

# Reliable forest carbon monitoring – systematic reviews as a tool for validating the knowledge base

G. PETROKOFISKY<sup>1</sup>, P. HOLMGREN<sup>2</sup> and N.D. BROWN<sup>1</sup>

<sup>1</sup>*Department of Plant Sciences, University of Oxford, Oxford OX13RB*

<sup>2</sup>*Natural Resources Department, Food and Agriculture Organization of the United Nations, Rome, Italy*

Email: Gillian.petrokofisky@plants.ox.ac.uk, peter.holmgren@fao.org and nick.brown@plants.ox.ac.uk

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## SUMMARY

With global carbon credits valued at over US\$100 billion/year, accounting under REDD will drive demand for high quality forest monitoring systems. The choice of system to adopt should be guided by good science. The adequacy and comparability of different national systems for forest carbon measurement under REDD have not been fully evaluated. There is a growing body of scientific and technical information on ground-based and remote-sensing methods of carbon measurement. This extensive, often conflicting, knowledge base has not been systematically reviewed in the transparent, readily-repeatable manner consistent with evidence-based practice. This paper argues that such an approach, regarded in medicine as the gold standard for evidence evaluation, is long overdue in forestry generally and carbon monitoring and assessment specifically. Preliminary findings from an international project set up to scope the potential for a systematic review approach indicate that this evidence-based approach would add value to REDD implementation.

Keywords: Evidence-based forestry, systematic reviews, REDD; carbon assessment

## Surveillance fiable du carbone forestier: rapports systématiques en tant qu'outil pour valider la base de connaissances

G. PETROKOFISKY, P. HOLMGREN et N.D. BROWN

Alors que les crédits du carbone global sont évalués à plus de 100 milliards de \$ US par an, la comptabilité sous l'égide de la REDD va pousser la demande pour des systèmes de gestion forestière de haute qualité. Le choix de système à adopter devrait être guidé par une science fiable. La nature adéquate et la comparabilité de différents systèmes nationaux de relevés de mesures du carbone forestier dans le cadre de la REDD n'ont pas été pleinement évalués. Une masse croissante d'information technique et scientifique a vu le jour, basée sur des méthodes de prises de mesure du carbone sur le terrain et à l'aide de détecteurs à distance. Cette base de connaissances étendue, et souvent conflictuelle, n'a pas encore été observée de la manière transparente et facilement renouvelable allant de pair avec la pratique factuelle. Cet article propose qu'une telle approche, considérée comme le nec plus ultra de l'évaluation des preuves en médecine, a déjà trop tardé à avoir été adoptée dans le secteur de la foresterie en général, et dans l'évaluation et la gestion du carbone en particulier. Des découvertes préliminaires provenant d'un projet international créé pour évaluer le potentiel d'une approche d'étude systématique indique que cette approche factuelle ajoutait de la valeur à la mise en pratique de la REDD.

## Un monitoreo fidedigno del carbono forestal – las revisiones sistemáticas como herramienta para validar de la base de conocimientos

G. PETROKOFISKY, P. HOLMGREN y N.D. BROWN

Puesto que el valor global de los créditos de carbono excede los 100 mil millones de dólares por año, la aplicación de la REDD impulsará la demanda de sistemas de monitorización forestal de alta calidad. La elección del sistema a adoptar debería tener una buena base científica. La idoneidad y comparabilidad de los diferentes sistemas usados a nivel nacional para medir el carbón forestal bajo la REDD no ha sido evaluada en su totalidad. Sin embargo cada vez es mayor la información científica y técnica disponible sobre los métodos de medición del carbono en el terreno y a distancia. Este extenso, y a veces contradictorio, conocimiento base no se ha revisado de una forma sistemática, de la manera transparente y fácilmente repetible que conviene para las prácticas basadas en la evidencia. Este artículo plantea que dicha aproximación, considerada en medicina como el método de referencia para la evaluación de la evidencia, hace tiempo que se necesita en el campo de la silvicultura en general y en la monitorización y evaluación del carbono en particular. Los resultados preliminares de un proyecto internacional establecido para evaluar el potencial de un enfoque sistemático de revisión indican que este método basado en la evidencia añadiría valor a la puesta en marcha de la REDD.

