values per ton of carbon stored considered by Schneider (1994) are from enacted carbon taxes: US\$ 6.10 t^{-1} in Finland and US\$ 45.00 t^{-1} in the Netherlands and Sweden (Shah and Larson, 1992), and from a proposed penny-a-gallon (US\$ 0.0027 l^{-1}) gasoline tax in the United States equivalent to US\$ 3.50 t^{-1} of carbon. Low, medium, and high values

Table 1. Carbon stocks in tropical countries

Location	Extent of remaining forest cover in 1990 reported by FAO (1993) (10^3 ha)	Average above-ground biomass reported by FAO (1993) for all forests (t/ha)	Above-ground dead & other biomass (t/ha)[a]	Below ground biomass (t/ha)[b]	Total biomass (t/ha)	Total biomass stock (10^9 t)	Carbon stock in biomass (10^9 t)[c]	Potential carbon stock in replacement landscape (10^9 t)[d]	Potential net committed emission from biomass (10^9 t C)	Potential soil carbon release (10^9 t C)[e]	Potential net committed emission from soil + biomass (10^9 t C)	Relative contribution (% of total net committed emission)
Africa	527,587	133.0	64.1	41.1	238.3	125.7	62.9	6.8	56.1	2.1	58.2	23.3
Central America and the Caribbean	73,838	97.3	46.9	30.1	174.3	12.9	6.4	0.9	5.5	0.3	5.8	2.3
Brazil	561,107	189.0	91.1	58.5	338.6	190.0	95.0	7.2	87.8	2.2	90.0	36.0
Other South America	282,979	200.2	96.5	61.9	358.6	101.5	50.7	3.6	47.1	1.1	48.2	19.3
Asia	274,595	179.4	86.5	55.5	321.4	88.3	44.1	3.5	40.6	1.1	41.7	16.7
Oceania	36,000	191.0	92.1	59.1	342.2	12.3	6.2	0.5	5.7	0.1	5.8	2.3
Tropics total	1,756,106	168.7	81.3	52.2	302.2	530.7	265.3	22.5	242.8	6.9	249.7	100.0

[a] Corrections for components omitted from FAO (1993) biomass data assumed same as omissions in Brazil (from Fearnside, 1994b): hollow trees = -6.6%, bark = +1.2%, vines = +5.3%, other non-tree components = +0.2%, palms = +2.4%, trees <10 cm DBH = +12.0%, form factor = +15.6%.
[b] Below ground assumed same as Amazonian forest, or 33.6% of above-ground live biomass (Fearnside, 1994b).
[c] Carbon content of original biomass 0.50 (FAO, 1993; Fearnside *et al.*, 1993).
[d] Replacement landscape biomass assumed to be 28.5 t/ha: the equilibrium landscape biomass in Brazilian Amazonia (Fearnside, 1996b). Carbon content of replacement landscape biomass 0.45 (Fearnside, 1996b).
[e] Soil carbon release to 20 cm depth; assumed same as transformation to pasture in Brazilian Amazonia: 3.94 t C/ha (Fearnside, 1985, 1997b).

of US$ 1.80, US$ 7.30 and US$ 66.00 t^{-1} are given by Nordhaus (1991). Schneider (1994) used estimates by Nordhaus (1991) for value per ton of carbon, in conjunction with biomass estimates from Fearnside (1992). This has been updated (Fearnside, 1997a) based on more recent values for greenhouse gas emissions from deforestation. The impact of each hectare of deforestation in 1990 was 191 t of CO_2-equivalent carbon, expressed as net committed emissions (Fearnside, 1997b, using 1994 IPCC global warming potentials from Albritton *et al.*, 1995: 222). Net committed emissions are not affected by inherited emissions, which in 1990 were greater than committed emissions because declining deforestation rates in the years preceding 1990 mean that substantial amounts of biomass left from the previous rapid clearing were oxidized through decay and through combustion in reburns (Fearnside, 1996a). The high biomass of Amazonian forests gives them a high carbon value per hectare, regardless of the index used to quantify the emissions when they are cleared.

The Amazonian countries, particularly Brazil, would stand to gain tremendously from mechanisms to convert environmental services of forests, including carbon benefits, into monetary flows. Using a "medium" value derived by Nordhaus (1991) of US$ 7.30 t^{-1} of carbon permanently sequestered as the value that might be captured from the developed countries, avoiding the net committed emissions from Brazil's 1990 deforestation would have had a value of US$ 1.9 billion, while considering the value of the carbon stock in the remaining forest as an annuity at 5% yr^{-1} would represent a value of US$ 24 billion annually (Fearnside, 1997a). Values for carbon stock maintenance in all of the nine countries of the 'Greater Amazon' are given in Table 2. The high value of the carbon service these countries provide greatly exceeds the revenue from destroying the forest, making it in the financial self-interest of these countries to work towards negotiating international agreements that reward these services.

1.5 OPPORTUNITY COST OF FOREGONE DEFORESTATION

The carbon value of forest is much greater than the sale price of land in Amazonia. Although land purchase is not proposed as a mitigation option, the comparison of price to carbon value is important because the sale price of the land reflects the discounted potential income from the land under other uses, such as agriculture. As a reflection of opportunity cost to the nation, land price is an indicator but not an equivalent. Price indicates the maximum that productive activities could yield, since it also includes gains to land sellers from nonproductive sources of value, such as speculation. In addition, it reflects the high discount rates used in practice by individuals and corporations in Amazonia, rather than the lower rates that might be appropriate to a national government concerned about future generations of citizens.

Information on both the expenditures needed to cause deforestation rates to fall and the opportunity cost of the foregone deforestation is necessary as an input to negotiating the price of carbon, regardless of how carbon accounting is done. These costs, however, are not the same as the value that Brazil could claim as a credit for refraining from deforestation. As in any commercial transaction, the price agreed upon is the result of a negotiation that represents a compromise between the seller getting as much as possible and the buyer paying as little as possible for the item or service in question. The price is constrained on the low side by the costs (including the opportunity costs) of supplying the product, and on the high side by the cost to the

Table 2. Value of carbon stocks in Amazonian countries

Country	Forest area in 1990 (10^3 ha)[a]	Average total biomass of forest (t ha^{-1})[b]	Carbon stock at risk in biomass and soil (10^9 t C)[c]	Annual value of carbon storage @5% yr^{-1} (10^9 US$)[d]
Bolivia	49,317	269	6.2	2.3
Brazil	561,107	339	90.0	32.8
Colombia	54,064	349	9.0	3.3
Ecuador	11,962	353	2.0	0.7
French Guiana	7,997	561	2.2	0.8
Guyana	18,416	444	3.9	1.4
Peru	67,906	423	13.8	5.0
Suriname	14,768	464	3.3	1.2
Venezuela	45,690	339	7.3	2.7
TOTAL	831,227		137.6	50.2

[a] FAO, 1993.
[b] FAO, 1993, with adjustments in Fearnside, 1994b, nd-a. Adjustments to above-ground biomass for dead material, trees <10 cm DBH, form factor, palms, vines, other non-tree components, and hollow trees total 48%. Root/shoot ratio = 0.31 (Fearnside, nd-a). Because FAO biomass data are not reported separately by forest type or sub-national political unit, values are for all forests in the country (not only the Amazonian portion).
[c] Fearnside, nd-a, updated from Fearnside, 1994b. Carbon content = 50% (Fearnside *et al.*, 1993); soil carbon loss in top 20 cm = 3.92 t C ha^{-1} converted to pasture (Fearnside, 1985, 1997b); replacement landscape average total biomass carbon = 28.5 t C ha^{-1} (Fearnside, 1996b).
[d] See Fearnside, 1997a.

buyer of simply doing without (in this case, the losses inflicted on the developed countries by the climatic changes expected to result from allowing deforestation emissions to occur in a "business-as-usual" scenario). Improving the estimates of these losses must be done as well. Of course, both sides are already aware of these restraints on whatever price is agreed upon. Strengthening the information base for this negotiation would be a wise investment to assure that the decisions made are advantageous to all sides and that the day when tangible carbon credits are paid comes sooner rather than later.

2. Mitigation and Monitoring

2.1. Reserve Establishment

Two approaches are frequently mentioned in proposals to use tropical forest maintenance as a carbon offset. One is to set up specific reserves, funding the establishment, demarcation and guarding of these units. Monitoring, in this case, consists of the relatively straightforward process of confirming that the forest stands in question continue to exist. In Amazonia, where large expanses of forest still exist, the reserve approach has the logical weakness of being completely open to "leakage": with the implantation of the project, the people who would have been deforesting in the area established as a reserve will probably clear the same amount of forest elsewhere in the region.

The amount of uncleared forest remaining is a key factor in determining the appropriateness of combating global warming through reserve creation versus policy changes to slow deforestation. Deforestation processes differ between situations where large areas of forest remain and those where forest is reduced to remnants (Rudel and Horowitz, 1993). Reserves are most appropriate where only remnants remain, as in Costa Rica or in Brazil's Atlantic Forest area. The Amazonian part of Brazil contrasts with this. Just the state of Rondonia is five times bigger than the whole country of Costa Rica.

The current criterion of "incremental costs" (or "additionality") implies that establishing a park in an area of forest that would not be cleared receives no credit, whereas one in an area experiencing rapid clearing is heavily rewarded. The park in the area with little clearing is likely to be cheaper to establish but, at least for the next few decades, there would be little additionality for greenhouse gas benefits because the areas would probably not be cleared anyway. How carbon credits are allotted can therefore influence where parks are created. Depending on how benefits are counted, the areas with the greatest benefit for a given investment in carbon offsets will not be the same areas that would be chosen for maintaining biodiversity. In Brazil, the least well-protected and most threatened types of forest are along the southern boundary of Amazonia where reserve establishment is very expensive per unit of area (Fearnside and Ferraz, 1995).

2.2. Policy Changes

The second approach is through policy changes aimed at reducing the rate of clearing, but not limited to specific reserves or areas of forest. This second approach has the great advantage of addressing more fundamental aspects of the tropical deforestation problem, but has the disadvantages of not assuring the permanence of forest and of not resulting in a visible product that can be convincingly credited to the existence of the project. In order for credit to be assigned to policy change projects, functioning models of the deforestation process must be developed that are capable of producing scenarios with and without different policy changes. While such models are not yet available, progress is being made towards their development by several research groups.

Assessment of deforestation avoidance as a mitigation option requires at least a rough quantification of the cost of slowing deforestation. No answer is currently available to the question of how much it would cost to avoid a hectare of deforestation in different parts of the region, by different actions, and by different means of inducement.

Understanding the causes of deforestation could lead to different priorities for combating global warming. For example, a "deforestation reduction initiative," later renamed the "alternatives to slash and burn project" aims at achieving these results by promoting agroforestry among small farmers. However, the relationship between the agricultural improvements promoted and reduction of deforestation is undocumented and highly unlikely to be of the level claimed by proponents (5-10 ha saved from the shifting cultivators' ax per ha put under sustainable agriculture) (Sánchez, 1990). While agroforestry has an important role to play in improving the lives of small farmers, it is unlikely to be a cost-effective mechanism to stem deforestation (Fearnside, 1995b). This is particularly true in Brazil, where approximately 70% of the clearing is done by large- or medium-sized ranchers (Fearnside, 1993a).

Whether policy change mitigation options are subject to leakage depends on how carbon credits are calculated. Because the policy change approach focuses on national level totals (whether these totals be of flows or of stocks), no leakage can occur through changes in the spatial distribution of deforestation activity within the country, as by movement of potential deforestation from a reserve to another forested area. Displacement of deforestation in time, however, can result in leakage if the accounting procedure requires "permanent" sequestration in either specific areas of forest or in the forest sector of a whole country.

I would argue that postponing deforestation is a valid mitigation measure even if the forests in question are later cut, including cutting up to the theoretical maximum of clearing all forests in a country. The credit for such a delay depends on two key parameters: time horizon and discount rate (or other alternative time-preference scheme). Decisions on these parameters, including using an infinite time horizon or a zero discount rate, reflect moral values and should be approached through democratic means. From a carbon perspective, postponing a given number of hectares of clearing for a year is equivalent to avoided emissions by reduced combustion of fossil fuels under conditions likely to apply to Brazil. In the fossil fuel case, avoided emissions are counted as *permanent* gain, even though the same levels of oil not burned in one year will be burned just one year later. The fossil fuel displacement is assumed to cascade forward, either (1) indefinitely (i.e., assuming that fossil fuel stocks are infinite for practical purposes), (2) until after the end of the time horizon, or (3) until fossil fuel burning ceases at some fixed point in time due either to development of technological alternatives or to enlightenment and social changes. In the case of deforestation, these assumptions can break down if the area of remaining forest is small enough that it could be exhausted within the time horizon under consideration. If a country runs out of forest (or of accessible or unprotected forest) within the time horizon, then no carbon advantage would accrue if the discount rate is zero.

The discount rate for carbon need not be zero, although zero discount rate is the current practice of the GEF in evaluating proposed mitigation projects. A discount rate greater than zero is justified by the fact that a given increase in temperature through global warming does not produce a one-time impact, but rather raises the frequency of droughts, floods and other undesirable events from that time forward. If global warming is delayed from time 1 to time 2, the impacts that would have been suffered between time 1 and time 2 represent *permanent* savings, thereby giving time a value independent of any additional value that might be assigned to it on the basis of selfish motives on the part of the current generation. A value for time is translated into economic decision-making by use of a discount rate (or equivalent). Discounting can radically alter choices of energy sources and mitigation options (Fearnside, 1995a, 1996c, 1997c, nd-b).

Irrespective of whether the discount rate used is zero or greater than zero, carbon accounting needs to be done on a carbon ton-year basis rather than on the basis of "permanent" sequestration if comparisons are to be made between reserve creation and policies to slow deforestation. A ton-year accounting is also needed for comparing avoided fossil fuel emissions with silvicultural plantations and other mitigation options in the forest sector. Under a ton-year system, credit would be given for the number of tons of carbon held out of the atmosphere each year. Discounting, zero or otherwise, would apply to the carbon value calculated for each year over the time horizon when the expectations for different proposed mitigation projects are compared. Keeping a ton of carbon out of the atmosphere during any given year has the same value, whether the carbon atoms are cycled through successive rolls of toilet paper that each last only a few weeks or months, or whether they are in a mahogany desk that lasts a century. Under a ton-year accounting system, delaying deforestation merits credit irrespective of the long-term fate of the forest, although the cumulative credit that can be earned from a forest stand is obviously greater the longer the forest remains standing.

Understanding the process of deforestation provides the key to making avoided clearing and/or carbon stock maintenance into global warming mitigation options. Monitoring is vital, not only to checking the results of any mitigation measures adopted but also to providing data for understanding the deforestation process. The recent history of deforestation monitoring in Brazil makes apparent some of the challenges to achieving this goal.

2.3. Brazilian Deforestation as a Mitigation Opportunity

Deforestation in Brazilian Amazonia has been monitored by the National Institute for Space Research (INPE) since the 1970s. The data applying to the originally forested portion of the Legal Amazon (a 5×10^6 km^2 administrative region that encompasses nine states) are shown in Table 3. LANDSAT mosaics for 1973 and 1975 were also interpreted (by the Brazilian Institute for Forestry Development-IBDF, now incorporated into the Brazilian Institute for the Environment and Renewable Natural Resources-IBAMA), but separation of forest and *cerrado* (scrub savanna) areas has not been done. Results for additional years are available for some of the states, but not for the whole region (see review in Fearnside, 1990a).

For calculating deforestation rates one must have estimates of the extent of deforestation at two points in time. In the case of the Brazilian Legal Amazon, annual deforestation rate for the 1978-1988 period has been estimated from area estimates for 1978 (derived from Skole and Tucker, 1993 with modifications by Fearnside, 1993b) and for 1988 (Fearnside *et al.*, 1990), yielding a value of 20.4×10^3 km^2 yr^{-1}, including flooding by hydroelectric dams (N.B.: an additional cloud cover correction has raised this slightly from the 20.3×10^3 km^2 yr^{-1} derived in Fearnside, 1993b). Annual deforestation rate declined to 18.9×10^3 km^2 for 1988-1989; 13.8×10^3 km^2 for 1989-1990 and 11.1×10^3 km^2 for 1990-1991 (Fearnside *et al.*, 1990; Fearnside, 1993a). Deforestation estimates announced by INPE on 25 July 1996 indicate that the annual rate subsequently rebounded to 13.8×10^3 km^2 for 1991-1992 and 14.9×10^3 km^2 for 1992-1994 (Brazil, INPE, 1996). The distribution of this clearing activity among the nine Amazonian states is given in Table 4.

The great surge of deforestation in Mato Grosso and Rondonia is apparent from the rates presented in Table 4. Mato Grosso, which had accounted for 26% of the deforestation activity in 1990-1991, rose in importance to 42% in 1992-1994, while

Table 3: Deforested Area in the Brazilian Legal Amazon

Political unit	Original forest area (10^3 km^2)	Deforested area (10^3 km^2)						
		Jan 1978	Apr 1988	Aug 1989	Aug 1990	Aug 1991	Aug 1992	Aug 1994
FOREST CLEARED (PRIMARILY FOR RANCHING AND AGRICULTURE)								
Acre	152	2.6	8.9	9.8	10.3	10.7	11.1	12.1
Amapa	115	0.2	0.8	1.0	1.3	1.7	1.7	1.7
Amazonas	1,481	2.3	17.3	19.3	19.8	20.8	21.6	22.3
Maranhao	143	65.9	90.8	92.3	93.4	94.1	95.2	96.0
Mato Grosso	528	26.5	71.5	79.6	83.6	86.5	91.1	103.6
Para	1,139	61.7	129.5	137.3	142.2	146.0	149.8	158.3
Rondonia	215	6.3	29.6	31.4	33.1	34.2	36.4	41.6
Roraima	164	0.2	2.7	3.6	3.8	4.2	4.5	5.0
Tocantins	59	4.2	21.6	22.3	22.9	23.4	23.8	24.4
Legal Amazon	3,996	169.9	372.8	396.6	410.4	421.6	435.3	465.1
FOREST FLOODED BY HYDROELECTRIC DAMS								
Legal Amazon		0.1	3.9	4.8	4.8	4.8	4.8	4.8
DEFORESTATION FROM ALL SOURCES								
Legal Amazon		169.9	376.7	401.4	415.2	426.4	440.2	470.0

Rondonia rose from 10% to 17%. Acre rose from 2.9% to 3.2%, while all of the remaining six states in the region declined in relative importance. The dominance of Mato Grosso, Para, and Rondonia in Amazonian deforestation is clear, these three states accounting for 88% of the total for the 1992-1994 period.

Little technical information on INPE's methodology is available since the estimate for 1988-1989. For the 1988-1989 rate estimate (in which this author participated), a procedure was applied to correct for gaps stemming from cloud cover (Fearnside *et al.*, 1990). The most recent estimate includes a correction for the date of each image within the annual clearing and burning cycle at each location (as in Fearnside *et al.*, 1990), but does not yet include any correction for cloud cover (Brazil, INPE, 1996). In both the 1992 and 1994 mosaics there were nine scenes (4% of the total) that were completely obscured by clouds (Brazil, INPE, 1996). Percentage of cloud cover, either for whole mosaics (including partially obscured scenes) or for areas of known deforestation activity, are not given in the INPE report. The report estimated the 1992-1994 rate of deforestation in Amapa as zero (Table 4), for which the likely explanation is that clouds obscured any clearing. Amapa is notorious for heavy cloud cover (Fearnside, 1990). The omission of a cloud cover correction means that the 1992-1994 rate was probably even higher than the 14.9 X 10^3 km^2 yr^{-1} value announced by INPE in July 1996.

The 1992 and 1994 mosaics revealed an additional 1703 km^2 of clearing that had occurred by 1991 but which had not been detected in the surveys for 1991 or earlier; INPE has not yet revised the estimate for 1991 and earlier years (Brazil, INPE, 1996). This additional clearing is not included in the values given in Tables 3 and 4 for any year.

The deforestation rates in the different Amazonian states (Table 4) make several features apparent. One is the relative increase in states with small deforested areas: increases by a factor of 15 over the 1978-1994 period in Amazonas and Amapa, and by a factor of 30 in Roraima. The advanced state of deforestation in Maranhao (67% cleared by 1994) and Tocantins (42% cleared) has slowed relative rates in these places, but the cleared area continues to grow. Differences in deforestation rates among political units are important in providing indications of the causes of deforestation and the policy changes that might slow the pace of forest loss. The distribution of clearing in both 1990 and 1991 indicated that small farmers (<100 ha of land) accounted for 30.5% of the clearing, the remainder being medium and large ranches (Fearnside, 1993a). The data for 1992 and 1994 are suggestive of a similar pattern, but fall slightly short of achieving a 5% level of statistical significance (not surprising given the increasing obsolescence of the 1986 agricultural census used as a measure of property size distribution). The more recent deforestation data suggest that the relative importance of medium and large ranches has increased even further, and that of small farmers has fallen to around 20% of the total.

2.4. TYPES OF MONITORING

Reducing deforestation rates through policy changes requires understanding the process of deforestation, which depends on monitoring in order to have information as a time series. Information is needed both from satellite imagery and from on-the-ground observations on who occupies the land and why the observed changes occur. Monitoring must be done by individual property if causal factors are to be identified reliably; this is best achieved using a data base in a Geographical Information System (GIS) that includes property boundaries. So far the only example of such a data base in Amazonia is one developed by the Institute for Man and the Environment in Amazonia (IMAZON) — a non-governmental organization in Belem. Deforestation and land use are mapped together with property boundaries in a single municipality (county) in eastern Para. The confused nature of land-titling records in Amazonia becomes apparent when such an effort is undertaken, creating resistance in some quarters.

Table 4: Deforestation rate in the Brazilian Legal Amazon

Political unit	Deforestation rate (10^3 km^2 yr^{-1})					
	1978-88	1988-89	1989-90	1990-91	1991-92	1992-94
Acre	0.6	0.6	0.6	0.4	0.4	0.5
Amapa	0.1	0.2	0.3	0.4	0.04	0.00
Amazonas	1.6	1.2	0.5	1.0	0.8	0.4
Maranhao	2.5	1.4	1.1	0.7	1.1	0.4
Mato Grosso	4.5	6.0	4.0	2.8	4.7	6.2
Para	6.8	5.8	4.9	3.8	3.8	4.3
Rondonia	2.1	1.4	1.7	1.1	2.3	2.6
Roraima	0.2	0.7	0.2	0.4	0.3	0.2
Tocantins	1.6	0.7	0.6	0.4	0.4	0.3
Clearing in Legal Amazon	20.0	18.0	13.8	11.1	13.8	14.9
Hydroelectric flooding	0.4[a]	1.0[b]	0.0	0.0	0.0	0.0
Deforestation from all sources	20.4	18.9[c]	13.8	11.1	13.8	14.9

[a] Hydroelectric flooding rates for 1978-88: Amazonas 186 km^2 yr^{-1}; Para 193 km^2 yr^{-1}.
[b] Hydroelectric flooding rates for 1988-89: Amazonas 535 km^2 yr^{-1}; Rondonia 436 km^2 yr^{-1}.
[c] INPE gives a 1988-89 rate of 17.86 X 10^3 km^2 yr^{-1} (Brazil, INPE, 1996). The lower rate appears to be mainly due to differences in assigning dates to hydroelectric flooding; the flooding schedules used here are derived in Fearnside (1995d). INPE's value also appears not to include a cloud cover correction (93 km^2 yr^{-1} for 1988-89).

Once policy changes are made in practice, not only deforestation but also the policies themselves must be monitored. Decrees and laws are not the same as changes in practice; the initiation and continued application of changes must therefore be confirmed regularly. The best example is Brazil's suspension of incentives for Amazonian cattle ranches.

The notion that incentives for cattle ranches have ceased to exist has been repeated so many times without checking original documentation that the idea has almost taken on a life of its own. Even the country's top leadership has sometimes lost sight of reality in this case. In June 1991 Brazil's president and the special secretary of the environment travelled to Washington, D.C., and, after giving speeches claiming that incentives had been suspended, they were embarrassed when environmentalists confronted them with copies of the *Diário Oficial* (Brazil's official gazette) indicating that the suspension had been revoked five months earlier (*Isto É/Senhor*, 3 July 1991, p. 21). Upon returning to Brazil they reinstated the suspension. Monitoring of changes under such circumstances requires continuous attention of an independent agency, and input from non-governmental organizations and other observers in addition to reports from government authorities.

Despite numerous official statements claiming that incentives have been abolished and are therefore no longer contributing to deforestation, what was actually done was suspension of approval of *new* projects, not revoking the incentives for the *old,* or already approved, projects. Because the backlog of several hundred old projects is much greater than the few new ones that were being approved each year, continuation of the existing incentives represents a force contributing to deforestation. Each year, the income tax forms for companies *(pessoas jurídicas)* continue to have spaces for declaring exemptions for income from agriculture and ranching projects approved by the Superintendency for Development of the Amazon (SUDAM). In addition, projects such as sawmills and pig iron plants never were included in the suspension, and so are eligible for approval as new projects in addition to continuation of incentives for already approved projects.

The frequent changes and ambiguous nature of policy changes made to discourage deforestation might appear to invalidate policy change as a global warming mitigation option. However, there is no real alternative to policy change as a strategy for slowing deforestation and avoiding the greenhouse gas emissions it provokes. Policy changes needed include removing the remaining incentives, revising the criteria for granting land tenure such that deforestation is not counted as a required 'improvement' *(benfeitoria)* on the land, and changing tax laws such that land speculation ceases to be a profitable activity (Fearnside, 1989).

2.5. Intensity of Monitoring

The intensity of monitoring, or the effort that should be devoted to monitoring, depends on the cost of improving estimates of carbon stocks and/or flows, and the financial rewards in terms of carbon credits for achieving these improvements. The cost of increasing the certainty of carbon estimates, that is, decreasing the width of the confidence interval surrounding the mean estimates, can be expected to increase in a fashion that is more than linear, perhaps exponential. Achieving very high levels of certainty would be prohibitively expensive. On the other hand, decreasing the width of the confidence interval (expressed in absolute terms, that is, tons of carbon) would have a linear relation to the carbon credit that a country could claim — the credit presumably being based on the bottom limit of the confidence interval. Under these conditions, curves representing the cost of incremental improvements in the certainty of estimates, and the value of carbon credits with increasing certainty of the estimation, would at some point cross. The point of crossing would represent the optimal level of certainty for monitoring programs to deliver. Such a level of certainty would correspond to a given percentage (up to "wall-to-wall"), a given frequency (up to annual), and a given level of resolution of the satellite imagery and other information sources used.

In the case of Brazil, a decision has been announced to produce annual deforestation estimates based on "wall-to-wall" LANDSAT-TM ($30\ m \times 30\ m$ resolution) imagery (G. Meira Filho, public statement, 1996). Although the cost of such estimates is not trivial, this author believes the decision to be a wise one given the tremendous potential value of carbon benefits from Amazonia, the need to eliminate any doubt regarding selectivity of information release, and the great value of annual information in associating policy and other changes with alterations in deforestation behavior.

Quantifying carbon stock changes over time requires continuous revisions of methods, including revision of previous estimates (e.g., estimates for locations covered by clouds). Small changes in methods (such as cloud cover corrections) can lead to big policy implications, especially in the case of carbon stocks (since flows are a small percentage of stocks annually).