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## INTRODUCTION

Tropical forests cover about 15% of the world's land surface (FAO 2006) and contain some 25% of the carbon in the terrestrial biosphere (Bonan 2008). Deforestation and forest degradation are estimated to be responsible for almost 20% of the world's total greenhouse gas emissions (Gullison *et al.* 2007, Van der Werf 2009). Although emitting substantially less carbon dioxide than electricity and heat generation and transport, which together account for two-thirds of global carbon dioxide emissions (OECD, 2010), agriculture, forestry, and land use changes represent a significant source of atmospheric CO<sub>2</sub>. In his Review of the economics of climate change Lord Nicholas Stern said,

“without prompt action emissions from deforestation between 2008 and 2012 are expected to total 40Gt CO<sub>2</sub>, which alone [is] greater than the cumulative total of aviation emissions from the invention of the flying machine until at least 2025.”

Some 13 million hectares of forest are converted to other land uses each year (FAO 2006). Current deforestation in Indonesia and Brazil releases carbon equal to four-fifths of the annual reduction target for Annex I countries of the Kyoto Protocol (Santilli *et al.* 2005). Forests, carbon emission and climate change are all firmly linked in the public's eye.

Although the 1997 Kyoto Protocol permitted emissions trading it did not sanction the use of reduced deforestation as a carbon emission reduction project in non-Annex I countries. It was not until the 15th Conference of the Parties at Copenhagen in December 2009 that details of a mechanism for Reduced Emissions from Deforestation and Degradation (REDD) were defined within the United Nations Framework Convention on Climate Change (UNFCCC). For developing countries, REDD and REDD<sup>+</sup> could include mitigation actions through reduced rates of deforestation or forest degradation, but also through sustainable forest management, conservation of forest ecosystems and enhancement of forest carbon stock, for example on degraded land. The REDD+ instrument, as agreed in Cancún, Mexico at COP-16 of the UNFCCC in December 2010<sup>2</sup>, will alter the situation for developing countries. It includes the implementation of five mitigation actions:

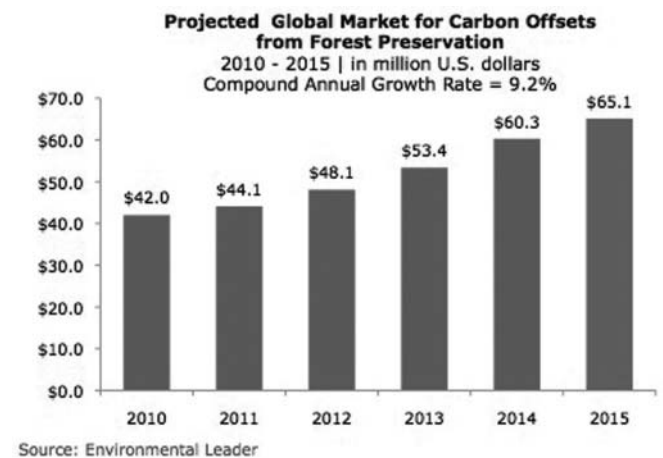
- Reducing emissions from deforestation;
- Reducing emissions from forest degradation;
- Conservation of forest carbon stocks;
- Sustainable management of forest; and
- Enhancement of forest carbon stocks.

All forest resources in developing countries are potentially subject to accountable mitigation actions. Such actions would

be rewarded to their value of tons of carbon mitigated. The Cancún Agreements also stipulate that robust and transparent national monitoring systems of these mitigation activities should be developed. In order to implement REDD+ successfully, it will be crucial to determine the spatio-temporal variation of carbon stocks. Obtaining field measurements and developing estimation models to do so is an expensive and time-consuming task.

With credits globally valued at US\$126 billion in 2008 (up from \$31 billion in 2006) (Capoor and Ambrosi 2009) and the global forest carbon offset market projected to grow from \$42.0 million in 2010 to \$65.1 million in 2015 (Figure 1), carbon credit accounting under REDD brings into sharp focus the current poor performance of national forest monitoring systems (Holmgren and Marklund 2007) and the necessity of adopting carbon monitoring and assessment methods that are reliable and based on sound science.

FIGURE 1 *Projected global market for forest carbon offsets from forest preservation. Source: environmentalleader.com*



There has been no systematic analysis of the relative levels of accuracy, precision or comparability of the wide range of methods used to assess and measure forest carbon. There are now over 600 scientific papers published each year on topics of relevance to measuring carbon in forests, too many for even subject specialists to be able to read and understand. Contradictory results and questionable methods threaten to delay or damage the credibility of attempts to negotiate a workable REDD mechanism.

When confronted with the twin challenges of a large volume of evidence and conflicting findings, the worlds of medicine and social policy use robust reviewing tools to bring order to the chaos. Medicine pioneered the use of systematic reviews over a decade ago as an essential component of

<sup>1</sup> REDD + is understood to be: “policy approaches and positive incentives on issues relating to reducing emissions from deforestation and forest degradation in developing countries; and the role of conservation, sustainable management of forests and enhancement of forest carbon stocks in developing countries” (UNFCCC 2007).

<sup>2</sup> <http://unfccc.int/2860.php>

evidence based medicine (Sackett *et al.* 1996); they are now considered to be the ‘gold standard’ for evidence (Figure 2) not only in medicine and public health, but also in many areas of social science, notably education, crime and justice and social welfare (Petticrew and Roberts 2006) and, more recently, nature conservation (Pullin & Knight 2009).

This paper describes a methodological and analytical framework for developing an evidence-based approach to the issue of forest carbon monitoring, which can serve as a model for wider use in forestry and natural resource management where decision-making must take account of diverse scientific findings.

## EVIDENCE BASED FRAMEWORKS

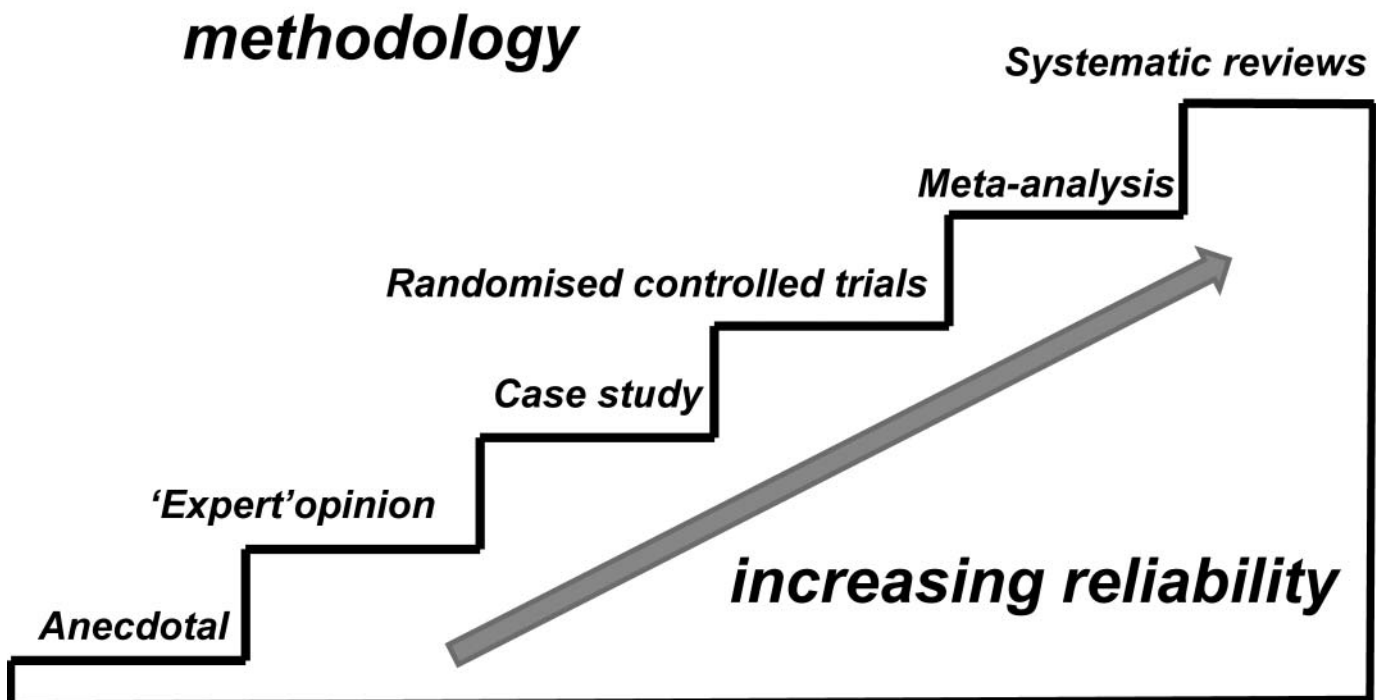
Evidence-based frameworks evolved from evidence-based medicine and have three key elements: the question; the systematic review of evidence; and active dissemination of results (Figure 3). The participatory nature of these frameworks for