2.6. INDEPENDENCE AND TRANSPARENCY

Need for independence in monitoring is demonstrated by the history of problems and delays in Brazil's handling of its project for deforestation monitoring (PRODES). Although the monitoring and error-checking techniques are now quite reliable, the priority given to the monitoring effort fell precipitously when the 1987-1991 decline in deforestation rates ended. In addition, long delays occurred in releasing some of the numbers even after the results were ready. The 1978 LANDSAT mosaic was analyzed by 1980 (Tardin *et al.*, 1980), but a decade-long gap then ensued (during which deforestation increased though its peak in 1987). Analysis of the LANDSAT mosaic for 1988 was completed in April 1989 (Tardin and da Cunha, 1989) in a rush effort that produced an estimate less than two months after the images were received; the rush was in order to counter an estimate by the World Bank (Mahar, 1989) that had claimed a higher amount of deforestation (see Fearnside, 1990b). The mosaic for 1989 was completed in 1990, which, after correcting errors, confirmed that deforestation rates were declining (Tardin *et al.*, 1990).

The mosaics for 1990 and 1991 were then analyzed as an annual effort, the results being released in 1991 and 1992, respectively (Brazil, INPE, 1992). After the June 1992 United Nations Conference on Environment and Development (UNCED, or ECO-92) had passed, media attention to Amazonia evaporated. Repeated government statements succeeded in convincing much of the world that deforestation was under control (although, in fact, the effect of the system of clearing permits, fines for unauthorized clearing, and ceasing to approve new fiscal incentives, was probably much less than claimed; see Fearnside 1993a). No further deforestation numbers were released over the ensuing four years—until the July 1996 announcement. INPE did, however, analyze the LANDSAT mosaic for 1992, and completed checking the results by March 1994, according to a public statement by the head of INPE's remote sensing department (Fearnside, 1994a, 1995c). Apparently, the 1992 mosaic was subsequently reanalyzed using a different methodology for digitizing the boundaries of the clearings (scanning of overlays versus tracing on digitizing tablets). INPE did not release the 1992 numbers until 25 July 1996, including them with the announcement of the 1994 results.

Release of INPE's results now requires approval of a commission composed of a variety of ministers and agency heads. Assuring the technical accuracy of the estimates is clearly not the purpose of such a procedure, but rather assuring that the timing of any information released is politically convenient. Such orchestration of what should be a scientific event, rather than a political one, represents an impediment to Brazil's gaining credibility in the emerging international market for environmental services. Efforts to maximize such credibility would be a wise investment for Brazil, given the tremendous potential value of the environmental services that the country has to offer (Fearnside, 1997a). This requires mechanisms to prevent gaming with monitoring by choosing the timing and content of the information released.

Brazil suffers from a lack of institutional credibility. As in many countries, no person or institution in Brazil can say that deforestation will be controlled or decreased, and expect to have other countries believe this and move financial resources on the basis of promises. Brazil is presently fortunate to have a strong conservationist (Eduardo Martins) as head of IBAMA since the last change of that agency's leadership in May 1996. The history of IBAMA does not inspire confidence, with over a dozen persons having headed the agency since it was founded in 1989 — or about one every six months.

The political sustainability of measures is a perennial problem in government efforts to restrain deforestation. In addition to frequent policy changes linked to leadership changes in environmental agencies like IBAMA, measures are often amended or revoked through executive decrees or suspended by court orders. For example, the granting of new fiscal incentives to cattle ranches has been suspended on several occasions (October 1988, April 1989, December 1990, February 1991 and June 1991). Except for the last of these (Decree 153 of 25 June 1991), the suspensions were always short-lived. The facility with which policies can be reversed makes it easy for dramatic "packages" of measures to be announced, but ranchers or other interest groups suffering restrictions (and sometimes perhaps also the officials making the announcements) know that the decisions can be quietly reversed a short time later. This makes it important to focus attention on quantitative indicators, such as reduced deforestation rates detected through monitoring, rather than simply relying on decrees or policy announcements.

The problem of credibility is dramatized by the recent revelation that deforestation rates were really increasing over a period of three years while official sources had been leading the public to believe that they were declining. The long delay in releasing the data is best explained by reluctance to divulge bad news, with possible consequences in terms of international concern over destruction in Amazonia. Such concern can translate into tangible costs through increased scrutiny and environmental conditions on multilateral development bank and bilateral loans, restrictions on imports of tropical timber from unsustainable sources (a description that applies to virtually all exports from Amazonia today), and less willingness to finance roads, dams and other infrastructure that speeds the process of forest loss.

Independence and transparency in monitoring are prerequisites for transforming the environmental services of Amazonian forest into a basis for sustainable development for the region's rural population. The credibility of environmental services (including carbon) provided by Amazonia depends on transparent accounting, monitoring protocols and institutional processes. Without these, it will be difficult to argue for the carbon stock approach and thereby capture the much larger values that this could potentially make available for supporting Amazonia's human population. The rural population must be given a real stake in seeing that Amazonian forest is kept standing, as it is ultimately they who must decide to maintain the forest or not maintain it.

3. Conclusions

Global warming mitigation by slowing forest loss in Amazonia can best be achieved by policy changes aimed at removing the motives for deforestation rather than by investing in establishment and defense of specific reserves. The choice of approaches depends on the way that carbon accounting is done and credits assigned. Strong arguments exist for accounting for carbon on a ton-year basis rather than insisting on options that result in "permanent" sequestration. There are also valid reasons for applying some form of discounting or alternative time-preference weighting to carbon. Credit for maintaining carbon *stocks* would avoid the reward for bad behavior (i.e., rapid clearing of tropical forests) that is implicit in rewarding only "incremental" changes in carbon *flows*. Brazil stands to gain substantially more credit from an accounting system based on stocks, thereby increasing the potential for the value of environmental services forming a basis for sustainable development for the region's rural population, and increasing the motivation for maintaining the forest. Monitoring would be a key element in any plan to transform Amazonian forest maintenance into a global warming mitigation option. Monitoring provides both a check on program effectiveness and a source of input to models for predicting the result of different policy scenarios on deforestation and carbon stocks. Not only areas of forest and rates of deforestation must be monitored but also policies both as announced and as implemented in practice. The monetary value of carbon credits available to Brazil and other Amazonian countries can be expected to increase in proportion to each country's credibility in providing this environmental service. This credibility is directly proportional to the independence of the monitoring process.

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MONITORING CARBON SEQUESTRATION BENEFITS ASSOCIATED WITH A REDUCED-IMPACT LOGGING PROJECT IN MALAYSIA

MICHELLE PINARD
Department of Forestry, MacRobert Builing
University of Aberdeen, AberdeenAB24 5UA, UK

FRANCIS PUTZ
Department of Botany, University of Florida
Gainesville, Florida, USA

Abstract. The Reduced-Impact Logging Project, a pilot carbon offset project, was initiated in 1992 when a power company provided funds to a timber concessionaire to implement timber-harvesting guidelines in dipterocarp forest. The rationale for the offset is that when logging damage is reduced, more carbon is retained in living trees, and, because soil damage is minimized, forest productivity remains high. To estimate the carbon benefit associated with implementation of harvesting guidelines, a monitoring program was developed based on 1) field studies for measuring carbon stocks and flows; 2) a computer model of forest carbon dynamics for simulating various combinations of harvesting intensity and damage; and, 3) a projection model for calculating carbon balance over the project lifespan. Seventy-five percent of the carbon stored in this forest is in biomass, and of this, 59% is in large trees (>=60 cm diameter); consequently, reliable estimates of variables related to large trees are critical to the estimate of carbon benefits. Allometric methods for estimating belowground biomass are recommended over pit-sampling methods because of low cost-effectiveness of obtaining precise estimates of woody root biomass. Sensitivity analyses of variables used in the simulation model suggest that maintenance of ecosystem productivity has a large influence on long-term carbon storage in the forest. Projections of differences in carbon stores between the reduced-impact and conventional logging sites rely on assumptions about tree mortality, growth, and recruitment; published data for comparable sites in Malaysia are probably appropriate for estimating forest recovery from conventional but not reduced-impact logging. Continuing field work is expected to provide the data needed to evaluate assumptions of the models.

Keywords: biomass; carbon offsets; logging damage; Malaysia; monitoring program; simulation model; tropical forest

1. Introduction

1.1. THE REDUCED-IMPACT LOGGING (RIL) PROJECT

Commercial logging reserves in Sabah, Malaysia, are selectively logged insofar as all mature trees (>60 cm dbh) of commercial species are felled during the first harvest (Kleine and Heuveldop, 1993). On average, 8-15 trees are extracted per ha and 40-70% of the residual stand is damaged (Sabah Forestry Department, 1989). Typically, bulldozers are used to drag the logs out of the forest. Depending on the terrain, 15-40% of the ground surface is crushed, scraped, and traversed by bulldozers (Chai, 1975; Jusoff, 1991) and is slow to recover (Cannon *et al.*, 1994). Improved harvesting systems exist and have been demonstrated in Malaysia (Chua, 1986; Malvas, 1987), but incentives to improve or to enforce regulations are lacking (Whitmore, 1995).

In 1992, a pilot carbon offset project was initiated in Sabah in which a power company (New England Electric Systems, NEES) provided funds to a timber concessionaire (Innoprise Corporation, ICSB) to implement guidelines aimed at reducing logging damage (Pinard *et al.*, 1995). The investment was used to help pay the costs of training operators and implementing improved harvesting practices. The rationale for the carbon savings is that by reducing the number of trees killed, losses in biomass are reduced, carbon emissions from the decay of logging debris are decreased, and the capacity of the forest to sequester carbon is maintained (Figure 1). In contrast, forest recovery in areas logged with conventional methods is slow due to such factors as topsoil removal and compaction, competition with colonizing vegetation, and because the majority of the large trees are killed. Within the 60-year cutting cycles prescribed for these commercial forests (Sabah Forestry Department, 1989), projected forest recovery in areas logged conventionally is far below recovery in areas logged according to the guidelines.

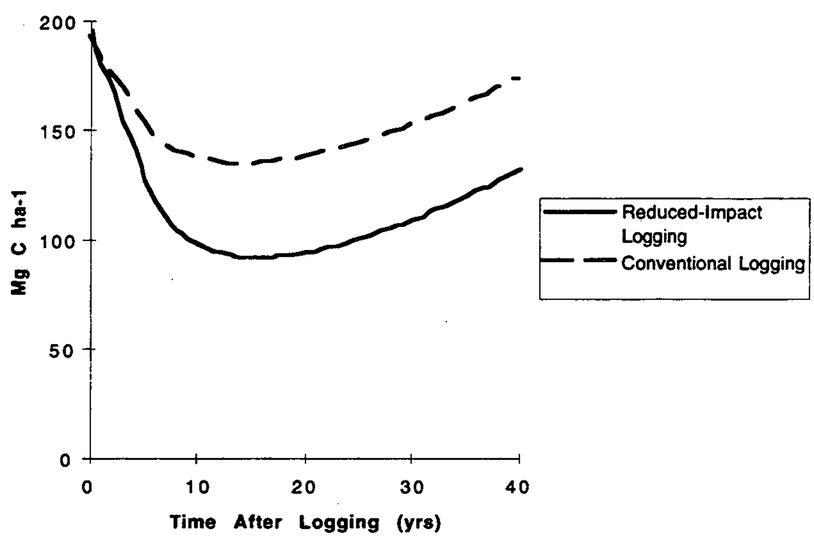

Figure 1. Estimated carbon storage in dipterocarp forest following selective logging using conventional or reduced-impact logging methods. With harvest, carbon storage immediately drops because carbon is removed from the forest in timber. Carbon storage continues to decline for several years due to the decomposition of logging debris and trees killed during harvest. Although carbon is sequestered in new growth during this time, the forest's net carbon balance is negative for as many as 10 years post-logging. In comparison, if logging damaged is reduced, carbon storage declines less during the first 10 years because there is less mortality from damaged trees. Recruitment and growth balance losses from decay of logging debris more quickly after logging, thus the curve becomes positive sooner after logging than does the curve for conventional logging. The area between the curves represents the carbon offset or the carbon kept on site due to implementation of harvesting guidelines.

1.2. Carbon Monitoring Program

The objective of the carbon monitoring program is to quantify the carbon sequestration (and carbon emission reduction) benefit associated with investment in improved harvesting practices. The program has the following three components: (1) field studies aimed at quantifying carbon stores and fluxes; (2) a model to simulate changes in biomass and carbon pools following logging, useful for identifying variables with relatively large influence on carbon storage over time; and, (3) a simpler projection model to generate an estimate of the carbon benefit. The interrelationships of the components, and the role of relevant, published literature, are illustrated in Figure 2. In this paper we aim to describe the monitoring program used for the RIL project and to present an overview of the results, emphasizing those that are more likely relevant to others interested in monitoring programs for carbon offsets in forestry. Because most of the carbon in a dipterocarp forest is in the trees,[1] the monitoring program emphasizes plant biomass. Contemporary conventional logging practices provide the reference case, or baseline, against which the reduced-impact logging case is compared. The fate of timber extracted is assumed to be equivalent for the two harvesting methods; forest products and their fates are not included in the analysis.

For the purposes of describing the carbon benefit associated with the project, tight boundaries have been drawn around the harvest area specifically dedicated to the project, and over one cutting cycle of 40 yrs. We have not included flows of carbon across project boundaries into forest products or over multiple rotations. Our estimates of project carbon benefits are, therefore, probably conservative, because RIL areas are likely to be more productive than CNV areas over multiple harvests in terms of carbon sequestered in biomass and in the production of durable wood products.

2. Methods

2.1. Field Studies

To quantify the carbon stores and fluxes in the study area, we compared dipterocarp forests logged according to the guidelines with forests logged by conventional methods in terms of above- and below-ground biomass both before and after logging. Extensive field studies were conducted as part of the pilot project in 1993-1995 by a research team from the University of Florida in conjunction with the Silviculture Division within Rakyat Berjaya. Detailed descriptions of the methods (Pinard and Putz, 1996) and an economic analysis (Tay, 1997) are presented elsewhere.

[1] Biomass contains approximately 200 Mg C ha^{-1}, woody debris and litter approximately 28 Mg C ha^{-1}, and soil organic matter approximately 33 Mg C ha^{-1} (Ohta and Effendi, 1992; Pinard, 1995; Pinard and Putz, 1996).

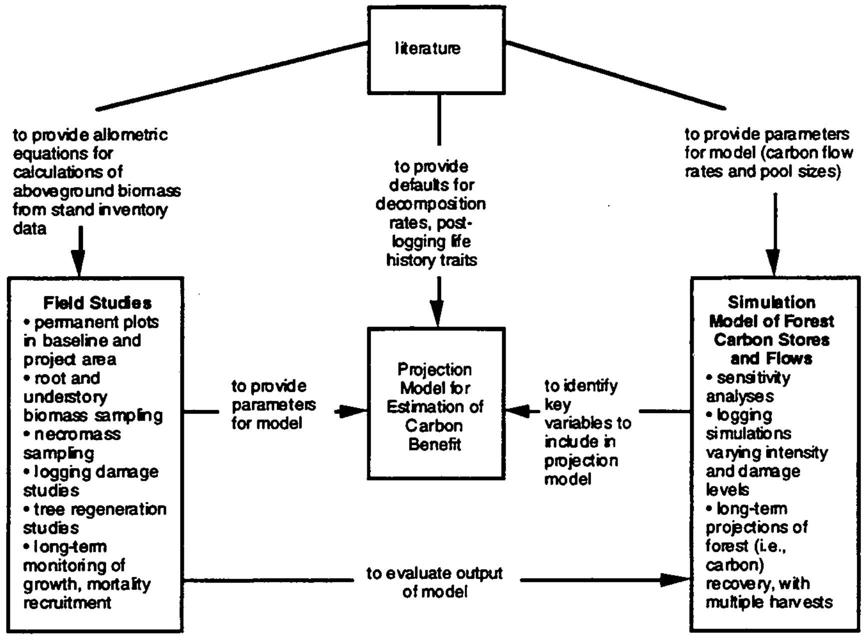

Figure 2. Components of the monitoring program used for the Reduced-Impact Logging Project in Sabah. Field studies, a computer simulation model of forest carbon stores and flows, and published literature support the calculations of the carbon sequestration benefit associated with the project.

Prior to logging, four logging units (30-50 ha each) were randomly selected from the 450 ha pilot project area; four additional logging units were randomly selected from an adjacent area to be logged conventionally. Within each unit, 20-40 permanent plots (1600 m^2) were established for pre- and post-harvest measurements. Trees within the plots were tagged, mapped, measured (diameter at breast height, dbh), and identified to species or timber species group. Aboveground tree biomass was estimated allometrically using tree inventory data and stem volume-diameter-height relations calculated for 15 local species groups in Ulu Segama Forest Reserve (Forestal International Unlimited, 1973) and a biomass expansion factor developed for good hill dipterocarp forest in Malaysia (Brown *et al.,* 1989). Belowground biomass was measured using pits (50 × 50 × 50 cm) for coarse roots (>5 mm diameter) and cores (5 cm diameter, 10 cm depth) for fine roots (<=5 mm diameter). To determine coarse root biomass directly beneath trees (hereafter, butt roots), partially uprooted trees along roadsides were sampled and a regression equation was developed, using dbh as the independent variable and butt root mass as the dependent variable. This equation was then applied to trees in the permanent plots to calculate butt root biomass per ha.

After logging, permanent plots were revisited, and tagged trees were classified by type and degree of damage. From the damage assessment data the following parameters were estimated: timber volume extracted; necromass produced from harvested trees; necromass produced from trees destroyed during harvesting; and necromass produced from damaged trees that died within the first 8-12 months after logging. Soil disturbance was mapped and measured in the eight logging units that contained permanent plots. Additional studies of wood decomposition rates, soil organic matter content, and plant colonization of disturbed sites are not described here. Trees in permanent plots were remeasured three years after logging and are scheduled to be re-measured every five years.

2.2. Simulation Model of Carbon Dynamics

To examine the effects of reduced levels of logging damage on long-term carbon storage in dipterocarp forests, we constructed a simulation model of dipterocarp forest development based on FORMIX, a model developed by Bossel and Krieger (1994). Our model tracks carbon stored in forest biomass and necromass pools over time and is intended to simulate forest recovery following logging. The amount of carbon stored in a logged or silviculturally managed forest is influenced by factors and processes that are both internal to the system (*e.g.*, species composition, growth rates, decay rates) and external to the system (*e.g.*, rotation times, logging damage, timber volume extracted). The model provides a tool for exploring, through sensitivity analyses, the relative contributions of the variables.

The model is presented only briefly here but a more detailed description may be found in Pinard (1995). The basic system is scaled to 1 ha, uses annual time steps, and includes carbon pools for aboveground biomass and necromass (Figure 3). Carbon storage in the pools is followed as trees grow, shed litter, die, and are replaced. The basic structure of our model is identical to FORMIX, as are processes describing carbon gain through photosynthesis, transition rates between layers, recruitment, and mortality rates. Our model differs from FORMIX in that it simulates carbon transfer from biomass to necromass through tree mortality and litterfall. Necromass decomposition is simulated as proportional mass loss. Coarse woody, small woody, and fine debris decay include transfer of carbon to soil organic matter. Carbon is lost from the soil organic matter pool at 5% mass loss per year (Yoneda *et al.*, 1977; Kira, 1978). Carbon stored in roots, shrubs, herbs, vines, and in mineral soil below 50 cm is not included in our model.

The model was run to simulate various scenarios, including no logging and logging with varying intensities of harvest and damage to residual stand. Also, sensitivity analyses were performed by increasing by 15% the values of a selection of variables, constants, and parameters used in the model and comparing the output values of various response variables. We focus here on the impact of damage on mean carbon storage over 40 years and on a series of simulations that held harvest intensity constant at 125 m^3 ha^{-1} (restricted to trees >60 cm dbh) but varying fatal damage from 10 to 90% of the residual stand.

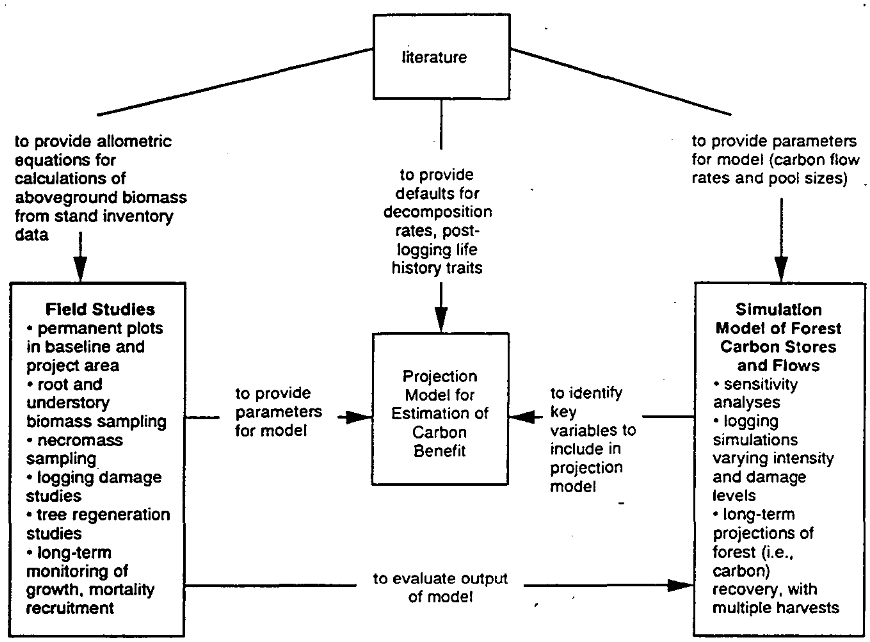

Figure 3. Diagram of carbon flow in a dipterocarp forest as represented in our simulation model. Modified from Pinard, 1995.

2.3. Projection Model for Estimating Carbon Sequestration Benefit

Projections of carbon sequestration and emissions in conventional logging and reduced-impact logging sites are based on the data from the pilot project and the assumptions listed in Table 1; results from sensitivity analyses conducted with the simulation model were useful for identifying which carbon pools were most important to include in the projection model (Figure 2). Importance here refers to relative size and vulnerability to change in response to project activities. The lifespan of the project was set at 40 years; the concessionaire agreed not to re-enter the project area for a second harvest during this period. The carbon sequestration benefits associated with the project are calculated as the difference between the carbon storage in RIL and conventional logging areas. All carbon leaving the site through decomposition is assumed to leave as carbon dioxide. Methane emissions are unlikely to differ significantly between the two sites (E. Zweede, pers. comm.). The principal source of methane in our sites is likely to be water impoundment caused by roads and, in the pilot area, road density and drainage effectiveness was similar for the two areas. The difference in logging debris produced between the two methods is not expected to generate a difference in methane emissions; evidence from research in Africa suggests that methane emissions associated with termites and decomposing wood are readily consumed by resident microbes (Delmas *et al.*, 1992).

Table 1. Assumptions in projection model of carbon recovery for forest logged by conventional or reduced-impact logging methods.

I.	Fossil fuel use (*e.g.*, bulldozer operations, log hauling) in RIL areas is equivalent to that in areas logged by conventional methods.
II.	Methane emissions in RIL areas are equivalent to those in conventional logging areas.
III.	The project area would have been logged conventionally if not for project.
IV.	Mortality during years 2-5 after logging is 5% of the stems and of the biomass (Wan Razali, 1989). Mortality after year 5 drops to 2% of the stems or 2.5% of the biomass (Wan Razali, 1989; Carey *et al.*, 1994).
V.	Logging debris and trees that die decompose at a rate of 19% of mass per year (Kira, 1978).
VI.	Growth rates for 2 years after logging are 0.5 cm dia increment, 0.3 cm dia, thereafter (Tang, 1987).
VII.	These forests receive no post-harvest silvicultural treatments.
VIII.	Carbon stored in soil does not change over time (Johnson, 1993).
IX.	The forest is not re-entered for harvest during the 40-yr projection period.
X.	The forest does not burn during the 40-yr projection period.
XI.	Root death and decay is simultaneous to aboveground biomass death and decay.

For the projections, residual forest biomass is tracked over time, losses from mortality subtracted, and gains from growth added. Emissions are calculated by following the decay of logging debris and dead trees, assuming a 19% loss in mass per year. Sequestration is calculated in three steps. First, annual volume increments are calculated by applying diameter increments to the average diameter in each diameter class in the residual forest. Second, population matrix models are used to calculate the number of individuals expected to exist in each diameter class for 40 years after logging (Leslie, 1945); the matrices of transition probabilities are based on the assumptions of growth and mortality rates listed in Table 1. Third, annual volume increments are multiplied by the number of trees in each diameter class and summed. The projections will be revised as new data become available from continuing field studies.

3. Results and discussion

3.1. FIELD STUDIES

Prior to logging, total plant biomass was about 400 Mg ha^{-1}; root biomass represented 17% of the aboveground biomass (Table 2). During the first year after logging, the mean difference between RIL and conventional logging areas in necromass produced per ha was 86 Mg (Table 3); about 62% of the difference was due to more trees killed in conventional as compared to RIL areas. Slash from extracted trees contributed greatly to the total necromass produced for both treatments.

Table 2. Above- and below-ground biomass for dipterocarp forest in Ulu Segama Forest Reserve, Sabah, Malaysia, before logging. Modified from Table 3 in Pinard and Putz (1996).

Means (Mg ha^{-1}) presented with SD (standard deviation) and N (i.e., number of plots or logging units) noted parenthetically.

Before Logging	Conventional Logging	Reduced-Impact Logging
Trees >60 cm dbh	190 (35, 4)	190 (53, 4)
Trees 40-60 cm dbh	53 (20, 4)	46 (6.5, 4)
Trees 20-40 cm dbh	46 (2.5, 4)	46 (6.3, 4)
Trees 10-20 cm dbh	21 (2.7, 4)	23 (2.8, 4)
Trees <10 cm dbh	13 (2.0, 4)	12 (2.0, 4)
Vine biomass	7.6 (3.8, 4)	7.6 (3.8, 4)
Understory biomass	2.87 (1.50, 45)	2.94 (1.67, 45)
Butt root mass	26.8 (6.2, 4)	24.5 (5.7, 4)
Coarse roots (alive)	35.9 (33.0, 40)	39.4 (38.7, 40)
Coarse roots (dead)	1.6 (2.6, 30)	1.8 (3.5, 26)
Fine root mass	2.57 (1.30, 31)	2.74 (1.43, 18)
Total mean (SD) biomass before logging	399 (40)	394 (59)

Fifty-nine percent of the total biomass was in trees >=60 cm dbh, placing particular importance on the reliability in estimates of variables related to big trees (i.e., number ha^{-1} pre-harvest, number harvested, number killed). Plot size (1600 m^2) and established (1000 ha to be logged 1996-1997), plot size for trees >=60 cm dbh was increased to 3200 m^2 (80×40m) but sampling intensity was reduced to an average of 2.4% of the total area. A slightly more intensive sample (3.2%) is being taken in the RIL area than in the conventional logging area (1.6%) because the variability in logging damage is expected to be higher in RIL than in conventional logging sites. Another change for the 1996-1997 site is that trees <10 cm dbh have not been included because they represent only about 3% of total biomass (Table 2).

For our study site, allometric equations relating stem volume to dbh and height were available for 17 timber species groups (Forestal International Unlimited, 1973). To convert from stem volume to biomass, however, we used generic equations that were developed from a composite data set of destructively-sampled trees from Peninsular Malaysia, Indonesia, Cambodia, and Brazil (Brown *et al.*, 1989). The models chosen for calculating biomass are expected to provide reasonable predictions for trees up to 300 cm dbh, but few data are available for large diameter trees (Brown and Iverson, 1992). Additional biomass data for large trees from tropical wet and moist forests are needed to improve biomass estimates for old growth forests.

Table 3. Mean (SD) Mg biomass ha^{-1} converted into necromass during logging and the first year following logging. Standard deviation describes variation among 4 logging units and does not incorporate error in biomass equations. Modified from Table 5 in Pinard and Putz (1993).

	Conventional Logging Units	Reduced-Impact Logging units
50% of extracted timber	32.22 (4.4)	25.50 (11.12)
Branches, stumps, and butt roots of extracted trees	67.14 (9.76)	45.93 (22.96)
Destroyed trees (uprooted and crushed)	67.49 (45.68)	14.28 (9.56)
Damaged trees dead within one yr after logging	7.20 (6.90)	4.01 (5.00)
Lianas destroyed	5.05 (3.23)	6.61 (3.3)
Understory plant death	1.74 (1.77)	1.78 (1.94)
Coarse root death (excluding butt roots)	10.8 (42.39)	10.4 (48.47)
Total necromass produced	192 (37)	108.5 (22.5)
Mean (SD) difference between two logging methods	86 (43) Mg necromass ha^{-1}	86 (43) Mg necromass ha^{-1}

For the purposes of monitoring carbon offset projects in natural forest, direct sampling of coarse roots, unless conducted at a relatively high intensity, may not provide a biomass estimate with the desired level of precision. In this study, coarse roots contributed disproportionally to the variance in the estimate for pre-harvest biomass and, consequently, to the difference between the two methods in necromass produced (Tables 2 and 4). However, the relationship between above- and below-ground biomass produced in this study is similar to values published for other tropical moist forests (Table 4), suggesting that the use of a simple factor adjustment to convert aboveground biomass to total biomass may be a reasonable approach to estimating carbon benefits for offset projects when resources for monitoring are limited and belowground biomass is unlikely to be a major contributor to the carbon benefit.

In the pilot area, plots were established in a randomly selected subset of logging units and were distributed within the units in a stratified random design, the strata being transects evenly spaced across the unit. This design has been successful in capturing the variability in logging impacts but inefficient in other regards. Under RIL harvesting guidelines for ground-based skidding, logging is prohibited on slopes >35 degrees. Consequently, any areas within the project site that are steep or inaccessible are likely to be left unlogged. Changes in carbon stocks in unlogged areas are likely to be less variable than the logged sites, and thus could be sampled at a lesser intensity.

Table 4. Examples of published studies of biomass relating belowground to aboveground biomass. Presentation is limited to examples from "old growth" forests.

Tropical Forest Type	Location and References	Percent of Total Biomass Belowground
Moist	Brazil, Fearnside (1993)	15.1%
Evergreen seasonal	Cambodia, Hozumi *et al.* (1969)	17%
Wet	Brazil, Klinge *et al.* (1975)	24%
Wet	Thailand, Ogawa *et al.* (1975)	8%
Wet	Venezuela, Jordan & Uhl (1978)	15%

3.2. Simulation Model

In simulations of selective logging, mean carbon storage over 40 years was most sensitive to parameters describing tree allometric relationships (e.g., stemwood fraction) and physiological characteristics (e.g., rate of photosynthesis at light saturation). Results from the sensitivity analyses suggest that maintenance of forest productivity is important for carbon storage. Productivity (i.e., woody biomass production and accumulation) is most likely to be negatively impacted by a shift in tree species composition, from dominance by dipterocarps to dominance by pioneer species and invasion of the site by vines. The input of nutrients from logging debris may have a positive effect on nutrient availability (de Graaf, 1986), but damage to soils (compaction, erosional losses of topsoil) are likely to reduce site productivity. In some forests, changes in soil physical properties due to logging are apparent decades after logging (Congdon and Herbohn, 1993).

In general, as fatal damage increases, mean carbon storage decreases (Figure 4); the relationship between the two variables is not linear. Carbon storage in aboveground biomass declines steadily as fatal stand damage increases from 10 to 50% of the residual stand. At levels of damage above 50%, mean carbon stored in biomass over 40 years is low, about 25-30 Mg C ha^{-1}, regardless of level of damage. Conversely, mean carbon stored in necromass represents a larger proportion of the total carbon when damage levels are higher. Figure 4 suggests that more total carbon can be stored if damage is increased from 70 to 90% of the residual stand. This result is due to a greater proportion of the initial carbon being converted to necromass, and the large proportion of the necromass having a residence time longer than 40 yrs. However, it is likely that carbon stored in coarse woody necromass would have a relatively short residence time on site (Johnson, 1993).

3.3. Projection Model

During the project lifespan (40 years), we estimate that about 90 Mg C ha^{-1} will exist in forest biomass due to implementation of RIL harvesting guidelines. About 55% of the carbon savings will be realized during the first 10 years following harvest and is due to less severe logging damage in RIL areas. After the tenth year, RIL areas continue to sequester more carbon in biomass annually than conventional logging areas, principally due to a higher rate of biomass accumulation.

Our projections are based on the assumption that mortality and growth rates for undamaged trees in the two sites are similar. Most published data on tree growth and mortality rates following logging in Malaysia are based on sites logged by conventional methods; we have found no long-term data for sites logged using damage-controlled methods. We expect that mortality rates will be lower in RIL areas, at least initially. Longer term differences are hard to predict since little is known about how dipterocarps respond to minor damage. It is possible that during the later part of the rotation, mortality rates will be higher in RIL than in CNV areas because the RIL stands are relatively more mature than CNV stands. We expect that diameter increments will be similar for the two sites as any initial difference related to extent of canopy opening will be of short duration.

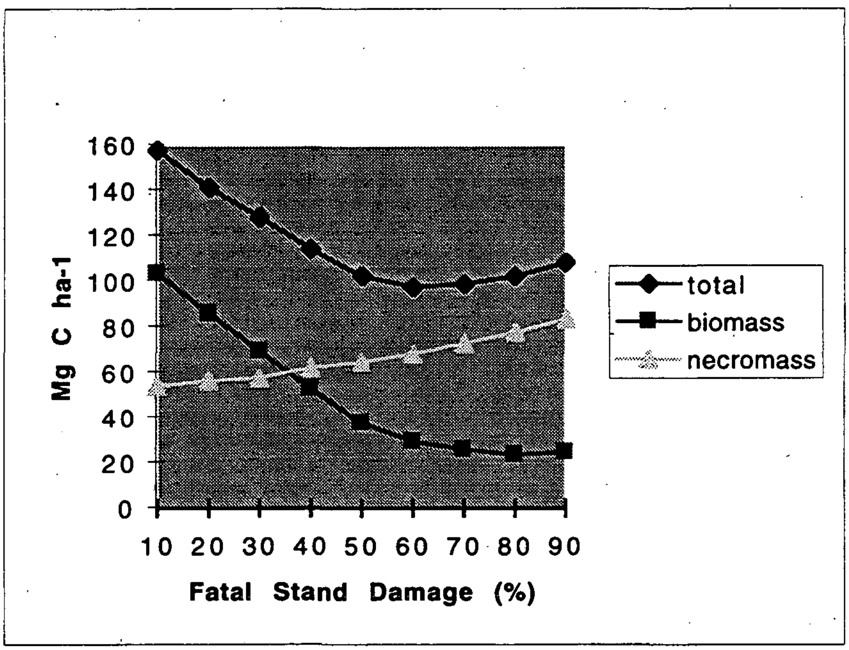

Figure 4. Results from simulations in which the proportion of the stand receiving fatal damage was systematically increased in 10% increments. Mean carbon storage in biomass and necromass was calculated over a 40 year period. For all damage levels, harvest intensity was 125 m^3 ha^{-1}. Biomass includes only aboveground biomass in trees; necromass includes leaf and twig litter, coarse woody debris, and soil organic matter. Total is biomass plus necromass.

To date, we have not tried to incorporate risk into our projection model, though fire and conversion to plantation are not unlikely fates for the conventional logging areas. Forests logged according to RIL guidelines, because they maintain a more complex forest structure and a more closed canopy than the conventional logging sites (Pinard and Putz, 1996), are less prone to dessication and, therefore, less vulnerable to ignition (Kauffman *et al.*, 1988; Uhl and Kauffman, 1988). Also, because the quality of the residual stand is fairly high, the RIL area is more likely to be maintained as production dipterocarp forest and less likely to be converted into plantations.

4. Conclusions

The monitoring program developed during the pilot phase of the RIL project was part of a broader research effort directed at gathering information and analyzing the rationality, feasibility, and cost-effectiveness of implementing harvesting guidelines as a carbon offset. The methodology used for estimating the carbon sequestration benefit was based on stand inventory data, allometric equations, and repeated measurements of permanent plots, and was supported by modeling efforts and relevant published literature (Figure 2). This methodology is readily applicable to other sites.

Our research efforts have provided insights into the relative significance of the various carbon pools within the system, significance in terms of relative size and magnitude of change during the lifespan of the project. General conclusions drawn from our experience with the monitoring program in Sabah include the following: 1) biomass in vines, small trees (<10 cm dbh), and understory vegetation is relatively insignificant in terms of pool size in this forest; 2) selection of the most appropriate allometric equations for a site and species is important because of their influence on biomass estimates; 3) use of a simple factor for converting aboveground biomass to total biomass is a reasonable approach when resources for monitoring are limited and when belowground biomass is unlikely vary independently of aboveground biomass; 4) project lifespan influences the relative importance of carbon pools to calculation of the carbon benefit, i.e., for long-term projects, carbon stored in durable wood products may be more important than for short-term projects.

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MONITORING OF CARBON ABATEMENT IN FORESTRY PROJECTS — CASE STUDY OF WESTERN GHAT PROJECT

N. H. RAVINDRANATH
P. R. BHAT
Centre for Ecological Sciences / ASTRA
Indian Institute of Science
Bangalore 560 012

Abstract. The forestry sector is being increasingly considered for abatement of greenhouse gases. A number of projects are likely to be implemented, particularly in tropical countries. It is essential to measure, record, and verify the carbon sequestered or emission avoided due to implementation of the forestry mitigation options. In this paper a set required parameters to be monitored for estimating carbon flows, monitoring methods, and institutional arrangements are presented along with a case study of the Western Ghat Forestry and Environment project.

Monitoring carbon flows in forestry sector projects is different due to a long gestation period and location- or site-specific variations in various parameters, particularly rates of C sequestration and emission. Parameters to be monitored include C sequestration in vegetation and soil, rates of wood extraction, wood use related emission, litter production, decomposition from litter, and soil. Methods include field vegetation monitoring, soil study, household and industry surveys, and laboratory investigation. Investigations, analysis, and report writing should be carried out using local educational institutions, NGOs, and consultancy firms. Verification could be taken care of by external agencies. Case studies of the Western Ghat Forestry and Environment project showed that less than 10% of the project budget may be adequate for intensive monitoring of carbon flows. The parameters to be monitored and methods required for any forestry mitigation project is nearly identical to that of any typical forest conservation or reforestation project.

Key Words: monitoring forest projects, forestry mitigation, carbon flow, parameters, monitoring methods

1. Introduction

The forestry sector is being increasingly considered for abatement of GHGs (greenhouse gases). The forestry sector offers a wide range of options for mitigating climate change: forest carbon (C) sink conservation, sequestration and storage of C in degraded forest lands and products, and biofuels substituting for fossil fuels. The potential (excluding bioenergy options) has been conservatively estimated to be 60 to 87 Gt for the period 1995 to 2050. Further, the cost of mitigation in the forestry sector is estimated to be low (in the range of US$ 2 to 7/t C abated). Further, the direct and indirect socio-economic benefits could offset the mitigation costs (Brown *et al*, 1996). Even for a populous country such as India, forestry mitigation options (by using only a part of the potential land available) could offset nearly half of the fossil fuel emissions (Ravindranath and Somashekhar, 1995).

India has implemented the tropical world's largest reforestation program (including afforestation) with an annual reforestation rate of 1.25 to 2 Mha since 1980, when the social forestry program was launched. By 1995 over 20 Mha of tree plantations have been raised (Ravindranath and Hall, 1995). Compared to the magnitude of the reforestation program, the research and monitoring of the social forestry program is inadequate. Few large-scale national studies have been conducted on the reforestation program (exceptions are PC, 1987; Saubeer, 1992; and IIPO 1990).

A recent study reviewing the studies on biomass productivity of tree plantations in India concluded that significant scale and systematic field studies are nearly absent (Ravindranath and Hall, 1996). Many of the internationally funded projects are monitored by external agencies and are rarely published. Long-term monitoring of forestry programs is rarely undertaken. Significant funding is often allocated to research and monitoring of particularly externally funded projects. There is no published evidence of this allocated money being used for any serious monitoring since the funding as well as implementing agencies are reluctant to divulge the details. Absence of any published reports or studies is evidence enough to state that monitoring is inadequate. For example, in the large Westernghat project, compared to an allocation of US$ 11.7 million for the main reforestation component, the funding allocated for research and monitoring is US$ 3.7 million. When the three large studies (PC, 1987; IIPO, 1990; and Seebauer, 1992) are considered, all of them refer to a single period and are largely based on single field visits and household questionnaire surveys. Systematic periodic monitoring of survival and growth rates of biomass have not been recorded or published for most projects. Only Seebuer (1992) has made some preliminary estimates of standing tree volumes and growth rates based on field measurements using some crude methods. Detailed studies along the following lines are required for any typical forestry project, but are not carried out:

- periodic monitoring of regeneration and survival rates,
- changes in biodiversity,
- growth rates of woody biomass and extraction,
- changes in carbon density in soil and vegetation (as t/ha),
- production and extraction of non-timber forest products,
- changes in soil carbon or organic matter content
- impact of the forestry project on the status of natural forests or vegetation, including the biomass or carbon density in the project area, and
- cost-benefit analysis.

Monitoring any carbon abatement project would also require nearly identical investigations. In India there has been no discussion on the need for or mode of monitoring forestry sector mitigation projects since no forestry mitigation projects have been planned or implemented. However, such a discussion is necessary even for the conventional forestry projects.

Many forestry projects for reducing atmospheric carbon are likely to be funded and implemented in the near future. Forestry projects have some uncertainties regarding land availability, sustainability of C abated in some of the options (such as C sequestered in soils and vegetation), and measurement and verification of C abated. The C conserved or sequestered in vegetation or soil is subjected to various natural and anthropogenic processes affecting the C stock or flows. The methods for monitoring are well known but the institutional arrangements for monitoring the C stock and fluxes are uncertain. In this paper an attempt is made to assess the methods and institutional arrangements required for monitoring C stock and flows in forestry projects. The specific issues considered in this paper are

(i) the features of the forestry projects
(ii) the parameters for monitoring C stock and flows,
(iii) methods for monitoring C stock and flows,
(iv) institutional arrangement and trained manpower requirement for monitoring C, and finally
(v) a case study of the Western Ghats Forestry and Environment project is considered to assess and suggest the institutional arrangement.

2. Features of forestry projects for monitoring C abatement

In the fossil fuel sector, the C abatement achieved is usually measured as tons of coal or petroleum combustion avoided and MWh of fossil fuel electricity conserved. The C abatement achieved could be directly measured on a daily, monthly or yearly basis. In comparison, C abatement in forestry mitigation options is characterized by the following features.

2.1 LONG GESTATION PERIOD

Forestry projects have long gestation periods. For example, timber forest for producing sawnwood could take about 25 to 50 years. Energy plantations to produce woody biomass feedstock would take at least 5 to 7 years to start harvesting. Thus, it is necessary to monitor annually till the end of rotation to estimate C abated.

2.2 DYNAMIC C STOCK AND FLOW

In both short- and long-rotation forest plantations as well as regeneration programs, C sequestration occurs annually and often at non-linear rates. Further, a part of C sequestered annually could also be emitted back to the atmosphere due to decomposition of litter or *in situ* forest fires. Sequestration and decomposition rates are often determined by temperature, rainfall, soil qualitys and species composition. Thus, to obtain C stock and flow estimates it is necessary to make periodic measurements of sequestration and emissions.

2.3 EXTRACTION OF WOOD

There are several modes of wood extraction: (i) extraction of only dead and fallen wood (in protected area projects); (ii) planned extraction of a part of standing wood for energy in a sustainable way annually; (iii) clearfelling at the end of the rotation period for sawnwood and (iv) illegal or unplanned extraction of wood. This affects the C stocks in the forests at any given time. Thus, it is necessary to identify diverse modes of wood removal and measure the quantities extracted. The modes and rates of extraction may vary from year to year. Thus, continuous recordings of all extraction is necessary.

2.4 END USE OF HARVESTED WOOD

A forest plantation project may provide woody biomass for multiple-product end uses in developing countries: main trunk of large trees can be used as sawn timber, branches and twigs as fuelwood, and thin stems as poles. All these products could be obtained from the same forest plot in a given year. The implications for estimates of C abatement are different for different end uses; for example, (i) wood used as feedstock for energy will lead to substitution of fossil fuel electricity during the year of harvest and combustion in the gasifier reactor and (ii) wood used for making furniture will store C for 50 to 100 years. This necessitates recording of wood harvested for different end uses annually to estimate C emitted or avoided C emissions.

2.5 BOUNDARY FOR MONITORING C STOCK AND FLOWS

It is necessary to define the boundary for monitoring the parameters. A reforestation project aimed at producing plantation timber to substitute for natural timber requires monitoring of C stock and flows in both the plantation area as well as the primary forest conserved from felling. Similarly, conversion of forest land to protected area (such as a wildlife sanctuary) may shift extraction to some other forest area. Thus, C density and extraction will have to be monitored in the newly created protected area as well as other forest areas from where extraction of wood is taking place to offset loss from the protected area. Thus, the boundary for monitoring the C stock and flows will have to be carefully defined.

Not every forestry project would require monitoring of all the parameters. However, a state or a country may adopt multiple forestry options. Thus, there is a need to study the features and identify the parameters to be modified for each forestry mitigation option.

3. Parameters be monitored in forestry mitigation projects

In any forestry project there is a need to assess C stock and emissions or flows for the baseline scenario and the project scenario. The methods, labor requirements, and costs of monitoring will vary for different options. The three broad categories of forestry mitigation options (according to Brown *et al.* 1996) are

- C conservation management (slowing or halting deforestation)
- C storage management (reforestation)
- C substitution management (bioenergy substituting fossil fuel energy)

Basic parameters to be monitored in forestry mitigation projects are listed in Table 1. The key parameters to be monitored are; annual C sequestration in vegetation and soil, decomposition rates of litter and soil, extraction and end uses of wood and rates of emission associated with the specific end use. Monitoring of costs and benefits and even social aspects of flow of benefits are also necessary in many projects. These basic parameters need to be monitored generally for any forestry option. Some of the option-specific parameters are given in Table 2.

Sustainability of the C abatement achieved and any leakage (such as use of fossil fuels in reforestation and unplanned felling and burning of trees) need to be monitored in the mitigation projects.

Table 1. Basic parameters to be monitored in a typical forestry mitigation project

Parameters	Unit	Periodicity of measurement
Soil C at different depth	t C/ha	- Baseline Y_o - Once in 2 or 3 years - At the end of project
Litter / slash	t/ha	- Baseline - Y_o - once in 5 years
Standing tree biomass - above ground	t of wood/ha	- Baseline - Y_o - Mid rotation - End of rotation
Annual C uptake	t of wood/yr	- Annually or periodically
Extraction of wood	t of wood/ha	- Annually - End of rotation
End uses of wood	t of wood/ha	- Annually - End of rotation
Soil and litter decomposition rates	t/ha/yr	- Annually
Root Biomass (below ground) accumulation (rarely measured due to complexities in methods of estimation	t of root biomass density /hectare.	-Baseline -End of rotation

3.1 TYPES OF INVESTIGATIONS REQUIRED

Monitoring of forest parameters is likely to involve the following types of investigations.

- Field sampling of soil, forest plots, and households
- Laboratory analysis of soil and tree carbon
- Household survey
- Field measurement of trees (survival rate, growth rate — DBH and height)
- Measurement of extraction/harvest
- Survey of enduse of woody biomass
- Data analysis and report preparation

Monitoring of financial costs and benefit flows

Table 2. Examples of parameters specific to different forestry mitigation options in addition to standard parameters listed in Table 1

Parameters	Units	Periodicity
FOREST C SEQUESTRATION PROJECTS		
- Area reforested	ha	Annual
- Total area reforested	ha	End of project
- Wood removed (if any)	t/ha	Annual
- Enduse of wood		
- Combustion	t of wood/ha	Annual
- Short term use		Annual
- long term storage		Annual
FOREST C CONSERVATION MANAGEMENT PROJECTS		
- Area projected to be deforested	ha/yr	- Annual - End of project
- Area prevented from felling or deforestation	ha/yr	- Annual - End of project
- Area converted to protected area	ha/yr	- Annual - End of project
SUBSTITUTION MANAGEMENT PROJECTS		
- Area reforested	ha	Annual
- Wood harvested	t/ha	Annual
- End use of wood * electricity generation * storage in long-term products	t/ha	Annual
- Fossil fuel energy substituted	- kWh of electricity - t of petroleum oil	Annual
- Steel or cement substituted	t of steel or cement substituted	Annual

3.2 STANDARDIZATION OF INVESTIGATIONS, PARAMETERS AND METHODS

The methods for monitoring the parameters listed in Table 1 are standard forestry, ecological, socio-economic, and laboratory methods found in any text books. Some of the methods are listed in Appendix I. The parameters to be monitored and methods for monitoring the parameters in any typical mitigation project are not different from that of any forestry projects. There is no need to standardize the parameters or methods for monitoring mitigation projects as they are taught even at undergraduate level.

4. Institutional arrangements for monitoring forestry mitigation projects

Every GHG project must plan, *a priori,* the labor, training, instrumentation, and laboratory facilities required for monitoring the stock and flows of C in the project sites. Further, the C stock and flows monitored by an agency may have to be verified by an external agency for accuracy and reliability. The institutional arrangements required and costing would vary for different forestry options. Institutional arrangements required for some of the forestry options are broadly considered in this section. The type of investigation, investigators, and institutions required for some of the major forestry parameters are given in Table 3.

Personnel requirement. To carry out the investigations, trained personnel are required for field vegetation measurement, laboratory analysis, and household and industrial surveys. The level of training required is only at the level of field investigator and laboratory technicians. There is a need for technical experts to guide the monitoring program, to analyze the results, and to prepare periodic reports only at the project level. The field investigators and field technicians should normally come from local institutions and villages.

Institutional arrangements for monitoring forestry mitigation projects. It is possible to visualize a number of institutional arrangements for monitoring the C stock and flow parameters. As far as possible local educational and research institutions should be involved. For field studies (vegetation and household surveys) local NGOs and educated youth could be used. Some examples of institutional arrangements are listed here.

- Laboratory studies — a local college or research laboratory
- Field studies — project team with adequate training
- Village committee members
- Teachers and students of local educational institution
- NGOs
- Analysis and report preparation — project scientists from a national level research or educational institution
- Training — by project scientists and external experts

A local research institute or university could undertake the monitoring study with a few full-time field and laboratory technicians and using the laboratory facilities of a local research or educational (undergraduate college) institution. Alternatively, task could be entrusted to a professional consulting agency or an NGO.

Verification and evaluation of field studies. The methods adopted for field and laboratory investigations and analysis, the findings of the analysis, and the report prepared by the project team need to be verified by an external agency. The potential external agencies are

- consultancy firm
- national or international NGO
- university research center
- project evaluation team; consisting of experts from donor agency, project team, university, local NGO, and local educational institution.

Table 3. Institutional arrangements for monitoring different forest parameters

Parameters	Type of study	Manpower	Potential institution
Soil C studies	- Field soil sampling - Laboratory estimation	- Trained field worker - Laboratory technician	-Project team -Laboratory of local educational Institution
Vegetation C density	- Field sampling - Field measurement of trees	-Trained field investigators -Computer analysts	-Project team - Education institution
Forest Litter C	- Field measurement - Laboratory estimation	- Field investigator - Laboratory technician -Computer analyst	- Village committee - Project team - Education institution
Extraction / harvest	- Daily field observation / recording - Household, trader, industry survey	- Field investigators -Computer analyst	- Project team - Consultancy agencies - NGO
End uses of wood	- Field observation -Survey of households, traders, industry	- Field investigator - Analyst	- Project team - Consultancy agencies - NGO

The external verification agency or committee will have to assess the following

- methodology (including sampling technique and size)
- laboratory facility and analysis
- data analysis (including statistical analysis)
- capacity of field and laboratory investigators
- findings (C stock and flow)

5. Institutional arrangements for the western ghats forestry project

Western Ghat (mountain range) forests along the western coast of India are rich in biodiversity. The forests in the region, as in the rest of India, are subjected to anthropogenic pressures leading to deforestation and forest degradation. In response to forest degradation, a number of forest regeneration and reforestation programs have been launched in Uttara Kannada (UK), one of the prominent districts in the region. Since 1991 a large Western Ghats Forestry and Environment Project (WGFE) is being implemented in the UK district. The institutional arrangements required for monitoring the C stock and flows are considered by taking the WGFE project as a case study. This project is funded under the British ODA for a period of six years from 1991. The project is being currently implemented in the region.

Goals, target and achievement of the project. The broad goals of the project are

- to maintain the ecological balance and environmental stability of the Western Ghat (WG) region
- to rehabilitate and protect the major environmental resources represented by the WG
- to ensure the sustainability of the living standards of those people whose livelihood is currently derived from the forests
- to ensure the sustained yield of all categories of produce from the natural forests for the economic benefits
- assisting institutional development of the Forest Department.

The goals of the project are very broad in scope and are compatible with the national goals for the sector and seem to cover ecological and socio-economic goals also.

Activities. To achieve these broad goals of the project, the dominant activity to be undertaken is reforestation of degraded forest lands. The reforestation program involves enrichment planting of trees in the partially degraded forests and raising multipurpose tree plantations in fully degraded forest lands. The multipurpose plantations are largely aimed at meeting the local needs of biomass and in turn conserve primary forests. One of the key features of the project is the participatory approach to reforestation and forest management. In each location, a VFC (village forest committee) is formed and involved in reforestation, forest protection, and management.

The projected area to be reforested according to different forestry options and their features are given in Table 4. Total area to be reforested is 42,000 ha at a total budget of US$ 11.7 million over a period of six years starting from 1991. The multi-purpose plantation is the dominant forest option accounting for 44% of the total budget for reforestation. The area reforested during the period 1991 to 1996 is given in Table 5. The area reforested is nearly close to the targeted area. In the first five years, 37,175 ha was reforested, which accounts for 88% of the targeted area. The cost of reforestation is US$ 609/ha for the dominant multi-purpose forest plantation. The density of planted tree seedlings is not significantly different for different models and it is in the range of 1010 trees/ha in moderately degraded forest to 1342 trees/ha in fully degraded forest (multi-purpose plantation).