all phases from question framing to active distribution of results in appropriate formats for different audiences is highly relevant to the issue of forest carbon monitoring under a REDD+ scheme.

The role of systematic reviewing as a potentially powerful tool to aid good decision-making is poorly understood in the forestry community and there have been very few reviews completed. However, the call for evidence-based policy continues to grow and terms like ‘evidence-based policy’ are used freely, largely without definition, in the literature. The number of peer-reviewed environmental science papers containing the phrase ‘evidence-based’ in the title or abstract of the paper grew from fewer than 50 in 2000 to over 350 in 2008 (Petrokofsky and Mills 2009). With the exception of a small number of papers published in association with the Collaboration for Environmental Evidence, which promotes Cochrane-style systematic reviews<sup>3</sup>, none of these publications employed a transparent method of weighing evidence, which is a pre-requisite for a study to be termed ‘evidence-based’ in medicine.

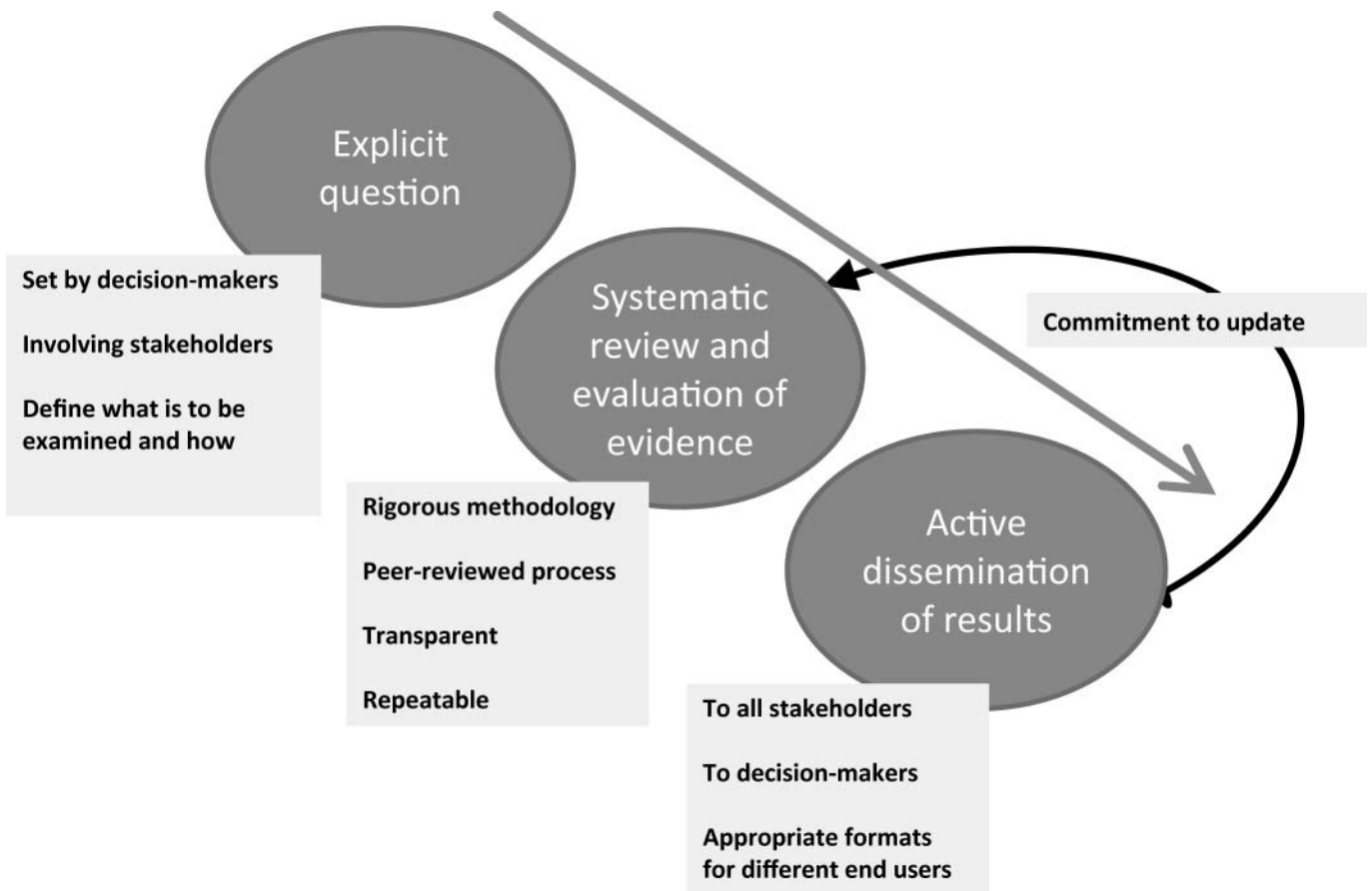
FIGURE 2 A hierarchy of evidence showing increasing reliability of evidence in a progression from anecdotal evidence as generally the least reliable to systematic reviews as generally the most reliable