Table 4. Forestry options; projected area to be reforested and cost per hectare in the Western Ghat Forest and Environment Project in Uttara Kannada district, India

Forestry options	Area projected to be reforested in ha	Total projected cost US $ 000	Density of trees planted/ha*
Selective planting and retention	5 500	1 238	1 010
Enrichment planting	8 500	1 542	1 310
Reforestation of partially degraded forests	13 500	3 036	1 270
Multipurpose plantation (fuelwood, fodder, green manure, NTFP plantations)	8 500	5 180	1 342
Bamboo plantation	6 000	711	-
Total	42 000	11 707	-

Sources: Forest Department, Bangalore.
* Density of tree seedlings planted from preliminary field studies

Table 5. Budget for establishing plantations and management support, target area for reforestation and area actually planted under the Western Ghat Forest Environment Project in Uttara Kannada district

Year	Plantation development cost in $'000	Management support cost in $'000	Total cost $'000*	Target area (ha)	Actual area reforested (ha)
1991-92	1397	580	1977	7500	6250
1992-93	1294	349	1643	8000	5789
1993-94	1789	283	2072	8500	7722
1994-95	1990	222	2212	9000	8130
1995-96	2184	187	2371	9000	9234
Total	8654	1621	10 275	42 000	37 125

* Total cost excludes cost of training infrastructure development administrative support and research.
Source: Forest Department, Bangalore

Carbon abatement in the project. C abatement is not specifically listed in the broad goals of the project. However, C abatement is going to be achieved through; (i) biomass production for substituting wood currently extracted from natural forest, leading to forest C sink conservation, (ii) C sequestration in standing tree vegetation and soil in partially degraded reserve forest lands (where there is a ban on logging), and (iii) enhancing soil C density.

Research and monitoring of the project. There is a specific budget of US$ 3.7 million for research and monitoring in the areas of forest ecology, forest hydrology, monitoring of reforested area (survival and growth rates of species planted), and socio-economic studies. The monitoring of C stock and flows could become a part of ecological research (for soil C), monitoring of reforested areas (for C sequestration), and socio-economic studies (for extraction of wood and enduse). The WGFE project has involved a number of research institutions, Universities, and NGOs to conduct research studies.

Institutional and infrastructure requirement for monitoring of Western ghats project. An attempt is made to suggest an institutional arrangement for the WGFE project along with the budgetary allocation. There are five forest divisions each covering an area in the range of about 1400 to 2000 sq km. The projected area for reforestation is 42,000 ha. There are mainly four major forest types; wet evergreen, semi-evergreen, moist deciduous, and dry deciduous forests.

The major studies to be conducted include the following;

- periodic monitoring of regeneration and survival rates,
- changes in biodiversity,
- growth rates of woody biomass,
- production and extraction of timber and non-timber forest products,
- changes in soil carbon or organic matter content
- costs and benefits
- impact of the forestry project on the status of natural forest or vegetation, including the biomass or carbon density in the project area including conservation of forests or forest woody biomass through plantation biomass production.

The point to be noted is that such studies would be on the agenda of any forestry project such as the Western Ghats project or social forestry project or even projects aimed at forest conservation or forest regeneration and of course forestry mitigation projects.

The 42,000 ha of reforestation is going to be spread over a few hundred villages. For assessing institutional, labor, and budget requirements the whole district, where 42,000 ha are likely to be brought under reforestation, could be grouped into about 100 clusters of villages or VFCs. All the biological, ecological, and socio-economic parameters could be monitored for all the 100 clusters or for a sample of locations. A further grouping of these 100 clusters based on some criteria will enable sampling of the clusters leading to reduction in cost and human effort required, without losing the reliability or quality of monitoring. The institutional and infrastructure requirement is considered next for the Western Ghat forestry project.

- Forest Divisions; 5 (each with an area of 1400 to 2000 sq. kms)
- Project (or district) level coordination and overall management of monitoring program by a national level research or educational institution in the region or a national level professional NGO
- At project level one leader and three experts; one each for forest vegetation, forest soil and socio-economic studies to lead the respective studies

- Forest Division level coordination of monitoring; one local research or educational institution - 5 divisions and 5 institutions
- Clustering of VFCs in each Forest Division; Divide the total number of villages or VFCs in the division to say about 20 clusters.
- Each cluster to cover about 400 to 500 ha of newly reforested forests and about 7000 to 10,000 ha of primary forests
- Forest Division level investigators. At each division level three field investigators are required for studies on forest vegetation, forest soil and socio-economic aspects. These will work under the guidance of Project level experts.
- Field workers. For each of 20 clusters or groups of villages in each division, there could be two field level trained field workers, one each for vegetation and socio-economic studies. They will conduct the field measurements and surveys under the guidance of Forest Division level field investigators.

Institutions. In the Western Ghat region, there are a number of undergraduate institutions including a forestry college and a few research centers. It is feasible to select one research or educational institute for each of the five forest divisions to undertake the laboratory studies. All the field studies could be contracted out to an NGO or a consultancy firm or to a national level research institution working in the region. The identified institution will work with local village forest committees, Forest Department, and NGOs to identify a band of field investigators and field technicians, who should normally come from local areas.

Verification Agency. A verification agency or committee should normally come from outside the region. It should consist of experts from the funding agency (say, British ODA), national NGOs, university researchers, and local implementation agency (Forest Department). The committee must be lead by an external expert.

Man power requirement. Total manpower and level of effort required for monitoring the full project is as follows:

1. Project leader; 1 (full time)
2. Full-time project level experts; 3
3. Full-time field investigators at division level; 15
4. Part-time field level trained workers; 200 to work for about four to six months per year; in other words, 800 to 1200 labor months per year. Field workers need only to be literate (who have passed the school) and they have to come from the same location. They need to be trained by the project level experts in conducting vegetation and socio-economic studies as well as in taking soil samples.

Budget for monitoring. The labor costs at current rates prevalent in India are around US$ 700,000 for the five-year period. The laboratory expenditure could be around US$ 100,000 as no expensive equipment is required. Further, training, travel, and other infrastructure (such as computers and jeeps) could be around US$ 200,000. Thus the total budget for the research and monitoring is around US$ 1.0 million. Given the total reforestation budget for 42,000 ha is at US$ 11.7 million, the research and monitoring cost is around 8.5%, or less than 10% of the project budget. The current allocation for research and monitoring in areas of forest ecology, forest hydrology, monitoring reforested area (survival and growth rates), and socio-economic studies is US$ 3.7 million, which accounts for about one third of the budget allocated for reforestation. Thus the total budget required for monitoring the carbon stock and flow changes is unlikely to be more than 10% of the project budget.

The British ODA or the State Forest Department is not currently focusing on the soil or vegetation C analysis though it forms a part of the research agenda indirectly. It is possible to conclude that even for a forestry project which is not directly targeted as a climate mitigation project, monitoring of C stock and flows in vegetation and soil C will be useful. Any forestry project aimed at forest conservation or reforestation for biomass production will have implications for C stock and flows in the forest location.

Sustainability of benefits of the project. The project provides several ecological, global environmental, and socio-economic benefits. The question is how to ensure the sustainability of benefits beyond the life of the project and further, how to monitor the sustainability of benefits. Currently no separate arrangements have been made to ensure these benefits or their monitoring. However, the institutions developed during the period, particularly the community level institutions as well as in the Forest Department are likely to continue to sustain the benefits. Forest Department is bound to continue the reforestation and forest conservation measures as a part of their normal responsibilities under the national and state level regulations and programs.

6. Conclusion

The forestry sector mitigation projects are more complex than energy sector mitigation projects due to their long gestation period, non-linear rates of carbon accumulation in vegetation and soil, varying rates of extraction of different woody biomass products, emissions from forest soil, forest floor, forest fire, and various end uses from wood removed. The parameters to be monitored, features of parameters, the methods of monitoring, labor and budget requirements for monitoring were presented in the study along with a case study of Western Ghats Environment and Forestry project. The total budget required for research and monitoring may be around 10% of the total forestry project budget. The study also showed that the parameters to be monitored and the types of studies required for monitoring the carbon stock and flows in forestry mitigation projects are not much different from monitoring any other typical reforestation or forest conservation project. Local institutions (educational, research and NGO) should be involved in the monitoring work and further, as far as possible field technicians and investigators should come from the local region, even the specific village if possible. The parameters to be monitored and methods for monitoring any typical mitigation project (not different from other forestry projects) are well known and reported in text books of forest ecology, silviculture, forest economics, and sociology.

Appendix I. Methods for monitoring forestry parameters

Parameters	Method
Vegetation C density	- Sample quadrats - Measurement of DBH and height - Estimation of basal area - Biomass estimation methods
Soil C density	- Soil sampling - Soil; C estimation through acid digestion
Litter/slash C	- litter traps in forest - Periodic woody litter measurement
Annual or periodic C sequestration	- Sample quadrats - DBH and height measurement - Estimation of basal area periodically - Biomass estimation equation
Area data (forest, plantation, degraded land)	Measurement of area
Wood harvest and enduse	- Measurement of trees felled - volume or weight of wood extracted - Survey of households, traders, industry
Root Biomass Density (not measured normally due to complexities involved)	-Sample Quadrats -Digging, root extraction and estimation of weight of root biomass for a given volume of soil.

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A FRAMEWORK FOR MONITORING AND EVALUATING CARBON MITIGATION BY FARM FORESTRY PROJECTS: EXAMPLE OF A DEMONSTRATION PROJECT IN CHIAPAS, MEXICO

BEN H.J. DE JONG
El Colegio de la Frontera Sur, Carr. Panamericana-Periférico Sur s/n, San Cristóbal de las Casas, 29290 Chiapas, México

RICHARD TIPPER
Institute of Ecology and Resource Management, Darwin Building, Mayfield Road, University of Edinburgh, Edinburgh EH9 3JU, UK.

JOHN TAYLOR
Unión de Crédito "Pajal Ya Kac Tic" S.A. de C.V., Josef Ortiz de Dominguez 7, San Cristóbal de las Casas, 29200 Chiapas, México

Abstract. In Mexico an estimated 4.5×10^6 ha are available for farm forestry, while up to 6.1×10^6 ha could be saved from deforestation by making shifting agriculture more productive and sustainable. Various farm forestry systems are technically, socially, and economically viable, including live fences, coffee with shade trees, plantations, tree enrichment of fallows, and taungya, with a C-sequestration potential varying from 17.6 to 176.3 Mg C ha^{-1}. A self-reporting system with on-site spot checks is presented for the monitoring and evaluation (M&E), and will be tested in a farm forestry C-sequestration pilot project, to begin in Chiapas, Mexico, in 1997. The M&E procedure will facilitate the collection of field data at low cost, help ensure that the systems continue to address the needs of farmers, and give farmers an understanding of the value of the service that they are providing.

Keywords: Farm forestry, carbon sequestration, monitoring, evaluation

1. Introduction

Because of international concern about climate change due to anthropogenic greenhouse gas emissions, there has been considerable interest in the potential of increasing the storage of carbon in terrestrial vegetation through forest conservation, afforestation, farm forestry, and other methods of land management. Several studies have indicated that the global potential for enhancing carbon storage in forest and agricultural ecosystems may be considerable. (Dixon *et al.*, 1991; Dixon *et al.*, 1993; Schroeder *et al.*, 1993, Masera *et al.*, 1995; De Jong *et al.*, 1995). Where these systems replace low biomass cropping or pasture systems or provide economic alternatives to the conversion of tropical forests they reduce the net flux of CO_2 to the atmosphere by (1) accumulating carbon (C) in new trees on agricultural land, (2) protecting stocks of C in existing forest biomass, and (3) substituting energy intensive materials and GHG-emitting fuels.

Some preliminary estimates of the potential area available for carbon sequestration in Mexico are (Trexler and Haugen, 1995): 4.5×10^6 ha for farm forestry (with a C-sequestration potential of 33.3 to 113.4×10^6 Mg C), 1×10^6 ha for plantations (30.7 to 85.5×10^6 Mg C), and 30×10^6 ha for natural regeneration (1 to 3×10^9 Mg C). Furthermore, they consider that, by making established agriculture more productive and sustainable (e.g., by substituting slash-and-burn agriculture for sustainable permanent agriculture), forests that were once part of the slash-and-burn cycle can be allowed to recover, and agricultural expansion onto remaining forest areas can be curbed. They suggest that up to 6.1×10^6 ha (with a sequestration potential of 348.3 to 714.9×10^6 Mg C) could be saved from deforestation until 2040. These estimates for C-sequestration do not consider possible displacement of fossil fuel energy by biomass (Schlamadinger and Marland, 1995). However, if this potential is to be realized it will be necessary to devise practical schemes based upon appropriate economic mechanisms that will deliver GHG mitigation in objectively verifiable, sustainable, and socially and environmentally responsible ways.

Dixon *et al.* (1993) and Masera *et al.* (1995) consider agroforestry to be the most promising alternative for C-sequestration, in terms of biomass productivity and cost-efficiency. Initial studies by De Jong *et al.* (1995) indicated that in regions such as Chiapas, the most appropriate methods to enhance carbon storage on land managed in small holdings are the introduction of trees within agricultural systems as crop-tree combinations or the development of small- to medium-scale plantations. Such developments are referred to as "farm forestry" (Foley and Barnard, 1984). On communally held areas of natural forest or secondary vegetation, the main sequestration strategy should be to restore forest ecosystems and to conserve and manage the tree stock in initiatives referred to as "community forestry" (Foley and Barnard, 1984). In the feasibility study carried out by De Jong *et al.* (1995) in Chiapas, five farm forestry systems were considered to be technically, socially, and economically viable, including live fences, coffee with shade trees, strip plantations in abandoned pasture, tree enrichment of fallows, and taungya. The *ex-ante* estimated increase in carbon density of these systems in relation to the actual systems without the farm forestry project varied from 16.7 to 176.3 Mg C ha^{-1} (averaged over a 150-year rotation), with the lowest potential for living fences and the highest for the plantation systems (taungya and enriched fallow). The results of the study suggest that finance provided on the basis of C-sequestration, within the range of 5 to 15 US\$ Mg^{-1} C, can be used to initiate various farm forestry systems that will, in turn, provide a self-sustaining flow of outputs of commercial and subsistence products. This is the context of an international pilot project for carbon sequestration by forestry and agroforestry being developed in Chiapas. The objective is to develop a model for carbon sequestration that will be economically viable and technically reproducible in similar regions of Mexico and Latin America, where large areas of land are managed by small holder (*campesino*) farmers in both individual and communal units.

Farm forestry projects for GHG mitigation would be characterized by numerous participants, organized in various ways, but mainly individuals and small groups; generally varied, small-scaled systems, replicated over large areas; and site-specific management, with individual adaptations due to personal interest, local conditions, and previous experiences. It is argued that due to these specific characteristics the methods of sequestration assessment, monitoring, and evaluation proposed for large-scale forest preservation or plantation-type projects will require adaptation or modification if they are to be applied to farm forestry schemes. In this paper we detail the monitoring and evaluate farm forestry developments, taking into consideration the probable social, institutional, and technical constraints of such initiatives. The specific objectives of this paper are to clarify the main conceptual issues of assessment, monitoring, and evaluation as they will relate to farm forestry carbon sequestration projects; to describe the framework for monitoring and evaluation proposed for the pilot project, its purpose, and its social, institutional, and technical context; and to propose a set of criteria which monitoring and evaluation systems should fulfill in the context of farm forestry type projects.

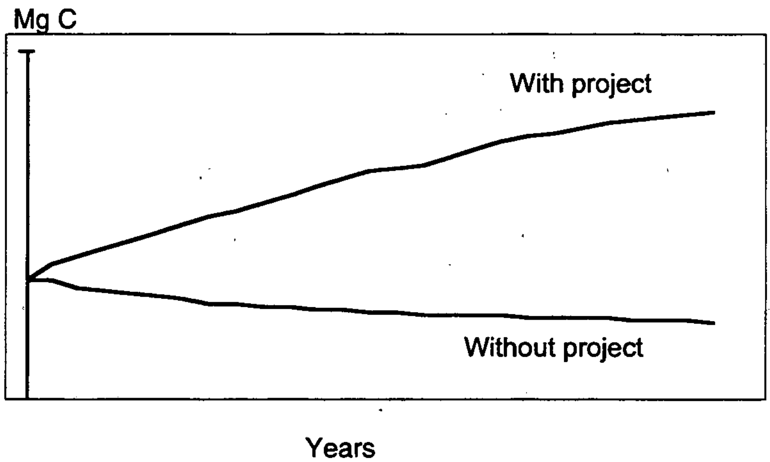

Figure 1. Hypothetical effect of a farm forestry project on C-mitigation, compared to a without-project baseline

2. Assessment, Monitoring and Evaluation of Forestry Projects

2.1 CARBON SEQUESTRATION ASSESSMENT

In this paper we refer to the Carbon Sequestration Assessment as the procedures used to define, at the institutional level (for purposes of project resource allocation and national emissions inventory) the sequestration impact of a given forestry project. As stated by Swisher (1992), "the relevant unit of measurement for carbon storage in forestry projects is the increment in CO_2 flux, expressed as tons of carbon equivalent (Mg C), out of the atmosphere, compared to existing conditions (in the case of carbon removal) or to a reference condition (in the case of prevention). The score-keeping procedure should explicitly account for the carbon storage of the land use without the project ."

Various methods and models are available to assist the assessment of sequestration projects. These vary in scope and complexity according to the scale and context at which they are designed to apply (Table 1). For example, the relationship between climate variables and major forest types and their respective biomass provided by Brown and Lugo (1982) is useful when considering the CO_2

fluxes associated with land-use changes at country or continental scales, but would not take account of variations in soil type, topography. and land-use practices that would be highly influential at scales of tens of km^2 or below.

The CO2FIX model by Nabuurs and Mohren (1993) and the model described by Schlamadinger and Marland (1995) provide an estimate of carbon uptake and storage at the level of a stand of trees. The model is driven by an equation describing the predicted growth (which can be derived locally from inventory data) and also accounts for the fractions of carbon stored in different components of biomass — soil, harvested products, litter, and leaves. However, these models do not account for shrub or herbaceous biomass C-fluxes, which are typical components of agroforestry systems.

Table 1. Methods used in the assessment of sequestration by forestry projects

Reference	Description of Method / Model	Comments
Brown and Lugo (1982)	Carbon densities of major forest and other vegetation types, related to climate variables	Applicable to large-scale changes in terrestrial vegetation. Does not take account of management options. Mainly applicable to national or regional level assessments rather than projects.
Brown, Gillespie and Lugo (1989); Gillespie *et al.* (1992)	Carbon densities of tropical forest types related to inventory data	Tree size and form are related to carbon content. Mainly applicable to national or regional level assessments rather than projects.
Fearnside and Malheiros-Guimaraes (1996)	Region-specific model to predict changes in C storage in Amazonia, based on land-use change modeling (using a Markov matrix of probabilities)	Similar models could be developed for other regions and would be useful for defining regional baseline scenarios.
WRI's LUCS model (Faeth *et al.*, 1994)	Estimates future carbon fluxes as a result of land-use change induced by socio-economic pressures.	Is specifically designed to provide assessment of project impact. However, consideration of additional socio-economic and environmental variables are required to provide realistic outcomes from scenario assessment.
CO2FIX by Nabuurs and Mohren (1993)	Derives carbon accumulation and storage by a tree plantation over the course of a number of rotations, based on an "expected growth" curve.	Model is adaptable to local variables, such as species and increment. Has to be adapted for agroforestry systems to include interactions between system components, and for management of mixed forests.
Schlamadinger and Marland (1996)	Similar to CO2FIX, but include the possibility of incorporating fuel and other product substitution.	Model is adaptable to local variables, but has to be adapted for agroforestry systems and for management of mixed forests. Soil carbon dynamics are poorly explained in the model.

With the exception of the WRI's LUCS model (Faeth *et al.*, 1994), the methods described in Table 1 are not designed to incorporate such project-specific variables as the projected uptake of forestry techniques by farmers or the effect of displacing the demand for food, timber, or other commodities. The LUCS model itself attempts to simulate the socio-economic pressure for land-use change between forest and agricultural land and associated carbon fluxes. The outputs of the LUCS model would require substantial modification in order to take into account local factors such as land tenure arrangements, government intervention in markets, socio-economic stratification, and cultural preferences. Therefore, while such methods are invaluable tools in the estimation of biomass changes in different scenarios, they do not provide comprehensive models for project level assessment of farm forestry projects.

The allocation of resources to a project are generally based upon *ex-ante* assessment. However, since only the *ex-post* case will be able to take account of actual project performance, drawing upon the results of monitoring and evaluation, it will be seen as more reliable and therefore used in preference to the original assessment, once projects are completed. Institutional arrangements to take account of the (inevitable) differences between successive assessments are likely to be required. Such differences may be significant in the case of farm forestry projects, whose characteristics and performance may vary considerably between locations and farmers.

2.2 Monitoring

Within the context of farm forestry programs the following definitions, adapted from Casley and Kumar (1987), for monitoring and evaluation are proposed:
Monitoring is a continuous assessment of the functioning of project activities, as compared with implementation schedules, the use of project inputs by the target populations, and the effects of the project as measured by physical, social, or biological indicators. The monitoring function is carried out by using the data within a management information system. Such a system includes the basic physical and financial records, the details of inputs and services provided to beneficiaries, and the data obtained from surveys and other recording mechanisms designed specifically to service the monitoring function. The objectives of monitoring are to inform interested parties about the performance of the project, to adjust project development, to identify measures that can improve project quality, to make the project more cost-effective, to improve planning and measuring processes (including C-Sequestration modeling), and to be part of a learning process for all actors.

It is suggested that, in the case of forestry carbon sequestration projects, monitoring systems will be required to operate at two main levels. First, to track the stock of tree biomass through periodic inventories or surveys, and second to track the development of social, economic, and institutional structures (e.g., local trust funds, forest management plans, wood-processing facilities, and training programs) that will influence the long-term viability of carbon uptake and storage.

2.3 EVALUATION

Evaluation is a periodic assessment of the relevance, performance, efficiency, and impact of the project in the context of its stated objectives. It usually involves comparisons requiring information from outside the project in time, area, or population. Evaluation will also draw on the management information system but, in selective cases, this will be supplemented with data from impact studies that may be designed and executed outside the project management system itself. Evaluation organizes and appraises the information collected by the monitoring procedures, compares this information with information collected in other ways, and presents the resulting analysis of the overall performance of a project at a time and place that is useful to funding agencies, shareholders, the public, and other stakeholders, so that they can make decisions about: (1) whether to continue the project, (2) to compare the performance of different projects, (3) to make changes in the project design, and (4) to make major changes in the projects' management.

In the case of carbon sequestration forestry projects, periodic evaluation will cover both the current performance of the project and the long-term prospects for storage and uptake of carbon. Periodic project evaluations will be used to determine the official level of sequestration that should be assigned to the project.

3 . Monitoring and Evaluation in the Scolel Té Pilot Project

Dixon *et al.* (1993) suggest five potential monitoring mechanisms: (1) self-reporting, with public access to findings; (2) consensus reporting by GHG producer, regulatory bodies, and/or third party; (3) self-reporting, combined with on-site spot-checks; (4) satellite monitoring; and (5) private third-party reporting. In the following sections we describe our approach to monitoring and evaluation that will be tested in a farm forestry C-sequestration pilot project, Scolel Té Pilot Project, to begin in Chiapas, Mexico, in 1997, which resembles the self-reporting mechanism, combined with on-site spot checks.

The project aims to develop a prototype scheme for sequestering CO_2 in sustainable forest and agricultural systems by providing the institutional structures and organizational methods to ensure that carbon is reliably sequestered for the long term in systems that are economically viable and socially and environmentally responsible. The model should be applicable on a larger scale in similar regions of Mexico and Latin America.

A local trust fund provides Mexican farmers with up to 25 years' financial and technical assistance to implement farm- or community-scale forestry and agroforestry developments on the basis of the carbon that will be sequestered. Companies or institutions wishing to offset greenhouse gas emissions can purchase "proto-carbon credits" from the local trust fund. The project is managed in the field by a local farmers organization (*Unión de Crédito Pajal*), with technical and scientific support from national and international scientific institutions (*El Colegio de la Frontera Sur* and University of Edinburgh). The project is supervised by the Mexican Government's National Institute of Ecology and is registered with both the Mexican and U.S. initiatives for "joint implementation".

3.1 PROJECT MANAGEMENT

At the heart of the project's management system is a "farmer-led" planning process known as the "Plan Vivo." Local promoters help farmers draw up "working plans" for forestry or agroforestry systems that reflect their own needs, priorities, and capabilities (Figure 2). The working plans are presented to the Trust Fund and form the basis of discussion between farmers and the Trust, regarding the technical feasibility, the social and environmental impact and the carbon sequestration potential of each plan (Table 2). Once plans are judged to be viable, they are then registered with the Trust and become eligible for assistance. The level of financial support to farmers will be related to the expected carbon sequestration.

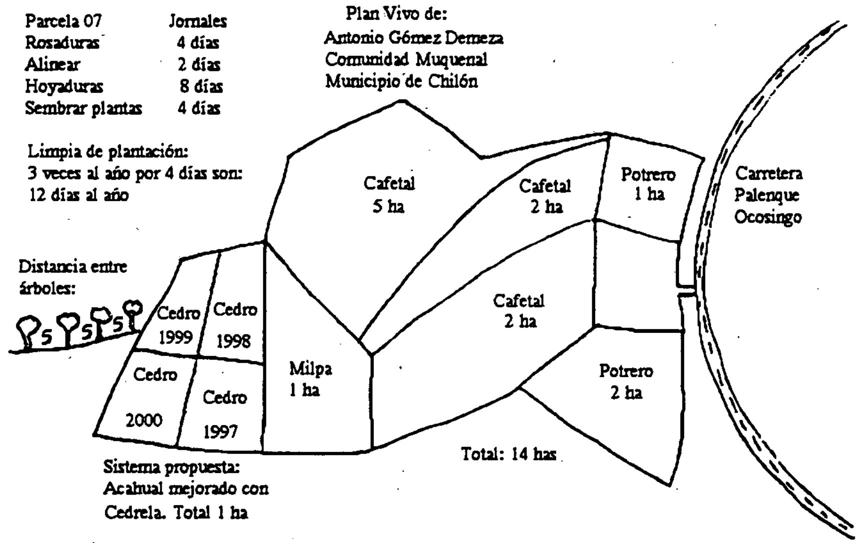

Figure 2. Example of a "Plan Vivo" map

The farmers are responsible for reporting on the progress of their plan and these progress reports are periodically checked by technical staff from the local farmers' organization. At appropriate intervals the data gathered by these monitoring procedures are reviewed by an internal evaluation team to determine whether the project is "on track" in terms of carbon accumulation, whether the potential for future uptake or storage is satisfactory, and whether corrective actions need to be initiated.

Once these internal procedures for planning, monitoring, and evaluation are established, external evaluation and verification of these procedures can commence. At present, the main institution providing external evaluation is *El Colegio de la Frontera Sur* (ECOSUR). In due course it is hoped that ECOSUR and other Mexican institutions will develop a national verification and certification system in concert with the National Institute of Ecology, the official regulatory body. Box 1 describes in more detail the responsibilities of each group involved in the project, and Box 2 describes in more detail the factors monitored at each stage in the project cycle.

Table 2. Carbon mitigation categories (Mg C ha^{-1}) for three intervention intensities and two ecoregions.

Intervention	Sub-humid sub-tropical	Humid tropical
low intensity agroforestry (e.g., living fences)	< 40	< 60
low intensity forestry (e.g., forest reserves)	40 - 60	60 - 100
medium intensity agroforestry (e.g., strip planting in fallow)		
medium intensity forestry (natural forest management)	60 - 80	100 - 140
high intensity agroforestry (e.g., fallow enrichment)		
high intensity forestry (e.g., plantations)	> 80	> 140
high intensity agroforestry (e.g., taungya)		

Box 1. Responsibilities of Main Groups Involved in Monitoring and Evaluation

The Farmers will be responsible for (1) preparation of system proposals to be considered, (2) implementation of the systems, (3) maintenance of the systems, (4) system performance reporting, and (5) farmer-to-farmer training.

The Technical Team (professionals and local promoters) will be responsible for (1) assessing the viability of proposed systems (in coordination with the farmers and research team), (2) training of farmers in planning, implementation, and performance recording, (3) estimating C-fluxes of proposed systems, and (4) assessing project impacts. The training of the farmers should generate farmers' abilities to identify and evaluate their agricultural technologies, to identify specific practices that can be improved, to enhance their knowledge, skills, and appreciation of farm forestry, to design alternative land-use systems, and to keep records of their productive activities, including inputs and outputs. The estimation of C-fluxes of the proposed systems will be based on tree density and spatial arrangements, site conditions, silvicultural treatments, harvesting intensity and periodicity, the management of additional system components, and the previous history of land use.

The Research Team (researchers of ECOSUR, a regional research institute, and the University of Edinburgh, U.K.) will (1) develop C-flux models for each system category and ecological region, (2) train technical team in system appraisal and C-flux calculations, (3) train technical team in project impact assessment, (4) evaluate and refine project planning and implementation assessment procedures, and (5) assess methods for delivery of the sequestration service to potential purchasers.

The Technical and Research Team will verify the quality of the information provided by the farmers through random checks and will evaluate the proposals on their ability to meet sectorial needs where communal resources are used or where member groups are formed around shared ecological zones such as watersheds.

Box 2. Factors Monitored and Evaluated at Each Stage in the Project Cycle

STAGE 1. PROMOTION AND TRAINING

The purpose and processes of the project are explained to farmers at meetings. The variety of potential farm forestry systems appropriate for given areas are discussed and the requirements for entry into the scheme are set out. Local promoters are selected and given training in the farm forestry planning procedures.

Stage 1. Monitoring &Evaluation (M&E): Progress in promotion and training and qualitative feedback from farmers and promoters are recorded. Expected uptake by farmers can be estimated and initial insight into the socio-economic constraints on the project can be obtained. Further training requirements can be determined.

STAGE 2. PLANNING AND PROCESSING OF APPLICATIONS TO THE SCHEME

Local promoters will assist individual farmers or small groups to plan appropriate forestry systems. Working plans including sketch maps, descriptions of current vegetation and land uses, and descriptions of the forestry system to be established. Defined milestones and lists of inputs are drawn up and submitted to the local project management team for assessment. The local management team assesses working plans for completeness and technical feasibility, according to documented criteria. Plans that are acceptable are then categorized into probable ranges for C-sequestration, according to criteria provided by the research team. The C-mitigation potential for various representative farm forestry systems applicable to the pilot project area in Chiapas has already been estimated *ex-ante*, using the CO2FIX model (Nabuurs and Mohren, 1993), calibrated with local tree growth data and adapted to the proposed systems (De Jong *et al.*, 1996). Proposals can be either promoting C sinks or avoiding C sources (e.g., sustainable permanent agriculture as an alternative for slash-and-burn agriculture (Figure 3). The system proposals will be grouped in potential C-mitigation categories for each ecological zone (Table 2). When plans are rejected, farmers will be provided with explanations for the decision, so they will be able to adjust and re-submit the plans. Farmers whose plans are accepted are notified and offered places on the scheme. Details of the financial and technical support available are provided. Agreements are signed with farmers entering the scheme.

Stage 2 M&E: Documented working plans will be used to make estimates of expected sequestration impact. Areas to be planted, planting arrangements, species to be used, and existing vegetation types provide inputs to a C-flux model, which provides an sequestration estimate over time for each area approved.

STAGE 3. ESTABLISHMENT OF SYSTEMS

Farmers will be provided with financial assistance and technical advice through local promoters, local farmers organizations/credit agencies and by qualified foresters. Farmers will be responsible for reporting on the progress of establishment and on problems, as they occur. Payment of annuities shall be contingent upon the farmer providing adequate records of progress.

Stage 3. M&E: Simple records of establishment will provide the necessary information to begin comparing the actual uptake of CO_2 with expected performance. Farmers will be primarily responsible for collecting data. However, the technical team will conduct internal verification of data collection from a random sample of participants. This process will continue in successive stages, to provide longitudinal comparisons. Problems such as pest attack will be reflected in revised sequestration estimates, and this information will also be used to initiate corrective action.

STAGE 4. MAINTENANCE, EXPANSION AND UPGRADING OF SYSTEMS

Farmers on the scheme continue to maintain their farm forestry plots and may expand or upgrade by modifying their working plans, in consultation with the technical team. This flexibility will allow farmers to gradually increase the area of tree cover on their farms while working within the constraints of the supply of labor and materials available.

Stage 4. M&E: Monitoring continues as in Stage 3. Estimates of biomass will be derived from measurements of tree height, diameter, and absolute numbers of trees. Comparative storage of C in soils under farm forestry and conventional farming will be monitored on a stratified sample of plots.

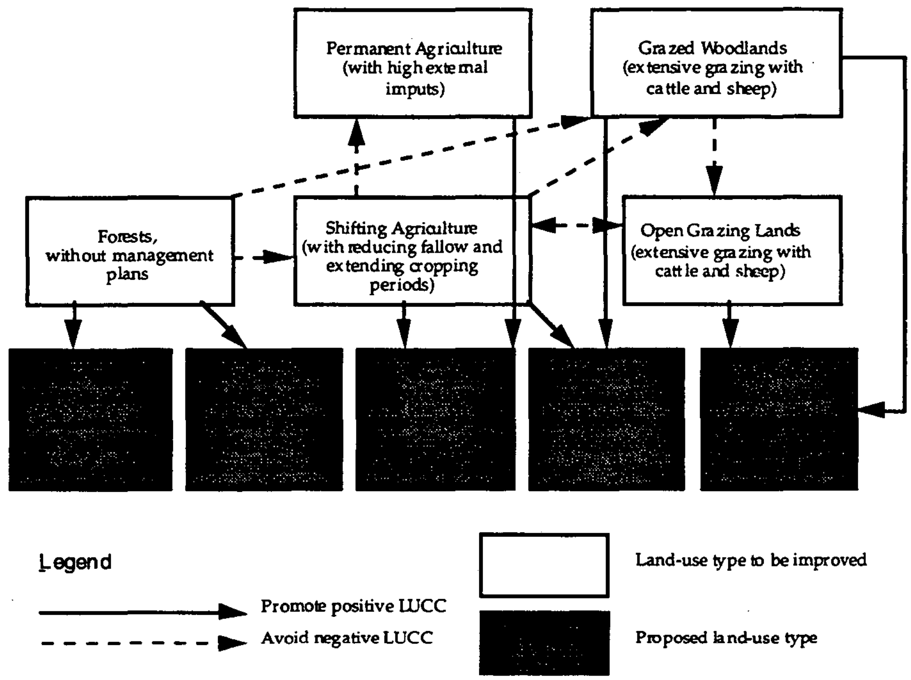

Figure 3. Current and porposed land-use change strategies, based on De Jong and Montoya (1994)

4. Concluding Comments

In general terms, the system proposed for assessing the carbon sequestration effect of the Chiapas Pilot Project can be described as based upon internal monitoring and evaluation with external verification or audit, as advocated by Mitchell and Chayes (1995) in the context of national GHG inventories.

It should be emphasized that while projects are, by definition, time-limited interventions, they purport to initiate processes that will continue long into the future. Claims for C-sequestration by forestry must, therefore, include plausible arguments indicating the sustainability of the new land-use systems developed. Principles, criteria, and indicators for sustainability of forestry systems have been developed by several international agencies, including UNCED (Heissenbuttel *et al.*, 1992) and the Forest Stewardship Council (FSC, 1996). Table 3 lists some possible criteria and verifiable indicators that could be used to assess the sustainability of farm forestry systems initiated by a C-sequestration project.

With this in mind, and based on our limited experience to date, we suggest that efficient and effective systems of monitoring and evaluation for farm forestry carbon sequestration projects should fulfill the following criteria.

Table 3. Sustainability criteria and indicators to be used in the farm forestry C-sequestration pilot project.

Criteria For Sustainability	Objectively Verifiable Indicators
1. Farm forestry is established on land where ownership and usufruct rights are clearly established	1.1 Areas included within the scheme are marked clearly on maps.
	1.2 Forestry plans are approved by owners and appropriate official tenurial documentation is available.
2. Farm forestry systems suit local needs	2.1 The scheme is voluntary.
	2.2 The planning process is based upon local people's management objectives: - the methods used to ensure local input into design of forestry are described and records are kept documenting the process.
3. Farm forestry design and implementation is sensitive to gender differentiation	3.1 Women participate in the design of farm forestry systems: - the methods used to ensure adequate consultation are documented and progress is recorded.
	3.2 The impact of forestry system on women is assessed: - details of the method of assessment are documented.
4. The farm forestry system is economically viable once support from the project is withdrawn	4.1 Economic productivity compares favorably with other economic land uses: - income per ha and per work-day should be greater than for local maize-bean system. The method used to compare farm forestry with other economic activities is documented.
5. Farm forestry systems will not disrupt important ecological processes	5.1 Soil structure and organic matter content should be maintained at acceptable levels, or improved: - to be monitored by farmers
	5.2 Biological diversity at farm, village or municipal levels should not be significantly reduced.
	5.3 Intra-species genetic diversity of trees used for forestry will be maintained: - the use of native species will be encouraged; seed stocks of native species will be conserved; conservation measures will be documented.
	5.4 Watercourses should not be polluted or damaged and watershed integrity should be maintained.
	6.1 Farmers participating in the scheme will receive adequate training in farm forestry management: - details of training courses and implementation of training are documented.
6. Skills and expertise required to manage farm forestry will be available locally after termination of the project	6.2 Affordable specialist forestry expertise is available to farmers beyond the course of the project.

4.1 INTEGRATED

Monitoring and evaluation of carbon storage parameters should be fully integrated with other aspects of project M&E, including financial accounting, input delivery, and institutional development milestones. It should be recognized that the long-term viability of the storage and uptake of carbon in the project area will be affected as much, if not more, by the future capacity of local institutions to promote and support economically viable tree-based production systems than by current increments in biomass. Furthermore, the integration of biometric monitoring with other aspects of project management will both reduce costs and enhance the potential for corrective action in response to problems. Thus, in the Pilot Project the monitoring of tree-stand development will be undertaken primarily to ensure that corrective measures such as pest control, beating up (re-planting), thinning, and in certain cases pruning, are carried out promptly and effectively. Biomass estimates should be obtainable from the standard mensuration data with minimal additional effort or expense.

4.2 PARTICIPATORY

Given the small scale, high diversity, and dispersion of forestry plots in farm forestry projects, farmers themselves must be the prime source of data on growth and development of stands (measurement of stand data by technical staff would be too expensive). For this to occur successfully, substantial effort must be made both to train farmers how make the required measurements and to engender positive relationships between technical staff and farmers, so as to encourage accurate record keeping. As with all well-managed projects, the aim of monitoring should be to identify and address problems before they become serious; and this applies to organization and social aspects as well as technical considerations. In the case of the Pilot Project, community representatives help to liaise between technical staff and farmers. These representatives also participate on the board of the Trust Fund responsible for funding the local sequestration program. They are therefore well placed to view the system from the perspective of the offset purchaser as well as from that of the service providers (farmers).

4.3 SIMPLE

Both the methods of data collection and recording procedures should be as simple as possible. Farmers should understand the methods they are using to collect data, and they should also understand how these data will be used. Monitoring systems have a tendency to be "greedy" for data. However, it is important to critically review the requirements of monitoring so that redundancy and irrelevancy are avoided. For example, in small-scale projects it may not be necessary to evaluate the effect of activities on biodiversity. In the Pilot Project, the Plan Vivo format is designed to be simple and relevant to farmers' objectives for production improvement: most of the information required to monitor the progress of plots can be easily recorded on successive translucent paper overlays.

4.4 REFLECTIVE

As with other areas of the management system, the procedures for monitoring and evaluation should be constantly subject to improvement and refinement. The key to improvement is to reflect upon the main sources of error within the system. In the case of estimates of the carbon density of different land uses in various ecological conditions used by the Pilot Project; these are currently based partly on direct biomass measurements supplemented by the best available data in the literature. However, the C-flux models will be adjusted periodically, as new data are gathered, showing C-densities of the pools that are likely to change rapidly and substantially, such as phytomass, necromass, and soil carbon. Figure 4 illustrates the information flow between monitoring and evaluation results for the C-flux estimation. Another area likely to require on-going improvement is the compliance of farmers with monitoring schedules. This will be subject to gradual improvement through modification of the Plan Vivo methodology, training of farmers, and linkage of incentive payments to fulfillment of reporting requirements.

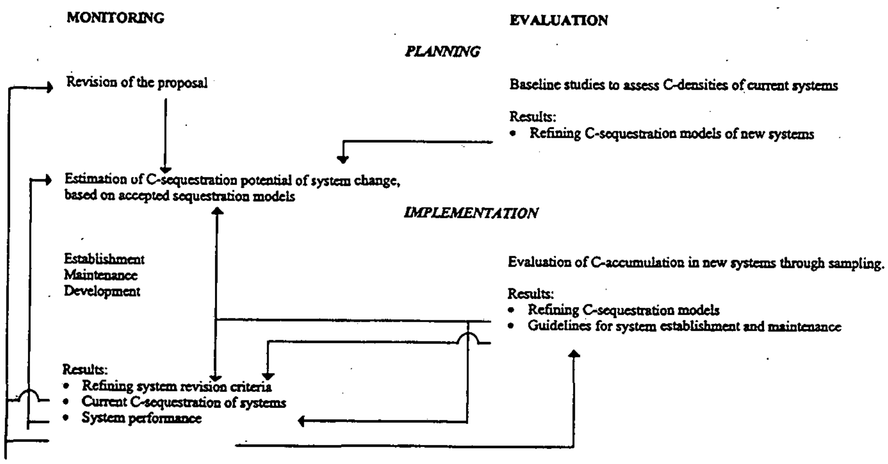

Figure 4. Information flows between monitoring and evaluation results for carbon sequestration estimation.

Acknowledgments

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ESTIMATING THE CARBON CONTENT OF RUSSIAN FORESTS; A COMPARISON OF PHYTOMASS/VOLUME AND ALLOMETRIC PROJECTIONS

STEVEN P. HAMBURG
Center for Environmental Studies, Brown University, Box 194
Providence, RI, 02912, USA

DMITRI G. ZAMOLODCHIKOV, GEORGE N. KOROVIN,
VIKTOR V. NEFEDJEV
Center for the Problems of Ecology and Forest Productivity
Russian Academy of Sciences, Novocheriomuskinskaia str. 69
Moscow, 117418, Russia

ANATOLY I. UTKIN, JAKOV I. GULBE, TATJANA A. GULBE
Institute of Forestry Science, Russian Academy of Sciences, Uspenskoe
Moscow Region, 143030, Russia

Abstract. As increased attention is being paid to the role Russian forests play in the global carbon budget, the desirability of being able to accurately and easily estimate the carbon content of the Russian forests is clear. In Russia timber volume has been estimated regularly and systematically as part of the former Soviet Union's forest inventory system. To determine the accuracy of using a volumetric approach to determining forest carbon pools, we developed allometric equations for the dominant trees (5 taxa) of two regions (Vologda and Volgograd) of Russia. Using these allometric equations and the phytomass/volume ratios previously developed to exploit the volume inventory data, we compared the forest carbon content of 51 forest stands of varying ages, composition and structure estimated using the two approaches.

Carbon estimates for the Vologda region were on average 8% (±4% 95% CI) greater using the volume approach than the allometric approach, and 4% greater (± 4%) in the Volgograd region. The greatest difference was for pine dominated stands (-15%) and the least for birch dominated stands (+1%). We also compared the carbon estimated for the 26 Vologda stands utilizing allometric equations developed for the same genera growing in similar forest types in North America. The North American allometric equations predicted slightly higher carbon content on average as compared to the Russian derived equations (2% ± 4).

The data presented suggest that using volumetrically derived carbon estimates provide reasonably accurate estimates of forest carbon.

Key Words: Betula, carbon content, boreal forest, forest biomass, phytomass/volume ratios, Picea, Populus, Russia, timber volume

1. Introduction

Growing evidence of global climate change (Houghton *et al.*, 1996) has increased efforts to utilize forest management as a mechanism for sequestering carbon. Our ability to utilize forestry as a mitigation measure for increasing anthropogenic emissions of carbon dioxide is largely dependent on our ability to accurately predict changes in carbon storage (Brown *et al.*, 1996). The carbon accounting necessary for determining the impacts of any single management decision on carbon storage can be involved and complex. Yet if forestry is to become a viable mitigation option it is essential we identify simple and accurate techniques for assessing carbon changes in terrestrial ecosystems.

Though foresters have been making estimates of forest productivity for well over a century, those estimates have been largely in terms of timber volume (UN/FAO, 1995). Projects that increase merchantable timber and the economic value of a forest do not necessarily increase the carbon content of the forest. In order to utilize the vast knowledge available on the impacts of forest practices on timber volume to determine changes in carbon content of these same forests, we need to be able to easily convert from well established timber volume parameters to ecosystem carbon. (Schroeder *et al.*, 1997).

On a regional basis the conversion of timber volume to carbon is different than on a specific project basis. In regional estimates we are trying to determine standing stocks over large areas, thus we are utilizing carbon values of average stand characteristics for large regions. In individual offset projects increased carbon sequestration is claimed as a result of a management policy change. If these project-specific estimates are biased, or skewed, they may not result in additional sequestered carbon. In order to ensure that project-based carbon benefits are realized, it is essential that the methodological limitations to measuring carbon in forestry projects is well understood.

If volume-based approaches provide reliable estimates of carbon changes it would enhance the usefulness of forestry-based carbon off-set projects. Since the accuracy of allometric approaches is well established (Siccama *et al.*, 1994) a comparison of volumetric- and allometric-based approaches is the most direct way to determine the suitability of volumetric approaches. The relationship of carbon content to volume of an individual tree is often non-linear, thus, it is not intuitively obvious whether volume estimates of stand carbon will be consistent or accurate across forest stands. By contrast allometrically derived carbon estimates incorporate genotypically determined relationships between tree diameter (diameter at breast height- dbh) and tree height, and tree weight and carbon content. By using stand inventory data, dbh and height, and allometric equations for the species of interest, it is possible to accurately determine tree biomass. Such an approach however requires a level of information that will not be readily available to all carbon off-set projects. Regrettably, regional compilations of allometric weight equations for forest tree species (see Tritton and Hornbeck, 1982) are not universally available.

We compared the volume and allometrically derived carbon estimates of 51 Russian forests with a wide range of ages. The sites were from the Vologda region, an area of boreal forest and the Volgograd region, representing the transition between temperate forests and steppe grasslands. Russia provides an ideal setting for comparing these two approaches since large data sets, collected from across the country, include tree volume, tree weights, and stand characteristics. A system of phytomass/volume ratios was developed to convert timber volume to stand carbon (Isaev *et al.*, 1993 and 1995). These tables represent a very efficient means of estimating carbon changes in forest biomass resulting from forestry off-set projects if they can be shown to provide a good estimate of forest carbon. The study described below evaluates the differences in estimates of forest carbon derived from allometric and volume approaches.

To reduce the costs of carrying out forest mitigation projects there will be an incentive to use existing allometric equations developed outside the project region to estimate forest carbon. The applicability of using generalized allometric equations was evaluated by comparing estimates generated utilizing North American allometric equations with the locally derived Russian equations developed in this study.

2. Methods

The Vologda region (58-61°N, 35-47°E) is characterized by little topographic relief (<5°), a mixture of moderately and poorly drained podzols (spodosols), and boreal vegetation dominated by *Picea abies, Pinus slyvestris, Betula sp.,* and *Populus tremula* L. The forests of the Volgograd region (50°N) by contrast are dominated by plantations of *Pinus sylvestris.* Representative stand data were selected from information in the Russian National Forest Inventory for forests with species compositions representative of the dominant vegetation of the two regions of interest. Fifty-one stands with a wide range of ages were selected (20 - 155 years). The Vologda plot data were collected in 1988, and the Volgagrad data in 1995.

Construction of the allometric equations utilized data from individual trees and shrubs (dry weights and heights) collected from 1970 to 1995 in the Vologda, Novgorod, Yaroslavl, Tver, Vladimir and Komi regions (55-62°N, 33-50°E). Construction of the allometric equations for *Pinus sylvestris* L. (south) utilized data from the Samara and Uljanovsk regions (53°N, 48-50°E) (Vompersky, 1982; Vompersky, Utkin, 1986, 1988; Smirnov, 1971; Dylis, Nosova, 1977).

2.1 DEVELOPMENT OF ALLOMETRIC EQUATIONS

One thousand individual trees of the five dominant species found in the Vologda and Volgograd (*Pinus* south) regions were destructively sampled. These trees were selected after all trees within a plot were inventoried and divided into diameter classes. They were selected proportionally to the size classes found in the forest plots. The size class distributions among the samples tress were: 0-5 cm dbh - 20%; 5-10 cm dbh - 25%; 10-15 cm dbh - 20%; 15-20 cm dbh 15%; 20-25 cm dbh - 10%; >25 cm dbh - 15%. An additional 350 trees and shrubs with a height of less than 12 m were also sampled. All trees were cut in late summer, prior to leaf fall. Trees were divided into four parts for development of the allometric equations; stem, branches, leaves, and roots.

The bole of each tree was cut into 1 m lengths (2 m for oldest trees) which were weighed in the field and a disk cut and dried (105°C) for wet/dry weight conversion. Branches from each 1 m section of stem were bundled and weighed in the field. A representative subsample was returned to the laboratory where leaves were separated from the branches and dried. Wet/dried weight conversions were applied to the field weight. Roots were sampled two ways; using small amounts of explosives placed under a stump and manual excavation. With both approaches the roots were subsampled, washed, and dried. Blasting resulted in 80% of the root mass in comparison to manual extraction. A belowground/aboveground biomass ratio of 0.21 was used to estimate the root biomass of Volgograd *Pinus sylvestris* stands, as no root weights were collected in that region.

Allometric equations were developed for the trees of interest using two equations:

$$W = aD^2H^b$$

$$W = aD^bH^c$$

where; W is kg dry weight (105°C) of the whole tree, or component of the tree (stem, branches, foliage, crown (branches + foliage), aboveground total, roots, total); D is dbh in cm; H is height in m; and a,b,c, are coefficients. For shrubs and small tress (< 12 m in height) a simpler equation was used;

$$W = aH^b$$

where W is the dry weight of the aboveground total and foliage.

On each plot the heights of 10-12 trees were measured and allometric equations relating tree height to dbh developed. These plot specific height predictions were used to estimate the height of each tree, which in turn was used as one of the independent variables for the determination of biomass.

Regression analysis was conducted using the nonlinear approximation procedure (SYSTAT).

2.2 CALCULATION OF CARBON CONTENTS

The carbon content of allometrically derived living biomass was assumed to be 50% for woody fractions and 45% for foliage (Isaev *et al.*, 1993 and 1995). Dead tree biomass was assumed to be 70% of that predicted using the appropriate allometric equation, with 53% of that mass carbon. For shrubs and small tress belowground biomass was assumed to be 30% of aboveground woody phytomass (total aboveground biomass minus leaves) for *Picea* and *Juniperus* and 20% of all other taxa. No consideration was given to non-woody species.

Volume-based estimates of carbon content of forest stands involved the application of zonal and regional species phytomass/volume ratios (Isaev *et al.*, 1993 and 1995), evaluated using the forest phytomass and productivity database available in Russia (Utkin *et al.*, 1994). These ratios are constructed by calculating the weight of representative stands and then taking the average phytomass/volume ratio by stand age and dominant species. These ratios require knowledge of stand age ± 5 y and the dominant tree species. From a look-up table one identifies the appropriate phytomass/volume coefficient and multiplies it by the established stand volume. These phytomass/volume ratios utilize the same carbon/dry weight percentages as was used in the allometric calculations.

2.3 COMPARISON OF NORTH AMERICAN AND RUSSIAN ALLOMETRIC EQUATIONS

To see if it is necessary to develop local allometric equations to accurately estimate forest carbon, North American-derived allometric equations were used to estimate the aboveground biomass of the 26 Vologda forest stands. The equations employed utilized parabolic volume as the independent variable and aboveground biomass as the dependent variable. Two sets of equations were employed, one of generalized regional equations and the second composed of four species specific equations for the same genera as those found in the Russian forests of interest (Tritton and Hornbeck, 1982; Siccama *et al.*, 1994). All of the equations were developed in the New England region of the United States that has a similar climate to that of Vologda. The aboveground biomass equations utilized were as follows:

USA 1 (Monteith 1979 as reported by Tritton and Hornbeck, 1982)

conifers

$$W(kg) = 1.5773 + 0.1304\ D(mm) - 1.2192\ H(m) + 0.0001774\ D^2H$$

hardwoods

$$W(kg) = 0.3167 + 0.04666\ D(mm) - 0.2082\ H(m) + 0.0002549\ D^2H$$

USA 2

Picea (Siccama *et al,*. 1994)

$$\log_{10}W(g) = 0.8219 + 0.7966\log_{10}(3.14(D(cm)/2)/2)H(cm))$$

Betula (Siccama *et al.* 1994)

$$\log_{10}W(g) = 0.0974 + 0.9615\log_{10}(3.14(D(cm)/2)/2)H(cm))$$

Populus (Monteith 1979 as reported by Tritton and Hornbeck, 1982)

$$W(kg) = 3.8124 + 0.09632\ D(mm) - 1.3154\ H(m) + 0.0002079\ D^2H$$

Pinus (Monteith 1979 as reported by Tritton and Hornbeck, 1982)

$$W(kg) = 0.5209 + 0.07434\ D(mm) - 0.5439\ H(m) + 0.0001516\ D^2H.$$

3. Results

Allometric equations developed to predict total biomass for five taxa from Vologda and aboveground biomass for one taxon for Volgograd have adjusted R^2s of > 0.97 (Table 1). Predicting the weight of some component parts is somewhat less reliable with the adjusted R^2s dipping as low as 0.77. Even estimates of root biomass were very consistent, with adjusted R^2s > 0.95 (Table 1). There was more variability in the relationship of height to aboveground and/or total biomass of the 14 taxa of shrubs and small trees examined, adjusted R^2s of 0.37-1.00 (Table 2).

Among the Vologda stands age varied from 26-155 years, while mean tree height (14-31 m) and mean tree diameter (10-33 cm) varied as well (Table 3). The relationship of tree height and tree diameter was very consistent within each plot, but showed some inter-plot variability (Table 4). Total living tree density varied from 3018 to 487 trees ha^{-1}, varying predictably with stand age and dominant species. Dead tree density varied less predictably with stand age (Table 3).

Biomass of the 26 Vologda stands averaged 101 Mg-C ha^{-1} (Table 5). Among the sites biomass varied widely as would be expected from forest stands of such a wide age-range. Dead trees and shrubs and regeneration on average accounted for about 2% of the total carbon in the stands (Table 5). Shrubs and regeneration never exceeded 3% of total forest carbon excluding soils (Table 5; plot 21) and dead standing trees never exceeded 9% of total stand carbon excluding soils (Table 5; plot 26). Sixty-nine percent of biomass was in the stems and 18% in the roots; the remaining 13% were in branches and foliage (Table 5).