# A Hierarchy of Evidence



<sup>3</sup> <http://www.environmentalevidence.org/>

FIGURE 3 Evidence framework for decision-making



Without unbiased evaluation of the best available evidence, there cannot be genuine evidence based practice. Given that very few systematic reviews exist in forestry, there is a real danger that talk of ‘evidence-based decision making’ is a gross deception. This has potentially serious implications for acceptance by the wider public, particularly where science is invoked as a justification for policy action.

Public loss of trust in science is a subject which periodically comes to the fore and has deep roots and a long history (Wynne 2006). The issue has resurfaced recently with widespread commentaries on the IPCC and its handling of science (Nature 2010, IPCC 2007). It could be argued that some of the weaknesses of the IPCC processes identified by the five climate scientists who discuss possible reforms could be addressed by the adoption of evidence-based frameworks for an issue for which, like forest carbon monitoring, “facts are uncertain, values in dispute, stakes high and decisions urgent” (Funtowicz and Ravetz 1990). Two of the five excerpts serve to illustrate this:

*“Rather than comprehensive reports every six years, this panel [Global Science Panel – one of suggested groups to replace the IPCC] would commission, on a rolling basis, a larger number of smaller, sharply focussed syntheses of knowledge on fast-moving topics that have great scientific or policy salience” (Hulme 2010);*

*“ICA [International Climate Agency – a suggested stronger, more independent version of the IPCC] reports should be independently reviewed in a transparent process, draw only on established, peer-reviewed literature, and highlight research gaps.” (Zorita 2010).*

#### APPLYING AN EVIDENCE-BASED APPROACH TO CARBON ASSESSMENT

REDD finance based on accurate and verifiable carbon assessment is highly likely to be the subject of a great deal of public scrutiny not only of governance but also of the science behind the figures.

At an initial Workshop held in FAO headquarters in March 2009, it was agreed that an international participatory initiative should be undertaken to scope the potential for using an evidence-based approach to validate the knowledge base on carbon monitoring methods. A project contact group of 50 people was chosen to represent a range of organizations with academic, policy, consultancy and/or training focus in different countries.

The contact group participated in iterative discussions (mostly by email and telephone) to develop a shared understanding of the problems which need to be addressed and

to develop a series of possible review topics. In addition to discussions the group shared knowledge, mainly published papers but also ‘grey literature’ (project reports and discussion documents), which contributed to an understanding of the potential scope of the review. The review topics were further developed by two scoping groups (one meeting in person and the other via a teleconference) during the Bonn climate change meetings in June 2009.

Outputs from this first phase of the project were the development of explicit review questions, and a preliminary evaluation of the existing evidence base that could provide scientific underpinning for these questions. In order to frame review questions precisely, a clear understanding of all the components of forest carbon assessment was developed.