Forest carbon estimated volumetrically was higher than the allometric estimate in all but four hardwood dominated plots (Table 5). The mean difference between the allometric and volume based estimates for the 26 Vologda stands was 8.2% with a 95% confidence interval of 4.2%. The range of differences between the two methods was -28% to +13%. The variation between the two estimates was correlated with dominant tree species. Allometrically derived carbon estimates were actually higher on average for the seven birch dominated plots (+1%), and lower for the other three species; spruce (-10.8%), pine (-15.0%), aspen (-9.3%).

Comparison of the biomass predicted using the North American and Russian allometric equations showed few difference for the 26 Vologda plots (Table 6). The USA 2 equations developed for congeners of the tree species present on the plots resulted in no significant difference in the biomass estimates (1.7%) from those using the Russian derived equations. The generalized North American equations did yield a small but significant difference (5.6%) when compared to the Russian equation based estimates. The differences were not uniform among the plots. The birch dominated plots had 12% more biomass using the North American species level equations (USA 2) relative to the Russian equations. In contrast the spruce dominated plots had the same biomass on average using North American and Russian equations (0.35% difference). The pine plots were 5% different and the aspen plots 4%.

The 25 Volgograd plots varied in age from 20-89 years-old, in canopy height from 9-22 m and tree density of 2280-412 trees ha^{-1} (Table 7). Total biomass averaged 65.6 Mg-C ha^{-1} (Table 8). Dead trees, shrubs and regeneration contain insignificant amounts of carbon relative to the living biomass. Comparison of allometric and volumetric carbon estimates for the 25 forest stands in Volgograd are very similar, differing by 4.4% (Table 9). A comparison among plots indicated relatively low variability (2.9% 95% CI), yet use of zonal versus regional carbon/volume coefficients made a large difference (9.5%). The more specific volume/carbon coefficients provided a result closer to the estimate generated through the allometric equations.

Table 1. Allometric relationships of four dominant Russian forest tree genera were developed using non-linear regression analysis of 890 sample trees. Diameter at breast height (D) in cm and height (H) in m were used as independent variables and weight of biomass fraction in kg dry weight as the dependent variable (Biomass = $a(D^2H)^b$ or Biomass = aD^bH^c). All data were collected during the growing season. All sample trees were collected in a latitude range of 55-62°N, except those included in Pinus (south) which was from 53 °N .

Dependent Variable by species and tree component	d range cm	n	Regression equations								
			$a(D^2H)^b$				aD^bH^c				
kg dry weight			a	b	adjusted R^2	standard error (kg)	a	b	c	adjusted R^2	standard error (kg)
Picea abies Karst.											
Stem	0.5-52	236	0.0420	0.8958	0.982	22	0.0442	1.8092	0.8618	0.982	22
Branches	0.5-52	231	0.0022	1.0087	0.925	8	0.0203	2.6514	-0.3337	0.949	7
Foliage	0.5-52	231	0.0233	0.7211	0.879	5	0.0803	2.0941	-0.3486	0.905	5
Crown (branches+foliage)	0.5-52	230	0.0105	0.9010	0.921	12	0.0699	2.4712	-0.3868	0.948	10
Aboveground	0.5-52	222	0.0533	0.8955	0.981	29	0.0842	1.9443	0.5941	0.982	28
Roots	1-32	62	0.0239	0.8408	0.924	9	0.0386	2.5377	-0.1832	0.955	7
Total	1-32	48	0.1237	0.8332	0.986	19	0.1449	1.8246	0.6231	0.988	18
Pinus sylvestris L.											
Stem	1-34	315	0.0304	0.9231	0.972	13	0.0219	1.5923	1.2943	0.979	11
Branches	1-34	315	0.0047	0.8959	0.775	5	0.0165	2.7352	-0.5104	0.864	4
Foliage	1-34	315	0.0226	0.6249	0.695	2	0.0639	2.0764	-0.5824	0.793	2
Crown (branches+foliage)	1-34	315	0.0139	0.8143	0.774	6	0.0465	2.5379	-0.5367	0.867	5
Aboveground	1-34	315	0.0410	0.9076	0.976	13	0.0374	1.7459	1.0096	0.976	13
Roots	1-32	40	0.0144	0.8569	0.976	2	0.0060	1.4615	1.4390	0.979	2
Total	1-32	40	0.1036	0.8332	0.973	15	0.0427	1.4040	1.4288	0.976	14
Pinus sylvestris L.(south)											
Stem	2-39	80	0.0218	0.9652	0.988	11	0.0101	1.6941	1.4530	0.990	10
Branches	2-39	80	0.0002	1.2298	0.921	4	0.0080	3.4932	-1.0175	0.957	3
Foliage	2-39	80	0.0043	0.8164	0.875	2	0.0329	2.4914	-0.7262	0.931	1
Crown (branches+foliage)	2-39	80	0.0010	1.1028	0.929	5	0.0224	3.1758	-0.9079	0.970	3
Aboveground	2-39	80	0.0217	0.9817	0.989	12	0.0191	1.9249	1.0613	0.989	12

Table 1 (continued). Allometric relationships of four dominant Russian forest tree genera were developed using non-linear regression analysis of 890 sample trees. Diameter at breast height (D) in cm and height (H) in m were used as independent variables and weight of biomass fraction in kg dry weight as the dependent variable (Biomass = $a(D^2H)^b$ or Biomass = aD^bH^c). All data were collected during the growing season. All sample trees were collected in a latitude range of 55-62°N, exept those included in Pinus (south) which was from 53 °N .

Dependent Variable by species and tree component	d range cm	n	Regression equations $a(D^2H)^b$				$a D^b H^c$				
kg dry weight			a	b	adjusted R^2	standard error (kg)	a	b	c	adjusted R^2	standard error (kg)
Betula pendula Roth. & *B. pubescens* Ehrh.											
Stem	0.2-72	217	0.5621	0.6323	0.901	37	0.0038	0.9349	2.5439	0.949	27
Branches	0.2-72	216	0.0257	0.7621	0.789	11	0.0008	1.3637	2.0000	0.799	10
Foliage	0.2-72	216	0.0200	0.5887	0.813	1	0.0167	1.1625	0.6615	0.813	1
Crown (branches+foliage)	0.2-72	216	0.0358	0.7422	0.798	12	0.0018	1.3372	1.8351	0.807	11
Aboveground	0.2-72	216	0.5443	0.6527	0.889	48	0.0054	1.0221	2.3905	0.926	39
Roots	1-19	21	0.0387	0.7281	0.950	2	0.0607	2.6748	-0.5610	0.995	1
Total	1-19	21	0.0557	0.9031	0.988	5	0.0562	2.3501	0.3932	0.993	4
Populus tremula L.											
Stem	1-35	142	0.0179	0.9850	0.994	7	0.0046	1.7325	1.6526	0.995	6
Branches	1-35	142	0.0015	1.0439	0.907	4	0.0140	2.4855	-0.0675	0.911	4
Foliage	1-35	142	0.0069	0.6869	0.827	1	0.0411	1.8706	-0.3812	0.836	1
Crown (branches+foliage)	1-35	142	0.0029	0.9893	0.901	5	0.0312	2.4247	-0.2127	0.905	5
Aboveground	1-35	142	0.0208	0.9856	0.994	8	0.0102	1.8450	1.3386	0.994	8
Roots	1-12	12	0.0145	0.8749	0.977	1	0.0307	2.4427	-0.0708	0.998	0.2
Total	1-12	12	0.0968	0.8070	0.987	2	0.1462	1.9715	0.3096	0.993	1

Table 2. Allometric relationships of 12 genera of common unerstory trees and shrubs in the southern boreal forests (55-62°N) of Russia were developed using non-linear regression analysis. *Pinus* (south) is from a latitude of 53 °N. Height (h) in m was used as the independent variable and weight of biomass fraction in kg dry weight as the dependent variable in the equation, Biomass = a H^b. *Pinus, Betula* and *Populus* sample trees were from regenerating forests stands with no overstory (some of the sample trees were used in development of both forest tree and understory regressions), with all other samples collected from closed canopy forests.

Species	Biomass fraction kg dry weight	Height range m	n	a	b	adjusted R^2	standard error (kg)
Picea abies Karst.	Stem	0.8-11.5	59	0.0858	2.0326	0.936	0.3
	Branches	0.8-11.5	59	0.1352	1.4244	0.579	0.5
	Foliage	0.8-11.5	59	0.1134	1.5018	0.694	0.3
	Aboveground woody	0.8-11.5	59	0.2081	1.7756	0.839	0.7
	Aboveground total	0.8-11.5	59	0.3173	1.7011	0.810	1.1
Pinus sylvestris L.	Stem	2.0-10.0	53	0.0866	1.7812	0.586	1.0
	Aboveground woody	2.0-10.0	53	0.1410	1.5935	0.521	1.2
	Aboveground total	2.0-10.0	53	0.2169	1.4172	0.449	1.3
	Roots	2.2-7.1	14	0.0030	2.6807	0.542	0.2
	Total	2.2-7.1	14	0.0802	1.9142	0.435	1.3
Pinus sylvestris L.(south)	Stem	2.6-7.1	10	0.2161	1.3058	0.698	0.5
	Aboveground woody	2.6-7.1	10	0.3735	1.0801	0.581	0.6
	Aboveground total	2.6-7.1	10	0.6448	0.8595	0.430	0.9
Betula pendula Roth. & *Betula pubescens* Ehrh.	Stem	1.5-11.9	99	0.0264	2.2684	0.804	0.5
	Aboveground woody	1.5-11.9	98	0.0388	2.1373	0.754	0.7
	Aboveground total	1.5-11.9	98	0.0489	2.0529	0.788	0.8
	Roots	3.1-10.8	9	0.0356	1.4149	0.205	0.4
	Total	3.1-10.8	9	0.1561	1.6129	0.377	0.7
Populus tremula L.	Stem	2.7-9.0	40	0.0135	2.5486	0.659	0.6
	Aboveground woody	2.7-9.0	40	0.0204	2.4008	0.561	0.9
	Aboveground total	2.7-9.0	40	0.0264	2.2978	0.521	0.9
	Roots	2.7-8.1	6	0.0747	1.2262	0.309	0.5
	Total	2.7-8.1	6	0.3162	1.2762	0.335	2.2
Corylus avellana Mill.	Aboveground woody	0.2-4.5	31	0.0665	1.8775	0.911	0.1
	Foliage	0.2-4.5	31	0.0114	1.3714	0.888	0.01
	Aboveground total	0.2-4.5	31	0.0768	1.8329	0.920	0.1
Lonicera xylosteum L.	Aboveground woody	0.2-1.3	11	0.0544	1.9326	0.929	0.01
	Foliage	0.2-1.3	11	0.0053	2.0581	0.883	0.001
	Aboveground total	0.2-1.3	11	0.0597	1.9419	0.930	0.01

Table 2 (continued). Allometric relationships of 12 genera of common unerstory trees and shrubs in the southern boreal forests (55-62°N) of Russia were developed using non-linear regression analysis. *Pinus* (south) is from a latitude of 53 °N. Height (h) in m was used as the independent variable and weight of biomass fraction in kg dry weight as the dependent variable in the equation, Biomass = a H^b. *Pinus, Betula* and *Populus* sample trees were from regenerating forests stands with no overstory (some of the sample trees were used in development of both forest tree and understory regressions), with all other samples collected from closed canopy forests.

Species	Biomass fraction kg dry weight	Height range m	n	a	b	adjusted R^2	standard error (kg)
Rhamnus sp.	Aboveground woody	0.1-3.2	9	0.0137	1.4805	0.983	0.003
	Foliage	0.1-3.2	9	0.0020	1.2856	0.923	0.001
	Aboveground total	0.1-3.2	9	0.0157	1.4600	0.983	0.003
Euonymus verrucosa Scop.	Aboveground woody	0.1-1.3	8	0.0179	2.8026	0.951	0.003
	Foliage	0.1-1.3	8	0.0014	1.0499	0.691	0.000
	Aboveground total	0.1-1.3	8	0.0195	2.6069	0.954	0.003
Viburnum opulus L.	Aboveground woody	0.2-2.0	5	0.0240	2.7603	1.000	0.000
	Foliage	0.2-2.0	5	0.0048	1.9840	1.000	0.000
	Aboveground total	0.2-2.0	5	0.0294	2.6318	1.000	0.000
Sorbus aucuparia L.	Aboveground woody	0.2-6.7	13	0.0521	1.6344	0.889	0.1
	Foliage	0.2-6.7	13	0.0065	1.6122	0.910	0.01
	Aboveground total	0.2-6.7	13	0.0586	1.6318	0.911	0.1
Padus sp.	Aboveground woody	2.1-8.9	14	0.0145	2.7835	0.832	0.5
	Foliage	2.1-8.9	14	0.0035	1.9469	0.707	0.03
	Aboveground total	2.1-8.9	14	0.0168	2.7304	0.829	0.5
Juniperus excelsa M.B.	Aboveground woody	0.8-1.4	6	0.2874	1.1713	0.869	0.03
	Foliage	0.8-1.4	6	0.1442	0.7049	0.919	0.01
	Aboveground total	0.8-1.4	6	0.4316	1.0244	0.890	0.04

Table 3. Stand characteristics of 26 forest plots in the Vologda region of Russia. Stand age represents the mean age of the dominant canopy trees. Site index and tree volume were determined using standard Russian forestry methods based on: dominant species, stand age, mean height and mean diameter. Minimum tree size inventoried was 6 cm in 15 plots, in the other 11 plots it varied from 2-10 cm.

Plot #	Stand age	Dominant tree species	Plot size	Mean tree height	Mean tree diameter	Site index	Tree volume	Tree density trees ha^{-1}					
	yr		ha	m	cm		$m^3\ ha^{-1}$	*Picea*	*Pinus*	*Betula*	*Populus*	total living	total dead
1	26	aspen	0.18	13.8	10	Ia	112	0	0	183	1828	2011	0
2	35	aspen	0.11	16	12	I	246	0	0	1045	1973	3018	327
3	40	birch	0.18	19	14	Ia	275	0	0	1250	567	1817	183
4	40	birch	0.25	17	14	2	158	160	56	884	248	1348	0
5	43	birch	0.2	19.3	14	I	224	80	0	1140	275	1495	65
6	45	birch	0.184	24	18	Ia	286	0	0	1098	158	1255	27
7	50	birch	0.2	22	20	I	402	0	0	1015	410	1425	65
8	50	spruce	0.14	23.5	13	3	279	1571	150	0	0	1721	43
9	50	birch	0.263	24	20	I	403	0	0	844	255	1099	8
10	60	pine	0.28	23	20	I	398	214	725	229	211	1379	129
11	60	aspen	0.275	27	-	I	454	633	0	251	749	1633	33
12	60	spruce	0.264	20	21	I	323	777	11	19	110	917	4
13	62	birch	0.25	17	15	3	184	100	0	1204	0	1304	84
14	65	spruce	0.33	25	23	2	321	645	30	52	42	770	18
15	65	spruce	0.225	-	-	2	267	889	4	129	53	1076	22
16	65	pine	0.5	26	24	I	276	0	468	102	0	570	16
17	70	spruce	0.23	18	18	3	230	996	30	0	0	1026	0
18	72	pine	0.2	20	18	2	311	10	1235	55	0	1300	220
19	75	spruce	0.33	22.3	21	2	359	624	133	109	6	873	12
20	77	aspen	0.7	31.4	33	Ia	493	69	0	69	350	487	14
21	80	pine	0.5	14.5	18	4	149	186	466	268	0	920	0
22	87	spruce	0.35	22	23	3	371	654	0	203	0	857	46
23	107	spruce	0.54	21	26	3	300	281	0	115	102	498	9
24	115	pine	0.4	15.5	21	5	145	83	503	0	0	585	13
25	130	spruce	0.325	24.8	24	3	451	631	58	175	55	920	62
26	155	spruce	0.25	19.4	18	2	221.5	808	24	152	0	984	244

Table 4. Relationships of height (h) in m and diameter at breast height (D) in cm of *Picea abies* trees in five sample plots in the Vologda region of Russia (60°N).

Diameter range (cm)	plot number	n	Regression equations $h = a\,d + b\,d^2$			$h = a\,d^b$		
			a	b	adjusted R^2	a	b	adjusted R^2
8-41	12	24	1.20977	-0.01443	0.996	3.09657	0.58813	0.995
8-46	17	23	1.10051	-0.01292	0.990	2.73563	0.59225	0.986
12-43	22	26	1.32553	-0.01736	0.996	4.90677	0.45528	0.993
8-48	23	23	1.28463	-0.01707	0.996	6.08259	0.37203	0.996
10-43	25	25	1.34669	-0.01561	0.996	3.58145	0.57862	0.995

Table 5. Biomass and carbon content of the vegetation of the 26 forest stands in the Vologda region of Russia. Allometrically derived estimates of stand carbon contents were compared with those determined using regional carbon/volume coefficients. Percentage differences between allometric and volume derived living tree carbon were calculated using the following equation: (allometric carbon - volume carbon) / allometric carbon.

		Allometric Approach													Volume Approach		
		biomass (Mg dry weight ha^{-1})							carbon (Mg-C ha^{-1})								
Plot #	Age yr	stems	branches	roots	foliage	total in trees	shrubs and regeneration	stand total	living trees	dead trees	total in trees	shrubs and regeneration	stand total	C/volume coefficient Mg-C m^{-3}	carbon in living trees Mg-C ha^{-1}	Allometric vs volume carbon (%)
1	26	52	7	17	2	78	0	78	39	0	39	0	39	0.442	50	-27.9
2	35	134	17	32	4	188	0.7	189	94	3.5	97	0.3	98	0.416	102	-9.1
3	40	154	21	30	4	209	2.5	211	104	4	108	1.2	109	0.392	108	-3.4
4	40	91	12	18	3	123	0.1	123	62	0	62	0.1	62	0.392	62	-0.7
5	43	136	19	25	4	184	0.8	185	92	0.9	93	0.4	93	0.392	88	4.4
6	45	173	25	31	4	233	0	233	116	0.8	117	0	117	0.392	112	3.6
7	50	202	29	42	5	278	0	278	139	1.3	140	0	140	0.366	147	-6.1
8	50	110	15	36	12	173	0.4	173	86	0.6	86	0.2	87	0.334	93	-8.8
9	50	202	31	41	5	278	0	278	139	0.6	139	0	139	0.366	148	-6.3
10	60	179	24	44	8	254	4	258	127	2.1	129	2	131	0.346	138	-8.7
11	60	220	32	62	11	325	1.2	326	162	0.4	162	0.6	163	0.309	140	13.4
12	60	132	21	43	13	208	0.4	209	103	1.2	105	0.2	105	0.353	114	-10.2
13	62	121	17	20	4	160	0.2	161	80	2.7	83	0.1	83	0.367	68	15.5
14	65	134	21	42	12	208	0	208	103	0.6	104	0	104	0.353	113	-9.5
15	65	120	18	37	11	186	4.4	191	93	1.6	94	2.2	96	0.353	94	-1.7
16	65	116	14	27	5	162	3.6	165	81	0.6	81	1.8	83	0.346	96	-18.6
17	70	95	14	32	10	152	0.8	153	75	0	75	0.4	76	0.353	81	-7.7
18	72	128	15	33	7	183	2.7	185	91	2.4	93	1.3	95	0.346	108	-18.3
19	75	152	22	45	12	232	0.2	232	115	0.3	116	0.1	116	0.353	127	-9.7
20	77	213	33	54	5	305	0.4	305	152	1.3	153	0.2	154	0.35	173	-13.6
21	80	71	9	18	4	102	3.2	105	51	0	51	1.6	52	0.346	52	-1.7
22	87	160	25	48	14	246	0.2	247	123	3.3	126	0.1	126	0.369	137	-11.9
23	107	118	19	33	7	177	1.4	179	88	1	89	0.7	90	0.369	111	-25.5
24	115	54	7	15	3	79	3.6	82	39	0.6	40	1.7	42	0.346	50	-27.7
25	130	185	29	54	14	282	1.8	284	140	1.9	142	0.9	143	0.369	167	-18.8
26	155	102	15	31	9	157	0	157	78	7.4	85	0	85	0.369	82	-5
Mean	69	137	20	35	7	198	1.3	200	99	1.5	100	0.6	101	0.365	106	-8.2
SD	30	46	7	12	4	66	1.5	65	33	1.7	33	0.7	33		35	10.9
95% CI	12	18	3	5	2	25	0.6	25	13	0.6	13	0.3	13		13	4.2

Table 6. Aboveground mass of trees of the 26 forest stands in the Vologda regions of Russia, estimated using Russian (RUS) and two American (US1 and US2) sets of regression equations. Percentage differences between estimations were calculated using the equations (RUS mass - US mass) / RUS mass for RUS vs USA1 and RUS vs USA2 and (USA1 mass - USA2 mass) / USA1 mass for USA1 vs USA2.

Plot #	Age (yr)	Dominant tree species	Aboveground mass of trees Mg-dry weight ha^{-1}			Percentage difference in estimations (%)		
			RUS	USA1	USA2	RUS vs USA1	RUS vs USA2	USA1 vs USA2
1	26	aspen	61	80	57	-30.4	6.7	28.4
2	35	aspen	156	168	145	-7.8	7.3	14.0
3	40	birch	178	187	187	-4.5	-4.7	-0.2
4	40	birch	106	99	105	6.6	0.3	-6.7
5	43	birch	159	152	166	4.2	-4.4	-9.0
6	45	birch	202	220	239	-9.1	-18.6	-8.7
7	50	birch	236	282	274	-19.4	-16.3	2.6
8	50	spruce	136	120	136	12.2	0.4	-13.4
9	50	birch	238	305	312	-28.6	-31.5	-2.3
10	60	pine	210	237	222	-12.7	-5.5	6.4
11	60	aspen	263	274	219	-4.2	16.9	20.2
12	60	spruce	165	161	151	2.4	8.5	6.2
13	62	birch	141	129	150	8.2	-6.9	-16.4
14	65	spruce	167	174	164	-4.3	1.8	5.9
15	65	spruce	149	143	152	4.0	-1.7	-5.9
16	65	pine	134	146	132	-8.8	1.9	9.8
17	70	spruce	120	112	113	6.3	5.6	-0.8
18	72	pine	150	149	132	0.2	12.0	11.8
19	75	spruce	187	186	185	0.5	1.0	0.6
20	77	aspen	251	351	291	-39.7	-15.7	17.2
21	80	pine	84	80	76	4.7	9.6	5.1
22	87	spruce	199	197	196	1.0	1.1	0.1
23	107	spruce	144	172	160	-19.0	-10.7	7.0
24	115	pine	64	68	59	-6.0	7.9	13.1
25	130	spruce	228	242	238	-6.0	-4.5	1.4
26	155	spruce	126	121	132	3.8	-5.0	-9.1
Mean			164	175	169	-5.6	-1.7	3.0
SD			61	68	66	12.8	10.7	10.7
95% CI			263	28	26	4.9	4.1	4.1

Table 7. Stand characteristics of 25 pine (*Pinus sylvestris*) forest plots in the Volgograd region of Russia. Stand age represents the mean age of the dominant canopy trees. Site index and tree volume were determined using standard Russian forestry methods based on: dominant species, stand age, mean height and mean diameter. Minimum tree size inventoried was 6 cm in 8 plots, in the other 17 plots it varied from 2-16 cm.

Plot #	Stand age yr	Plot size ha	Mean tree height m	Mean tree diameter cm	Site index	Tree volume m^3 ha^{-1}	Tree density trees ha^{-1}	
							growing	dead
1	20	0.2	9.2	10.4	1	79	2010	0
2	22	0.1	9.2	10.6	1	89	2110	0
3	26	0.2	11.3	8.8	1	68	1640	50
4	31	0.25	10	12	3	66	988	0
5	31	0.125	13.4	14.2	1	219	1992	24
6	31	0.37	12.3	17.6	2	111	686	0
7	32	0.24	12.8	20.9	1	262	1100	75
8	32	0.15	11	14	2	186	1987	7
9	32	0.12	11.5	15	2	92	858	0
10	32	0.37	13	18.9	1	149	786	32
11	33	0.45	14.3	14.6	1	160	1280	47
12	33	0.2	14	15.4	1	184	1350	15
13	41	0.15	13	14	2	239	2280	47
14	42	0.1	16.9	13.9	2	294	2260	510
15	55	0.25	16.1	22	2	245	812	4
16	62	0.4	17	21.2	3	259	865	23
17	66	0.5	22	27.9	0	257	412	0
18	68	0.2	15.5	18	2	230	1400	0
19	74	0.4	25	29	1	530	705	3
20	77	0.32	19.4	21.6	3	295	788	0
21	78	0.5	22	24	2	494	1098	12
22	82	0.4	16.5	21.4	4	216	773	45
23	87	0.48	20.3	28.7	3	308	490	0
24	88	0.5	14.8	24.3	4	147	412	2
25	89	0.4	21.9	24.2	3	444	930	10

Table 8. Allometrically derived biomass and carbon content of the vegetation of the 25 pine forest stands in the Volgograd region of Russia.

Plot #	Age	Biomass Mg -dry weight ha^{-1}							Carbon Mg-C ha^{-1}				
	yr	stems	branches	roots	foliage	total in trees	shrubs and regeneration	stand total	living trees	dead trees	total in trees	shrubs and regeneration	stand total
1	20	35	2	8	2	47	0	47	23	0	23	0	23
2	22	39	2	9	3	52	0	52	26	0	26	0	26
3	26	27	2	6	2	36	0	36	18	0	18	0	18
4	31	25	2	6	2	33	0	33	17	0	17	0	17
5	31	89	7	20	5	121	0	121	60	0	61	0	61
6	31	42	4	10	2	58	0	58	29	0	29	0	29
7	32	100	9	23	5	137	0	137	68	0	69	0	69
8	32	72	5	16	4	98	0	98	49	0	49	0	49
9	32	38	3	9	2	51	0	51	26	0	26	0	26
10	32	59	5	14	3	82	0	82	41	0	41	0	41
11	33	64	5	14	4	87	1	87	43	0	44	0	44
12	33	77	6	17	4	105	0	105	52	0	52	0	52
13	41	99	8	23	6	135	0	135	67	0	68	0	68
14	42	125	11	28	7	171	0	171	85	4	89	0	89
15	55	101	10	23	5	139	0	139	70	0	70	0	70
16	62	107	11	25	5	148	0	148	74	0	74	0	74
17	66	109	14	26	5	154	0	154	77	0	77	0	77
18	68	119	11	27	6	163	0	163	81	0	81	0	81
19	74	232	31	55	10	328	0	328	163	0	163	0	163
20	77	126	14	29	6	176	0	176	87	0	87	0	87
21	78	216	25	51	10	302	0	302	151	0	151	0	151
22	82	89	9	21	5	123	3	126	62	1	63	1	64
23	87	128	16	30	6	181	0	181	90	0	90	0	90
24	88	59	6	14	3	82	0	82	41	0	41	0	41
25	89	190	23	45	9	266	0	266	133	0	133	0	133
Mean	51	95	10	22	5	131	0	131	65	0	66	0	66
SD	24	55	8	13	2	78	1	78	39	1	39	0	39
95% CI	9	21	3	5	1	30	0	30	15	0	15	0	15

Table 9. Stand carbon content of the 26 pine forest stands in the Volgograd region of Russia. Allometrically derived estimates of stand carbon contents were compared with those determined using zonal and regional carbon/volume coefficients. Percentage differences between allometric and volume derived living tree carbon were calculated using the following equation: (allometric carbon - volume carbon) / allometric carbon.