## A FRAMEWORK FOR MEASURING FOREST CARBON

This framework defines components of forest carbon measurements, as a starting point for an investigation into reliable carbon monitoring. It builds on experiences from national forest inventories (Ranneby *et al.* 1987) and remote sensing technology (Foody and Cutler 2003; Goetz *et al.* 2009) and takes into account the suggestions in the IPCC Good Practice Guidance for Land Use, Landuse change and Forestry (Penman *et al.* 2003).

The framework defines the components of a national assessment of carbon stock, then extends this to change-assessment between two points in time.

### 1. Assessment of C within area *a* at time *t* ( $C_{at}$ )

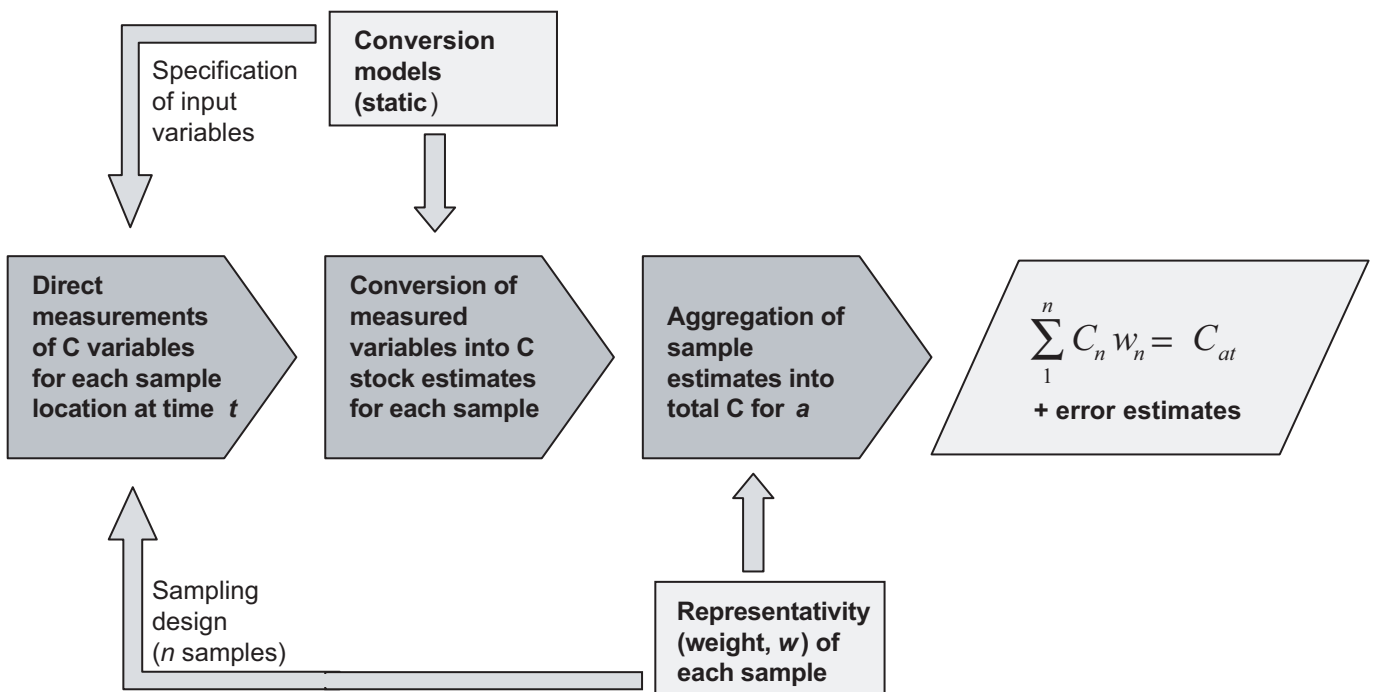
For efficiency and non-destructive reasons, direct measurements must be made on proxy variables, such as tree diameter and height, that are applied in conversion models to estimate the carbon stock at the measured location, for the set of carbon pools considered, in this case the five terrestrial pools<sup>4</sup> identified by the IPCC (Penman *et al.* 2003). For efficiency reasons, measurements are normally made at sample locations and not for the entire area in question.