Plot #	Age yr	Allometric Approach carbon in living trees Mg-C ha^{-1}	Volume Approach					
			zonal			regional		
			C/volume coefficient Mg-C m^{-3}	carbon in living trees Mg-C ha^{-1}	allometric vs volume carbon %	C/volume coefficient Mg-C m^{-3}	carbon in living trees Mg-C ha^{-1}	allometric vs volume carbon %
1	20	23	0.348	28	-4.3	0.296	23	-1.0
2	22	26	0.348	31	-4.8	0.296	26	-1.2
3	26	18	0.348	24	-5.9	0.296	20	-13.3
4	31	17	0.348	23	-6.4	0.296	20	-18.5
5	31	60	0.348	76	-15.7	0.296	65	-7.5
6	31	29	0.348	39	-10.0	0.296	33	-15.0
7	32	68	0.348	91	-22.5	0.296	78	-13.4
8	32	49	0.348	65	-15.7	0.296	55	-12.7
9	32	26	0.348	32	-6.5	0.296	27	-7.2
10	32	41	0.348	52	-11.1	0.296	44	-8.6
11	33	43	0.348	56	-12.4	0.296	48	-9.9
12	33	52	0.348	64	-11.9	0.296	55	-4.7
13	41	67	0.334	80	-12.5	0.303	72	-7.4
14	42	85	0.334	98	-13.1	0.303	89	-4.5
15	55	70	0.334	82	-12.4	0.303	74	-6.8
16	62	74	0.353	91	-17.8	0.300	78	-5.6
17	66	77	0.353	91	-14.2	0.300	77	-0.7
18	68	81	0.353	81	0.1	0.300	69	15.1
19	74	163	0.353	187	-23.7	0.300	159	2.6
20	77	87	0.353	104	-16.6	0.300	89	-1.2
21	78	151	0.353	174	-23.6	0.300	148	1.7
22	82	62	0.369	80	-18.1	0.282	61	1.2
23	87	90	0.369	114	-23.6	0.282	87	3.6
24	88	41	0.369	54	-13.7	0.282	42	-2.0
25	89	133	0.369	164	-31.4	0.282	125	5.6
Mean	51	65	0.351	79	-13.9	0.296	67	-4.4
SD	24	39		45	7.3		37	7.5
95% CI	9	15		17	2.8		14	2.9

4. Discussion

There is no comprehensive inventory of applicable forest allometric or biomass data, but where such data exist they can be profitably exploited. If forestry mitigation projects are adopted as a prescribed tool under the Framework Convention on Climate Change, it would be highly profitable to undertake a systematic inventory of the relevant allometric equations and weight data available for the forests of the world.

The consistent form and high degree of constancy among the allometric equations developed indicates that allometric approaches to estimating tree weight are straight forward and effective. The very high adjusted R^2s are comparable to those found for species where the equations have been demonstrated to accurately predict forest biomass (Siccama *et al.*, 1994). The equations that were developed as part of this study are consistent in all respects with those reported for North American species.

The forest stands studied in Vologda and Volgograd represented a good cross section of the regions' forests. The variation in average tree size and density provided a very robust comparison of the volumetric versus allometric approaches to estimating forest carbon. The five to ten-fold difference in carbon among stands within the two regions is a reminder that project based carbon estimates require reliable stand information. Regional stand averages have a high degree of uncertainty due to the natural variation in growing conditions, disturbance histories and stochastic factors such as seed sources and pest outbreaks. Generalized approaches to calculating changes in forest management impacts on carbon storage are of limited use if not tied to stand specific data.

The variation between the two carbon estimates was largely related to species composition within the stands. If one project involves birch stands, for which there was no net measurable difference (1%) between estimates using the two methods, and another involves pine stands, for which there was a rather large difference (15%), then the absolute accuracy will be considerably different depending on the method employed. For site specific forestry mitigation projects it is important to know tree heights and species composition and size distributions for the project forests. Further confirmation of the dry weight/carbon ratio would be very useful. Such additional data would allow more accurate estimates of the uncertainty that this conversion introduces.

As trees grow the bole to branch ratio does not vary consistently among species. This shifting ratio can lead to errors in volume based carbon estimates. Further complicating the consistency of the volume estimates among stands is the use of a single phytomass/volume conversion factor for estimating the carbon content of each stand. This single factor approach means differences in species composition within stands are not reflected in the carbon estimates, increasing the inaccuracy of this approach.

Does it matter whether an allometric or volumetric approach is employed when calculating the carbon that might be creditable to a forestry offset project? The results of our study indicate that it makes a moderate difference in some cases. The volumetric approach to estimating carbon proved a viable method, though the degree of consistency differed among species. The volumetric approach utilized in this study employs age specific conversion factors which greatly reduce the inaccuracy of the volumetric approach. If a single average conversion factor were employed it would add an additional 5-10 % inaccuracy to the carbon estimates.

We would recommend allometric equations as the preferred method of determining project level carbon. When volumetric approaches are employed there needs to be some form of discounting applied, as it is not possible to determine *a priori* the direction of any inaccuracies. This discounting need not be large, 5-10%, but it would help to protect against exploitation of the added uncertainty volumetric approaches introduce.

The North American derived allometric equations proved reliable, but were subject to species level variations in consistency. Until we develop more case studies like the one reported here, it will be very difficult to design a simple and fair set of rules for crediting sequestered carbon in forestry projects. We need a set of rules that meet the goal of insuring no net over reporting of carbon sequestered, while not imposing overly harsh penalties for uncertainty. The differences in carbon estimated using the methods reported here are not great ($\geq$15%). These results are very supportive of the feasibility of developing robust and universal rules for cost effective forestry mitigation projects.

5. Conclusions

- Volumetrically and allometrically derived carbon estimates of 51 Russian Forests were very similar.
- The error associated with volumetrically derived carbon estimates varied with species composition. For some species there was no apparent difference between volumetric and allometric estimates, but for others it averaged 15%. The systematic nature of potential errors has to be considered.
- The results suggest that it is appropriate to utilize allometric equations developed for one species for estimating the carbon content of another species growing in a different region, as long as they are for phenotypically similar.
- Both volumetric and allometeric approaches for estimating forest carbon are useful. For regional based studies of forest carbon volumetric approaches are preferred, because they are easy to use. For stand based estimates of forest carbon allometric approaches provide greater reliability.
- Results were very similar across the two Russian regions examined, suggesting the broad applicability of our results.

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INFLUENCE OF METHODOLOGY AND ASSUMPTIONS ON REPORTED NATIONAL CARBON FLUX INVENTORIES: AN ILLUSTRATION FROM THE CANADIAN FOREST SECTOR

JULEE A. GREENOUGH
ESSA Technologies Ltd., Suite 300, 1765 West 8th Avenue, Vancouver, B.C., Canada, V6J 5C6,

MICHAEL J. APPS
Canadian Forest Service, Northwest Region, 5320-122nd Street, Edmonton, AB, Canada, T6H 3S5 (author for correspondence)

WERNER A. KURZ
ESSA Technologies Ltd., Suite 300, 1765 West 8th Avenue, Vancouver, B.C., Canada, V6J 5C6,

Abstract. The Intergovernmental Panel on Climate Change (IPCC) has developed guidelines to standardize the international reporting of greenhouse gas emissions and removals by signatory nations of the UN Framework Convention on Climate Change. With regard to forest sector carbon fluxes, the IPCC guidelines require only that those fluxes directly associated with human activities (*i.e.*, harvesting and land-use change) be reported. In Canada, the Carbon Budget Model of the Canadian Forest Sector (CBM-CFS2) has been used to assess carbon fluxes from the entire forest sector. This model accounts for carbon fluxes associated with both anthropogenic and natural disturbances, such as wild fires and insects. We combined model results for the period 1985 to 1989 with additional data to compile seven different national carbon flux inventories for the forest sector. These inventories incorporate different system components under a variety of seemingly plausible assumptions, some of which are encouraged refinements to the default flux inventory described in the IPCC guidelines. The resulting estimated net carbon fluxes varied from a net removal of 185,000 kt carbon per year of the inventory period to a net *emission* of 89,000 kt carbon per year. Following the default procedures in the IPCC guidelines, while using the best available national data, produced an inventory with a net removal of atmospheric carbon. Adding the effect of natural disturbances to that inventory reversed the sign of the net flux resulting in a substantial emission. Including the carbon fluxes associated with root biomass in the first inventory increased the magnitude of the estimated net removal. The variability of these results emphasizes the need for a systems approach in constructing a flux inventory. We argue that the choice of which fluxes to include in the inventory should be based on the importance of these fluxes to the overall carbon budget and not on the perceived ease with which flux estimates can be obtained. The results of this analysis also illustrate two specific points. Even those Canadian forests which are most free from direct human interactions—forests in which no commercial harvesting occurs—are not in equilibrium, and their contribution to national carbon fluxes should be included in the reported flux inventory. Moreover, those forest areas that are subject to direct management are still substantially impacted by natural disturbances. The critical effect of inventory methodology and assumptions on inventory results has important ramifications for efforts to "monitor" and "verify" programs aimed at mitigating global carbon emissions.

Key Words: Canada, Canadian forest sector carbon budget, disturbances, fire emissions, greenhouse gas inventory methodology, IPCC guidelines

1. Introduction

Forest ecosystems play an important role in the global carbon (C) cycle. Forests store large amounts of C in biomass, soil, and litter and, depending on the stage of stand development, they can be either sources or sinks of atmospheric C. Both natural processes and human interventions influence the exchange of C between forest vegetation and the atmosphere (see papers in Apps and Price 1996). International efforts are underway to quantify the net balance of the C exchange between forests and the atmosphere, and to quantify the forest potential for mitigating the accumulation in the atmosphere of anthropogenic CO_2 and other greenhouse gases (*e.g.*, Tans *et al.*, 1990; Kauppi *et al.*, 1992; Apps *et al.*, 1993; Dixon *et al.*, 1995).

Estimates of the net exchange of C should be based on a comprehensive systems approach to accounting for all major sources and sinks. Compiling flux inventories based on the ease with which data are available or based on simplistic assumptions about which components to include or exclude from the inventory can lead to significant misinterpretations about the actual contribution of the forest sector to atmospheric C. Instead, we argue here, a flux inventory should include all fluxes that contribute significantly to the net balance. Moreover, such inventories must clearly document which components are included or excluded to enable meaningful interpretation of inventory results and comparisons among inventories.

1.1. THE CARBON BUDGET MODEL OF THE CANADIAN FOREST SECTOR

The Carbon Budget Model of the Canadian Forest Sector (CBM-CFS2) assesses the carbon pools and fluxes in the nation's forest sector (here defined as the forest ecosystem and the forest products sector). The model considers nearly all forest area (404.2 million ha) in Canada. It projects changes over time in the forest age-class distribution and estimates age-dependent biomass growth and mortality as well as the impacts of direct human activities (*i.e.*, harvesting, product processing, planting, and forest protection) and natural disturbances (*i.e.*, wild fires and insects). The full model is described in detail elsewhere (*e.g.*, Kurz *et al.*, 1995, Kurz and Apps, 1996, Kurz *et al.*, 1996, and references contained in these papers). Only those aspects of the model that are immediately relevant to this discussion will be presented here.

Figure 1a illustrates the C pools and the transfers between pools that are accounted for in the CBM-CFS2. The model projects the amount of carbon stored in above- and belowground tree biomass, "soils" (including litter and woody debris), and four classes of forest products (including landfills). The initial size of each C pool and the annual transfers between pools are based on detailed information compiled from a wide range of sources. For example, the model uses Canada's national biomass inventory (Bonnor, 1985) to estimate the amount of biomass C in each of 457 different ecosystem types and to derive age-specific biomass growth rates. The model also incorporates historic and contemporary statistics on the areas annually disturbed by fires, insects, and harvesting in all regions of Canada.

The CBM-CFS2 accounts for the fate of all biomass C harvested in Canada, regardless of the expected location of forest products derived from that biomass. Therefore, the model does not account for the export and import of wood products. Its estimates of forest product sector C fluxes refer to all biomass harvested in Canada, not the component remaining in Canada.

1.2 THE GUIDELINES OF THE INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE (1995)

In 1992, 150 nations signed the United Nations Framework Convention on Climate Change. The ultimate objective of the convention is to stabilize the amount of greenhouse gases in the atmosphere (IPCC, 1995a, page Preface.1). To monitor progress towards this goal, the signatories of the framework convention made a commitment to (1) publish national greenhouse gas inventories that show the fluxes due to human activity; and (2) use internationally agreed, comparable methodologies in the construction of these inventories (IPCC, 1995a, page Preface.1). Following an extensive review process, the Intergovernmental Panel on Climate Change (IPCC) approved and adopted a standardized inventory methodology, described in the Guidelines for National Greenhouse Gas Inventories (IPCC, 1995a,b,c). The present paper considers only the portion of the guidelines relevant to "Land-Use Change and Forestry." The guidelines are expected to be further developed in an iterative process, with the IPCC approving periodic updates as scientific understanding of the issues improves and better estimation methods become available (IPCC, 1995a, page Preface.3).

The IPCC guidelines have been deliberately kept simple to accommodate the different quality of information available in member nations (IPCC, 1995c, page 5.36). For this reason the guidelines do not demand rigid adherence. On the contrary, the guidelines encourage national experts to use more detailed methodologies and adopt assumptions and parameters appropriate to local conditions wherever possible (IPCC, 1995a,b,c). In fact, national experts may "use an entirely different methodology if they believe this better reflects their national situation" (IPCC, 1995a, page Introduction.3). Only the summary reporting of results and the accompanying documentation need to be standardized between countries, and not the methods of calculation.

The IPCC guidelines propose three sets of calculations to account for CO_2 fluxes due to "Land Use Change and Forestry." The first is "Changes in Forest and Other Woody Biomass Stocks," the second deals with the effects of "Forest and Grassland Conversion," and the third considers the "Abandonment of Managed Lands."

The IPCC inventory section on "Changes in Forest and Other Woody Biomass Stocks" aims to account for "emissions and removals of CO_2 from decreases or increases in standing biomass stocks due to forest management, logging, fuelwood collection, etc." (IPCC, 1995a, page 1.13). Figure 1b illustrates all the carbon transfers that are considered in this section of the IPCC inventory. Basically, the inventory takes account only of the uptake of carbon through aboveground tree biomass growth (including "non-forest" trees), and the release of carbon from aboveground biomass as a result of commercial harvesting

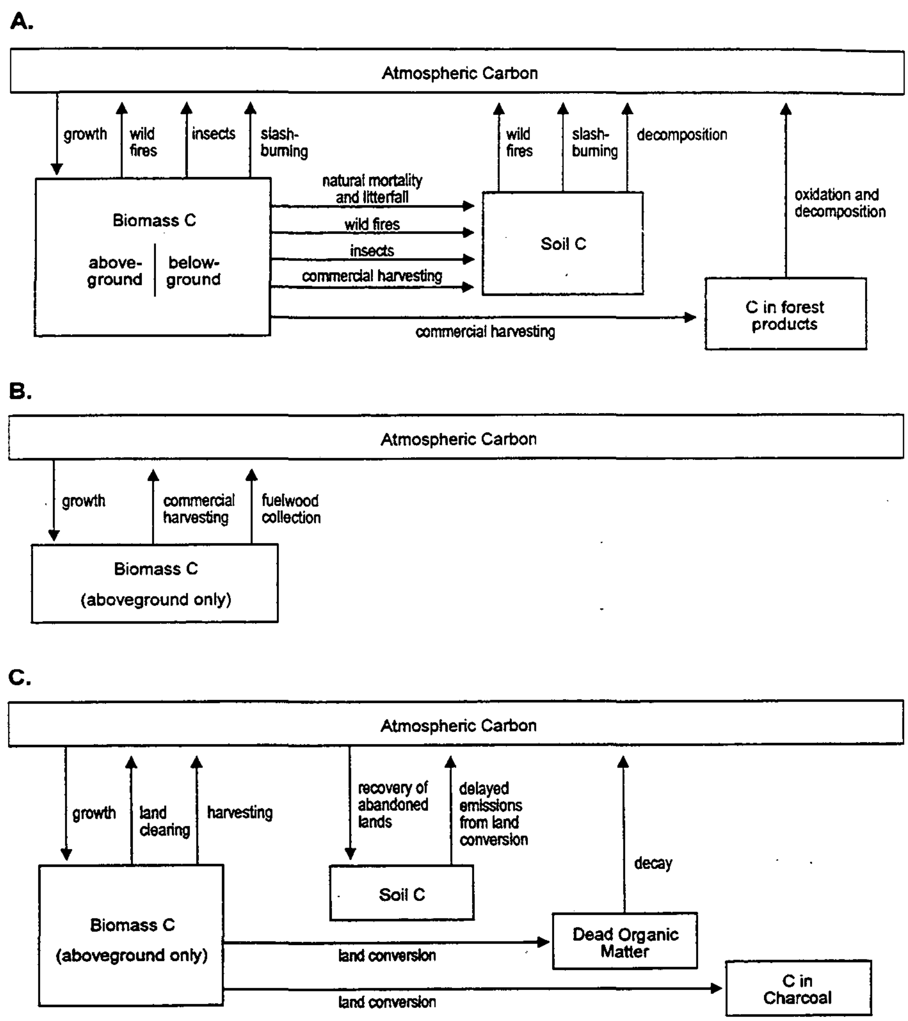

Figure 1. The carbon pools and carbon fluxes considered in each inventory methodology. In this figure, boxes represent "pools" of carbon, and arrows indicate possible carbon fluxes—the transfer of carbon between pools. The figure shows the pools and fluxes that are considered a) in the Carbon Budget Model of the Canadian Forest Sector; b) in the IPCC assessment of changes in "forest and other woody biomass stocks"; and c) in the IPCC assessment of the effects of land-use change. See text for further discussion.

and domestic fuelwood use. The IPCC guidelines' methodology differs substantially from that of the CBM-CFS2 (Figure 1a) because, in the current (1995) version, the guidelines do not account for the transfer of biomass carbon to forest products or soil (or dead wood). The guidelines assume instead that "emissions from the combustion or decay of wood and wood products ... take place ... within a year of harvesting" (1995a, page Overview.5). They also do not consider the contribution of belowground biomass C in roots (IPCC 1995c, page 5.11).

Under the guidelines' methodology, "natural, undisturbed forests"—forests with which "there is no significant current human interaction"—are "not considered to be either an anthropogenic source or sink, and are excluded from the calculations entirely" (IPCC, 1995c, page 5.11). The guidelines do not require indirect anthropogenic effects, such as CO_2 fertilization and acid deposition, to be considered in determining whether a forest should be included in the assessment (IPCC, 1995c, page 5.13). For simplicity, we will refer to "forests with which there is no significant current human interaction" as unmanaged forests.

The flux inventory methods proposed in the IPCC guidelines do not explicitly account for the impact of natural disturbances on the forests included in the assessment. This omission may appear to be consistent with the stated and implied goal of accounting for only anthropogenic effects on carbon stores (see the Reporting Instructions, page 1.13, and Reference Manual, page 5.11)—however, this point will be discussed further below.

Figure 1c illustrates the carbon pools and transfers that are considered in the IPCC guidelines' methodology for accounting for the effects of land-use change. Unlike the default methodology for forest carbon stocks (Figure 1b), the proposed methodology for land-use change does consider carbon storage in soils and dead organic matter (vegetative debris left to decay), and even in charcoal created during burning. The transfers between pools, however, are less detailed than those considered in the CBM-CFS2 (Figure 1a). Soil carbon is exchanged only with atmospheric carbon, the eventual release of carbon from charcoal is not considered, and the only carbon-transfer mechanisms considered are growth, burning, and decay. The two categories of land use change that the IPCC guidelines suggest have the largest impact on carbon fluxes are the conversion of forest and grasslands to agricultural lands, and the abandonment of managed lands (IPCC 1995c, page 5.10).

The three systems diagrams in Figure 1 demonstrate different assumptions about the components (pools and fluxes) to be included in the flux inventories. Excluding components of the C cycle from the flux inventory may facilitate the inventory's compilation but will not likely bring the resulting net flux estimate closer to the actual net flux. The purpose of our analysis is to examine how different assumptions used in the compilation of flux inventories influence the resulting flux estimates.

2. Methods of Inventory Compilation

In order to assess the impact of varying some aspects of the IPCC guideline's methodology, we compiled the seven inventories that are described in Table 1. These inventories report the average annual carbon flux from land-use change and forestry in Canada during the period from 1985 to 1989. This period was chosen because it is the closest period to the IPCC guidelines' requested reporting period (1989-1991) (IPCC, 1995a, pages Overview.5 and 2.1-2.2) for which data were readily available from the CBM-CFS2. Two of the inventories are based on the methodology of the CBM-CFS2. The remaining five inventories are based on the IPCC guidelines' methodology with a variety of adjustments, each of which might plausibly be considered a logical improvement on the default method.

Table 1. Summary of the assumptions used in the seven C flux inventories

I. CBM Base Inventory
Derived from the CBM-CFS2 by aggregating the results from all 11 Canadian Ecoclimatic Provinces (regions defined by ecological criteria (Ecoregions Working Group, 1989). Results are for the last 5-year time interval of a 70-year retrospective simulation from 1920 to 1989 (Kurz and Apps 1996, Kurz *et al.* 1995).

II. CBM Managed Inventory
As in Inventory I, but excluding the forest carbon fluxes from three Ecoclimatic Provinces (arctic, subarctic, and subarctic cordilleran) that have no reported commercial harvest activity and are assumed to contain only "unmanaged" forests. This reduces the total forest area included in the assessment by 21%, from 404.2 Mha to 317.4 Mha.

III. IPCC Default Inventory
Compiled according to the IPCC guidelines' proposed default methodology and employing the guidelines' suggested default parameter values. The CBM-CFS2 'base run' results were used to provide average harvest volume and forest area data for each of the 11 Ecoclimatic Provinces.

IV. IPCC National Inventory
As in III, except that Canadian national data were used to replace the default parameter values wherever possible. The CBM-CFS2 results were used to provide representative average growth rates.

V. IPCC +Roots Inventory
As in IV, except that CBM-CFS2 data were used to include root biomass in the calculation of total biomass C uptake and disturbance impacts (including harvest). Unlike inventory IV, estimated domestic fuelwood use includes an estimate of all non-harvestable biomass disturbed during fuelwood collection. The result is a 'worst case' estimate of fuelwood use under the assumption that all domestic fuelwood is obtained from live trees.

VI. IPCC +Disturbances Inventory
As in IV, except that CBM-CFS2 data were used to estimate the amount of aboveground biomass affected by outbreaks of forest insects and wildfires. This amount of biomass was reported under the heading "Other Wood Use" in the IPCC calculation of "Total Biomass Consumption".

VII. IPCC +Roots +Disturbances Inventory
Combination of V and VI, *i.e.*, both root biomass and natural disturbance impacts are considered.

Compilation of the two CBM inventories was a straightforward process of reporting data from the CBM-CFS2. The five IPCC inventories were compiled using worksheets based on those suggested in the IPCC 'Workbook' (IPCC, 1995b). The only change made to the IPCC worksheets that could impact the final flux estimates concerns the classification of post-conversion land uses—unlike the default version (IPCC, 1995b), the worksheet used in this analysis treated the areas of each land type that are converted to agriculture separately from the areas that are converted to urban use in order to apply different post-conversion biomass densities to each.

Except for Inventory III, national data were used wherever possible in compiling the IPCC inventories. Much of these data were obtained from the CBM-CFS2 and its databases, including data on forest area, harvest volumes, and annual disturbances (see Apps and Kurz, 1993; Kurz and Apps, 1996; and references cited therein). The CBM-CFS2 was also used to provide estimates of biomass growth that reflect changes in the forest age class distribution—growth estimates that are more rigorous than the minimum standard required by the IPCC guidelines. The resulting C flux inventories represent all Canadian forest land for which biomass data are available in the national inventory (Bonnor, 1985), which is expected to be essentially all forest land with significant forest biomass. Note, however, that the CBM-CFS2 data are presented here only for the purpose of comparing alternative methodologies. The detailed model results are undergoing peer review and are not intended for citation as the C fluxes of the Canadian forest sector in the period of study.

Data on factors not considered in the CBM-CFS2 (*e.g.*, growth of non-forest trees, domestic fuelwood use, and the effects of land-use change) were obtained from a variety of sources that are described below. It should be noted, however, that a scarcity of data required making a number of rough assumptions to complete the analysis of land-use change, so that the resulting flux estimate is itself considered to be only a rough approximation. It was only possible in this analysis to assess the carbon fluxes attributable to (i) the *net* conversion of forests and grasslands to agricultural land in each province, in provinces where the total amount of 'improved' agricultural land increased; (ii) the *net* abandonment of agricultural land in each province, in provinces where the amount of improved agricultural land decreased by more than the amount of improved land that was converted to urban areas; and (iii) the urbanization of forest lands, grassland, and agricultural land. In any one time period, accounting for the effects of the net change in land use is not the same as accounting for the net effects of land-use change.

Data on the growth rates of individual non-forest trees were obtained from Standish *et al.*, 1985. Data on the 1985-1989 average domestic fuelwood sales were obtained from Statistics Canada (see Statistics Canada, 1994 & 1995). An expansion factor to account for the amount of fuelwood which is used without commercial sale was obtained from IEA Consulting Group Ltd., 1984, and Pierre Boileau (pers. comm.; Environment Canada).

The area of urban 'roads, parks, and greenbelts' in Canada was obtained from Marshall (1982). The area of improved agricultural land was obtained from Statistics Canada data on the 1986 Agricultural Profiles of each province (*e.g.*, Statistics Canada, 1992). Statistics Canada also provided data on the area of

Table 2. Summary of results

1985-1989 Average Annual National Carbon Fluxes from Land Use Change and Forestry:

Comparison of Inventory Methodologies

	I. CBM Base	II. CBM Managed	III. IPCC Default	IV. IPCC National	V. IPCC +Roots	VI. IPCC +Disturbances	VII. IPCC +Roots +Disturb.	
				(kt Carbon / year)				
1. Changes in Forest and Other Woody Carbon Stocks								
a) Biomass								
Net Growth prior to Disturbance								
Forest Trees	160,700	157,400	301,700	127,200	160,700	127,200	160,700	
Non-Forest Trees			300	300	400	300	400	
Subtotal Growth	160,700	157,400	302,000	127,400	161,000	127,400	161,000	
Disturbance Releases to Atmosphere								
Wild Fire & Insects	-24,000	-17,700						
Slashburning	-2,000	-2,000						
Total Commercial Harvest (& all commercial products)			-111,200	-86,900	-109,400	-86,900	-109,400	(1)
Domestic Fuelwood Consumption			-3,600	-3,600	-7,900	-3,600	-7,900	
Other Wood 'Use'			0	0	0	-101,900	-130,500	
Subtotal Disturbance Releases to Atmosphere	-25,900	-19,700	-114,800	-90,500	-117,300	-192,400	-247,800	
Disturbance Transfers to Soil								
Wild Fire & Insects	-106,500	-92,400						
Commercial Harvest Practices	-57,500	-57,500						
Subtotal Disturbance Transfers to Soil	-164,000	-149,900						
Transfer to Forest Products (Harvest)	-50,200	-50,200						
Net Change in Biomass Stocks	-79,600	-62,500	187,200	37,000	43,700	-64,900	-86,700	
b) Forest Soils								
Net Detrital Inputs (prior to disturbance)	-135,600	-130,100						
Disturbance Inputs from Biomass	164,100	150,000						(2)
Disturbance Releases to Atmosphere								
Wild Fire & Insects	-16,400	-12,700						
Commercial Clearcut & Slashburn	-1,100	-1,100						
Subtotal Disturbance Releases	-17,500	-13,800						
Net Change in Forest Soil C Pools	10,900	6,000	0	0	0	0	0	

Table 2. Summary of results (continued)

c) Forest Products							
Inputs from Biomass (Harvest)	50,200	50,200					
Releases to Atmosphere	-26,600	-26,600					
Net Change in Forest Product Stocks	23,500	23,500	0	0	0	0	0
SUBTOTAL Change in Forest and Other Woody Carbon Stocks	-45,200	-33,000	187,200	37,000	43,700	-64,900	-86,700
2. Effects of Land Conversion							
On-Site Burning			*-200*	-200	*-200*	*-200*	*-200* (3)
Off-Site 'Burning' (includes transfers to forest products)			*-300*	-300	*-300*	*-300*	*-300* (3)
Decay of Aboveground Biomass (includes ongoing effects of past conversions)			*0*	0	*0*	*0*	*0* (3)
Release of Soil Carbon (includes ongoing effects of past conversions)			*-3,600*	-3,600	*-3,600*	*-3,600*	*-3,600* (3)
SUBTOTAL Effect of Land Conversion	0	0	-4,100	-4,100	-4,100	-4,100	-4,100
3. Effects of Land Abandonment							
Annual C Uptake in Aboveground Biomass			*1,100*	1,100	*1,100*	*1,100*	*1,100* (3)
Annual C Uptake in Soils			*1,200*	1,200	*1,200*	*1,200*	*1,200* (3)
SUBTOTAL Effect of Land Abandonment	0	0	2,300	2,300	2,300	2,300	2,300
TOTAL Annual Carbon Flux from Land Use Change & Forestry	**-45,200**	**-33,000**	**185,400**	**35,200**	**42,000**	**-66,700**	**-88,500**

Notes:
1) Values for IPCC Inventories are net of commercial timber removed in forest land conversion.
2) The IPCC National Inventory accounts elsewhere for C transfers due to harvesting, but does not account for natural disturbances.
3) Values in italics have been borrowed from the IPCC National Inventory, and were not re-calculated for the alternative inventories.

improved farmland in each of Canada's 10 political provinces, in 1986 and in 1991 (*e.g.*, Statistics Canada, 1992). The area of land in each province that was urbanized between 1981 and 1986, was obtained from Warren *et al.* 1989, and Environment Canada (unpublished data, 1996). These data were broken down according to whether the land was 'wooded', 'cropland or improved grassland', 'unimproved grassland', or already degraded before conversion.

The carbon content of grassland soils was estimated from the average amount of organic soil carbon in the Canadian grassland Ecoclimatic Province (Tarnocai, 1996). The average current soil carbon content of improved cropland in Canada was calculated from data in Dumanski, *et al.* (1996). This source also provided data to calculate the average proportion of soil carbon lost on all improved Canadian croplands since cultivation began.

3. Results

Table 2 shows the annual average carbon fluxes due to land use change and forestry that were estimated for each flux inventory for the period 1985 to 1989. The shaded boxes in this table indicate where each flux inventory methodology fails to account for a particular carbon flux. Spaces that have been left blank indicate that the flux in question is accounted for elsewhere in the inventory. Net uptake of atmospheric carbon (an increase in C storage) is represented as a positive flux, and net emission as a negative flux. The flux inventory totals are compiled by summing the bolded sub-totals in each column.

The different flux inventory methodologies yield widely different results (Table 2). The average annual carbon flux attributed to "Land Use Change and Forestry" varies from 185,400 kt carbon (a net sink) to -88,500 kt carbon (a net source). The effect of varying the inventory assumptions may be seen by considering first the IPCC Default flux inventory, and then successively adding different inventory components.

The IPCC Default flux inventory (III), which followed all the guideline's suggested procedures and employed the suggested default parameter values, produced the most extreme estimate of net carbon flux. Under this flux inventory, it was estimated that Canada's forests served as a net sink for atmospheric carbon during the inventory period, removing an average of 185,000 kt C per year. That this inventory produced the most extreme flux estimate is primarily because the IPCC guidelines' default growth rates are much larger than the average rates calculated by the CBM-CFS2. The IPCC default parameters also result in a larger estimate of the total amount of biomass affected by commercial harvesting (because the value used to convert harvest volume to affected biomass is larger than the CBM-CFS2), but the difference does not offset the increase in the estimated growth rates.

Replacing the default parameter values with more nationally appropriate values derived from the CBM-CFS2, as was done in the IPCC National inventory (IV), reduced the estimated net flux to an annual removal of 35,000 kt carbon.

Accounting for root biomass carbon, as in the IPCC +Roots inventory (V), increased the estimated net removal to 42,000 kt carbon per year.

On the other hand, accounting for the impacts of natural disturbances, as in the IPCC + Disturbances inventory (VI), reversed the sign of the net flux resulting in an estimated net *emission* of 67,000 kt C per year. The two CBM inventories, which also account for natural disturbances, also produced a final estimated net emission; in contrast, the three inventories that fail to account for natural disturbances (the IPCC Default, National, and +Roots inventories) all predict a net C uptake in the forest sector.

When natural disturbances were considered, accounting also for root biomass (as in the IPCC +Roots +Disturbances inventory; VII) increased the estimated emission by 22,000 kt C per year to a net flux of -89,000 kt C per year. In comparison, the CBM Base inventory (I) estimate of the net carbon flux of Canada's forest sector during this period was only -45,000 kt C per year. The difference between this value and the -89,000 kt C flux estimated by inventory VII is primarily due to accounting for C storage in soils and forest products. The CBM-CFS2 estimated that the amount of C stored in Canadian forest products worldwide increased by an average of 23,000 kt C per year, while the amount of carbon stored in forest soils in Canada increased by 11,000 kt C per year. The remaining rather minor difference between the two flux inventories, about 10,000 kt C per year, reflects the combined influence of accounting for domestic fuelwood use (an estimated maximum annual emission of 8,000 kt C), the effects of land-use change (a roughly estimated net annual emission of 1,800 kt C), and the growth of non-forest trees (an estimated removal of 400 kt C per year).

Some indication of the effect of including unmanaged lands in the inventories can be obtained by comparing the CBM Base (I) and Managed inventories (II). The CBM Managed inventory excludes three Ecoclimatic Provinces that have no reported commercial harvest activity and therefore likely experience little human intervention. Removing forests in the 'unmanaged' Ecoclimatic Provinces yields a 12,000 kt C reduction in the annual net emission (Table 2). This indicates that, during the inventory period, natural disturbances in these three Ecoclimatic Provinces caused a greater release of carbon than was taken up by growth. In other words, although relatively free from direct human interaction, forests in these Ecoclimatic Provinces were not in equilibrium.

Figure 2 provides a graphical illustration of the effects of adding or removing various components of the flux inventory, as just discussed.

The main differences between the CBM and IPCC inventory methodologies, and their influence on the resulting C flux inventories, are summarized in Table 3. The sign of each influence (+/-) indicates the direction of effect that adding this factor would have on the inventory. For example, including the growth of non-forest trees would increase the reported C uptake by 400 kt C per year, while including domestic fuelwood use would increase annual C emissions by 7,900 kt C.

4. Discussion

The purpose of this study was to assess how different methodologies for compiling C flux inventories may affect estimates of the net C exchange between the forest sector and the atmosphere. We emphasize that our focus is on the difference between inventories and not on the absolute values of our estimates. The differences between the seven flux inventories are the result of different assumptions about the components that are included and not because of different flux estimates for similar components

Table 3. Summary of inventory differences

Difference between IPCC and CBM-CFS2 Inventory Methodologies	Influence on Canada's C Flux Inventory (1985-1989)	Relevant Inventory Comparison
factors not accounted for in CBM-CFS2:		
• growth of non-forest trees	400 kt C / year	flux reported in the IPCC +Roots inventory
• domestic fuelwood use	-7,900 kt C / year	flux reported in the IPCC +Roots inventory
• land use change	-1,800 kt C / year	net flux from the IPCC National inventory
factors not accounted for in basic IPCC methodology:		
• root carbon	± 20 to 30% of net flux*	comparison of the IPCC National inventory with the IPCC +Roots, +Disturbances, and +Roots +Disturbances inventories
• wildfire and insect outbreaks	-101,900 kt C / year	comparison of the IPCC National and +Disturbances inventories (figure is the total transfer from aboveground biomass C)
• carbon storage in soil	10,900 kt C / year	flux reported in the CBM Base inventory (which includes belowground biomass C)
• carbon storage in forest products	23,500 kt C / year	flux reported in the CBM Base inventory (which includes belowground biomass C)
use of IPCC default parameters	150,300 kt C / year	comparison of Inventories the IPCC National and Default inventories
exclusion of 'unmanaged' lands	12,200 kt C / year	comparison of the CBM Base and Managed inventories

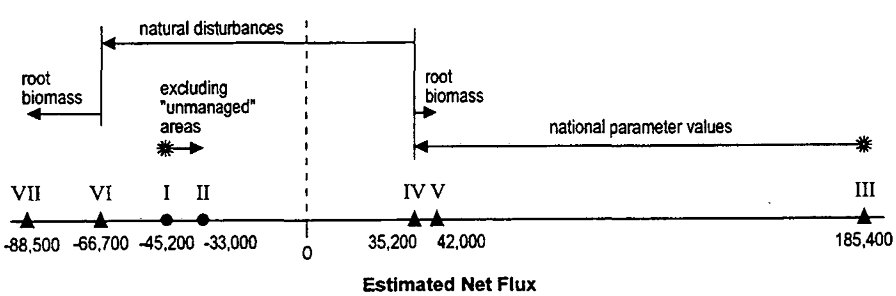

Figure 2. Effects of Changing Flux Inventory Assumptions and Parameter Values. The figure shows the net annual carbon flux of Canada's forest sector in the period 1985-1989, according to each of 7 different flux inventory methodologies. The results of the CBM-CFS2 methodology (inventories I and II) are shown with closed circles, results of modified IPCC guidelines' methodologies (inventories III to VII) are shown with triangles, and asterisks indicate the estimates produced by the base, or default, version of each methodology. The arrows connect the related CBM- or IPCC-style inventories to one another, indicating the effect of making the labelled changes to each inventory. It may be seen that successive 'refinements' do not necessarily make the resulting net flux estimate converge on a more precise value.

(with the exception of the differences between inventory III, which used default parameter values, and all other inventories).

Our results demonstrate the importance of properly defining at the outset the system for which the flux inventory is to be compiled, including all the major pools and fluxes. Flux inventories compiled following the IPCC guidelines (*i.e.*, inventories III to VII) define the forest sector solely by the amount of C stored in biomass pools. Of these, inventories III, IV, and V also discount the contribution of natural disturbances, such as fire or insects. These three inventories conclude that the forest sector in Canada was a C sink during the inventory period. The remaining four inventories account for the contribution of natural disturbances to the net flux and conclude that the forest sector was a C source during that period.

"Patching" an incomplete inventory by adding additional components can exacerbate rather than mitigate the errors of omission in the system analysis. Without accounting for natural disturbances, for example, adding root carbon to the IPCC guidelines' inventory just increased the size of the estimated sink (*i.e.*, inventory IV vs.V). Adding disturbance impacts without fully accounting for carbon storage pools can also distort the inventory results. In reality, the C contained in trees killed by insects, fire, or harvesting is not all released directly into the atmosphere but rather is added to litter and forest-product pools from where it will decompose over decades.

The period of analysis in this study (1985-1989) is the period with the largest area disturbed annually in Canada since 1920 (Kurz *et al.*, 1995), mostly because of significant wild fires. Accounting for all C affected by disturbances as if it was immediately released to the atmosphere will significantly overestimate the net flux during this period. This is why the net C emission in inventory VI is larger than that in inventory I. Note that in this case simply adding root carbon to the incomplete inventory makes the *source* estimate even larger (*i.e.*, inventory VI vs. VII).

The exclusion from flux inventories of processes that have an important influence on the C cycle, such as wildfires, misses important fluxes. Perhaps more significantly, however, it will also lead to incorrect conclusions about the role of human impacts on forest sector C cycles. Natural disturbances are common throughout the non-intensively managed circumpolar boreal forests (see also Apps and Price, 1996). Excluding C fluxes associated with natural disturbances from the flux inventories suggests that harvesting impacts are the sole reason for C losses from biomass stocks. Forest management activities are aimed at reducing natural disturbances and at harvesting some of the protected growing stock. The net impact on C fluxes therefore is the result of both reduced natural disturbances and increased harvesting. By excluding natural disturbances from the flux inventories, reductions in natural disturbances (or future increases) will go unnoticed, while any harvesting necessarily will appear as a net C emission.

A further source of error resulting from decisions on system boundaries is associated with the exclusion of forests that are not directly affected by human interactions. This exclusion appears to assume that the net C fluxes in these areas are zero (*e.g.*, see IPCC, 1995c, page 5.11 and 5.13). As shown by the comparison of flux inventories I and II, this is not the case in Canada, and will likely not be the case in any other country with significant forest areas classified as unmanaged. As before, temporal variation in natural disturbance regimes results in non-zero net C fluxes, so that even unmanaged forests may be contributing to changes in the global carbon balance. Moreover, if terrestrial ecosystems respond to the anticipated climate changes, even larger net C fluxes may result from these areas.

Thus unmanaged forests should be included in national inventories if the goal of inventory compilation is to better understand changes in atmospheric carbon levels. In any case, attempting to separate managed and unmanaged forests for the purpose of reporting C fluxes may be problematic in large, sparsely populated countries in which much forest management is non-intensive, *i.e.*, primarily localized harvesting, planting, and some suppression of natural disturbance agents. The separation between what is considered managed or unmanaged forest may be quite arbitrary.

The results of this study also show that the amount of effort spent on refining different components of national flux inventories should consider the importance of that component to the overall inventory. Not spending a lot of effort refining some inventory components may be justified in a sparsely populated boreal country such as Canada. The three factors that are included in the IPCC guidelines' inventory but excluded from the CBM inventory (*i.e.*, growth of non-forest trees, land-use change and domestic fuel wood use) together had one order of magnitude less impact than the natural disturbances that are excluded from the IPCC inventory (*e.g.*, inventory I vs. IV). Carbon storage in Canadian forest products is also a significant inventory component, with global storage increasing by 23,500 kt C per year (compared to a national net flux of -45,200 kt C per year; inventory I)—a result which suggests exceptions to the IPCC guidelines' generalization that stocks of forest products are not increasing in "most" countries (IPCC 1995c, page 5.16).

The IPCC Guidelines were developed to permit the compilation of forest sector C fluxes in all countries, even where the available data are limited. While we appreciate the reason for this decision, we caution that flux inventories that are designed on the basis of data availability may lead to incorrect conclusions. Instead, we suggest that inventories should be based on a systems analysis of all major pools and C fluxes. Only flux inventories that are complete in this way can provide reliable estimates of net atmospheric carbon exchange.

In the Canadian situation, the prior existence of the Carbon Budget Model of the Canadian Forest Sector, and the detailed national forest biomass inventory which it uses, made it possible to compile all of the inventories presented here at negligible additional cost. Once constructed, models such as the CBM-CFS2 are the most cost-effective means possible to update national inventory data to the desired flux inventory period and obtain appropriate, age-dependent average forest growth rates and disturbed-biomass estimates for use in the inventory.

Where the appropriate modelling tools and national forest databases are not available, it will be much more expensive to compile national C flux inventories as detailed as those that are summarized in this paper. The cost may in fact be prohibitive. While this suggests that it will not be possible to compile equally *detailed* and *precise* inventories in all countries, it need not justify the reporting of inventories based on only a partial consideration of the system. Instead, we recommend that a preliminary systems analysis be used to prioritize the allocation of resources to inventory compilation. As we have shown here, the reliability of an inventory may be much more heavily influenced by which fluxes are included than by the precision with which included fluxes are measured (*e.g.*, the influence of natural disturbances and carbon storage on the Canadian inventory is much greater than the influence of any likely inaccuracies in the estimates of land-use change and the growth of non-forest trees). A more reliable inventory will be constructed by including rough estimates of all *nationally-significant* C fluxes than by including precise estimates of some less- significant fluxes. Whatever resources are available for C flux inventory compilation in each nation should be allocated accordingly.

5. Conclusions

The seven flux inventories compiled in this study produced net C flux estimates that varied from net emissions to net uptake over a range of 274,000 kt C per year. The five C flux inventories based on the IPCC guidelines started with the suggested default assumptions and increased in complexity as components were added to account for additional C fluxes. Significantly, however, the estimates thus obtained did not converge towards a unique value.

These results emphasize four major conclusions: (1) C flux estimates for a national forest sector should be based on a comprehensive systems analysis of all major C pools and fluxes involved; (2) excluding components from the inventory may lead to significant discrepancies between the estimated and the actual C fluxes; (3) natural disturbances can have significant impacts on C flux estimates in managed forests and should therefore be included in the C flux inventories; and (4) even forests that are considered to be not directly affected by human impacts can make a significant contribution to the net flux estimates and arguably should be included in the C flux inventories.

Carbon flux inventories that are based on a systems analysis approach will include those components of the C cycle that are expected to make the largest contributions to the net fluxes in the inventory. Similarly, the allocation of effort to inventory refinements should be based on sensitivity analyses of the uncertainties in each component of the inventory. For example, the CBM-CFS2 does not include C flux estimates of either peatlands or land-use change. Estimates of C fluxes in peatlands; however, are both much larger and have greater absolute uncertainty than estimates of C fluxes due to land-use change. Improvements of the existing inventory should be focussed accordingly.

The reporting of C fluxes due to forestry and land-use change within the IPCC framework must be based on a common set of assumptions and methodologies that account for all major C fluxes. The inventory methodologies must be well documented if meaningful comparisons are to be made among national inventories.

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INTERNATIONAL WORKSHOP ON SUSTAINABLE FOREST MANAGEMENT: MONITORING AND VERIFICATION OF GREENHOUSE GASES FLOWS

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PARTICIPANT LIST

Marcos Adamson Badilla
Instituto de Investigaciones en Ciencias Económicas,
Universidad de Costa Rica
Apdo. 2060-San Pedro, San José
Costa Rica
Phone: 506-207-4166/224-3682

Marielos Alfaro M.
FUNDECOR
Apdo. 549-2150 Moravia
San José, Costa Rica
Phone: 506-240-2624, Fax: 506-297-1044
E-mail: fundecor@sol.racsa.co.cr

Eduardo Andrade M.
Corporación de Fomento Ganadero
Apartado 6378-1000 San Jose, Costa Rica
Phone: (506) 232-9355 / 232-1503 / 223-1949
Fax: (506) 223-2029 / 232-2086

Mike Apps
Forestry Canada
Northen Forestry Center
5320-122 St.
Edmonton, Alberta T6H 3S5 Canada
Phone: 1-403-435-2305, Fax: 1-403-435-2359
Email: mapps@nofc.forestry.ca

Xavier Baulies Bochaca
Department of Remote Sensing
Cartographic Institute of Catalunya
Barcelona 08038, Spain
Phone: 34-3-425-2900, Fax: 34-3-426-7442
E-Mail: xavierb@icc.es

José Joaquín Campos A.
CATIE
(Unit of Natural Forest Management)
Apdo. 7170 Turrialba, Costa Rica
Phone: 506-556-0401
E-mail:jcampos@catie.ac.cr

Max Campos
Comité Regional Recursos Hidráulicos
Proyecto Centroamericano Cambio Climático
Apartado 21-2300
San Jose, Costa Rica
Phone: 506-2315791 / 296-4641
Fax: 506-296-0047
E-Mail: crrhcr@racsa.sol.co.cr

Liza Carter
Climate Change Policy Division
Environmental Protection Agency (EPA)
Washington D.C., USA
Phone: 1-202-260-2761, Fax: 1-202-260-6405

Ana Rita Chacón A.
Oficina Costarricense de Implementación Conjunta
Edificio CINDE, San Jose, Costa Rica
Phone: 506-220-0036 Fax: 506-290-1238
E-mail: ocicgm@sol.racsa.co.cr

José Joaquín Chacón
Comité Regional Recursos Hidráulicos
Proyecto Centroamericano Cambio Climático
Apdo. 21-2300 Curridabat
Phone: 506-231-5791 / 296-4641
Fax: 506-296-0047
E-mail: crrhcr@racsa.sol.co.cr

Noel Cutright
Wisconsin Electric Power Co.
333 W Everett (A539)
Milwaukee, WI 53203,USA
Phone: 1-414-221-2179, Fax: 1-414-221-2169
E-Mail: Noel.Cutright@wemail.wisenergy.com

Selvadurai Dayanandan
University of Massachusetts, Boston
Boston, MA, USA
Fax: 1-617-287-6650
E-Mail: dayanandan@umbsky.cc.umb.edu

Philip Fearnside
Insitute for Research in the Amazon
Manaus, Brazil
Phone: 5-592-642-2918 Fax: 5-592-236-3822
E-Mail: pmfearn@cr-am.rnp.br

Beth Goldberg
Lawrence Berkeley National Laboratory
MS90-4000
1 Cyclotron Road
Berkeley, CA 94720, USA
Phone: 1-510-486-7081 Fax: 1-510-486-6996
E-Mail: b_gocd@dante.lbl.gov

Marco Antonio González
Vice-Ministro
Ministerio del Ambiente y Engía (MINAE)
Apdo. 10104 San José, Costa Rica
Phone: 506- 257 5658, Fax: 506- 222 4580

Adalberto Gorbitz
Oficina Costarricense Implementación Conjunta
San José, Costa Rica
Phone: 506-220-0036, Fax: 506-220-1045
E-Mail: ocicgm@sol.racsa.co.cr

Steve Hamburg
Brown University
Box 1943
Providence, RI 02912-1943, USA
Phone: 1-401-863-3449, Fax: 1-401-863-3503
E-Mail: Steven_Hamburg@Brown.EDU

Hugo Hidalgo
Director General
Instituto Meteorologico Nacional
Apdo. 7-3350-1000 San José
Costa Rica
Phone/Fax: 506-223-1837
E-mail: hidalgo@meteoro.imn.ac.cr

Catrinus Jepma
Department of General Economics
University of Groningen, P. O. Box 800
Groningen NL-9700 AV
The Netherlands
Fax: 31-50-363-7337

Ben de Jong
ECOSUR
Carretera Panamericana y Periférico Sur s/n
San Cristóbal de las 29200, México
Phone: 52-967-81883 ext.146
Fax: 52-967-82322
E-Mail: bjong@sclc.ecosur.mx

Markku Kanninen
CATIE
Apdo. 7170 Turrialba, Costa Rica
Phone: 506-556-1754, Fax: 506-556-6255
E-mail:kanninen@catie.ac.cr

Sadí Laporte M.
Instituto Costarricense Electricidad (ICE)
Departamento de Estudios Básicos
Apdo. 10032 San José, Costa Rica
Phone: 506-220-7309

Carlos León Pérez
CATIE
Apdo. 259-7150 Turrialba, Costa Rica
Phone: 506-556-1662
E-mail:cleon@catie.ac.cr

Cynthia Loría Picado
Instituto Tecnológico Costa Rica
Ingeniería Forestal
250 Sur Centro Nutrición San Nicolás
Cartago, Costa Rica
Phone: 506-551-8503 / 591-0180

Oscar Lucke
Universidad de Costa Rica
Apdo. 569-2070 San José, Costa Rica
Phone: 506-283-9298, Fax: 506-253-0991
E-mail: olucke@cariari.ucr.ac.cr

Ken MacDicken
Winrock International Institute
11030 159th Avenue, SE
Snohomish, WA 96290, USA
Phone: 1-360-568-7005
Fax: 1-360-568-2712
E-Mail: KM@msmail.winrock.org

Willy Makundi
Lawrence Berkeley National Laboratory
MS 90-4000, 1 Cyclotron Road
Berkeley, CA 94720, USA
Phone: 1-510-486-6852
Fax: 1-510-486-6996
Email: wrmakundi@lbl.gov

Pablo Manso
Instituto Meteorologico Nacional
Apdo. 7-3350-1000 San José, Costa Rica
Phone/Fax: 506-223-1837
E-mail: hidalgo@meteoro.imn.ac.cr

Gregg Marland
Environmental Science Division
Oak Ridge National Laboratory
P. O. Box 2008, Bldg. 1000
Oak Ridge, TN 37831-6335, USA
Phone: 1-423-241-4850, Fax: 1-423-574-2232
E-Mail: gum@ornl.gov

Stephen M. Petricone
Oficina Costarricense Implementación Conjunta
Edificio CINDE
San José, Costa Rica
Phone: 506-220-0036, Fax: 506-220-1045
E-Mail: spetrico@sol.racsa.co.cr

Michelle Pinard
University of Florida/Proyecto Balfor
Pronlogacion Beni#149, Casilla #6204
Santa Cruz, Bolivia
Phone: 591-336-4704, Fax: 591-336-4319
E-Mail: michell@mitai.nrs.net.bo

Jorge Edo. Rodríguez V.
Ministerio del Ambiente y Encgía (MINAE)
Apdo. 10104 San José, Costa Rica
Phone: 506-257-5658, Fax: 506-222-4580

Marianne Sagbom
Finish Meterological Institute
Apdo. 503,FIN 00101 Helsinki, Finland
E-Mail: marianne.sagbom@fmi.fi

Arturo Sánchez
CIEDES-Universidad de Costa Rica
Comité Regional Recursos Hidráulicos
Proyecto Centroamericano Cambio Climático
Apartado 21-2300, San Jose, Costa Rica
Phone: 506-231-5791 / 296-4641
Fax: 506-296-0047
Email: arturos@cariari.ucr.ac.cr

Jayant Sathaye
Lawrence Berkeley National Laboratory
MS90-4000, 1 Cyclotron Road
Berkeley, CA 94720, USA
Phone: 1-510-486-6294
Fax: 1-510-486-6996
E-Mail: jasathaye@lbl.gov

KD Singh
United Nations Food and Agriculture Organization
(UN-FAO)
Viale delle Terme de Caracalla
Rome 00100, Italy
Phone: 396-522-82960, Fax: 396-596-02863

David Skole
Institute for the Study of Eart, Oceans, & Space
University of New Hampshire
Durham, NH 03824, USA
Phone: 1-603-862-1804, Fax: 1-603-862-0188
E-Mail: dave@igapo.unh.edu

Claudia Solera M.
Instituto Costarricense de Acueductos y
Alcantarillado
Calle 5, Av. Central y 1era.
Edif. La Yacuna, San Jose, Costa Rica
Phone: 506-222-8436

Tom Sullivan
New England Power Service
25 Research Drive
Westborough, MA 01582-0099, USA
Phone: 1-508-389-9086, Fax: 1-508-389-9176
E-Mail: SULLIT@neesnet.com

Franz Tattenbach
Oficina Costarricense Implementación Conjunta
Edificio CINDE
San José, Costa Rica
Phone: 506-220-0036, Fax: 506-220-1045

Daan Van Soest
Department of General Economics
University of Groningen
P. O. Box 800
Groningen NL-9700 AV The Netherlands
Fax: 31-50-363-7337
E-Mail: D.P.van.Soest@eco.rug.nl

Eladio Zárate H.
Secretario Ejecutivo
Comité Regional Recursos Hidráulicos
Apdo. 21-2300 Curridabat
San Jose, Costa Rica
Phone: 506-231-5791 / 296-4641
Fax: 506-296-0047
E-mail: crrhcr@racsa.sol.co.cr

ERNEST ORLANDO LAWRENCE BERKELEY NATIONAL LABORATORY
ONE CYCLOTRON ROAD | BERKELEY, CALIFORNIA 94720

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