The measurement process (Figure 4) can therefore be described by three independent but interlinked components – actual measurements, conversion models and statistical representation. Each of these components contributes to assessment errors, and also incurs costs. Further to the direct measurement costs, the cost (and time) required to establish conversion models and design the measurement sample must be considered.

### 2. Change assessment within area *a* between $t_1$ and $t_2$ ( $\Delta C_{at,2}$ )

Measuring change introduces additional challenges. Two generic alternatives are:

FIGURE 4 Process for assessing carbon stock for an area *a* at time *t*



<sup>4</sup> Above-ground biomass, Below-ground biomass, Deadwood, Litter, Soil (including peat).

- i. to measure at two points in time and calculate the difference
- ii. to measure once and use modelling to estimate the change

(i) *Changes between independent measurements*

Building on (1), the change of C can be expressed simply as the difference between independent assessments at  $t_2$  and  $t_1$ , i.e.  $C_{at_2} - C_{at_1}$ . This will provide the net change of the carbon pool in question for  $a$  as a whole.

However, there may be requirements for determining 'gross changes' between carbon pools, i.e. the overall gains and losses from/to each pool, resulting in a change matrix. Further, there may be demand for measuring carbon changes in a spatially explicit manner, i.e., the gains and losses for defined area fractions over the overall territory. These approaches are similar in the sense that changes need to be assessed individually for a number ( $n$ ) of sub-areas (samples) that constitute a complete and non-overlapping representation of  $a$ , such that:

$$\Delta C_{at_{1,2}} = \sum_1^n (C_{a_n t_2} - C_{a_n t_1})$$

Noting that:

- $n=1$  is a special case expressing net change for  $a$  as a whole;
- very large  $n$  can be exemplified by a set of permanent national forest inventory plots, a complete set of land properties in a country, or a 'wall-to-wall' set of remote sensing observations, for which time series of carbon assessments can be provided and added up to totals for  $a$ ;
- the concept of 'gross changes' is related to the scale of measurement, i.e. the sizes of  $a_n$ . For large sized  $a_n$ , internal losses and gains may occur, but would not be recorded. Consequently, recorded gross changes will be larger when smaller units are considered in the assessment.

(ii) *Modelling changes based on one carbon stock assessment*

An alternative to independent measurements over time builds on having only one measurement of carbon stock at  $t_1$ , and then applying a dynamic model to estimate the stock at  $t_2$ . The estimate can be for past as well as future changes.

Direct measurement or observation of change may also improve assessment of  $\Delta C_{at_{1,2}}$  also without adding new assessment of the carbon stock *per se*.

This includes in particular remote sensing options for (a) estimating changes in signals that can be directly correlated to biomass/carbon pools, (b) reassigning weights to individual measurements through post-stratification approaches.

Developing this detailed conceptual framework provided a very robust means of 'unpacking' broad questions about carbon assessment and clarifying precisely what evidence in the published literature would need to be reviewed to provide

scientific underpinning for the development of credible national systems of monitoring and assessment.

## THE EXISTING EVIDENCE BASE ON FOREST CARBON MONITORING

There is a growing body of scientific and technical information on ground-based and remote sensing methods of forest carbon monitoring. Figure 5 shows the growth of literature reporting on topics of relevance to elements of the processes outlined in the framework for carbon measurement above (Figure 4).

Three bibliographic database which systematically index academic articles on natural resources research are Web of Science (<http://isiwebofknowledge.com>), Scopus (<http://www.info.scopus.com>) and CAB Abstracts (<http://www.cabi.org>). There is a large amount of duplication between the databases, but they have different strengths for applied natural resources research and operate independent selection policies. A preliminary search was conducted in each of these databases to determine the volume of literature that could potentially be included in the knowledge base which supports decision-making for carbon stock monitoring in REDD<sup>5</sup>. All three databases show a knowledge base currently containing over 5000 articles, which has been growing at the rate of over 600 articles per year since 2007, and shows no sign of abating.

In addition to the large volume of scientific literature which already exists and the growing volume which is being added each year, there are conflicting findings and discrepancies in methodologies which add to the difficulties of interpretation and consensus-building.

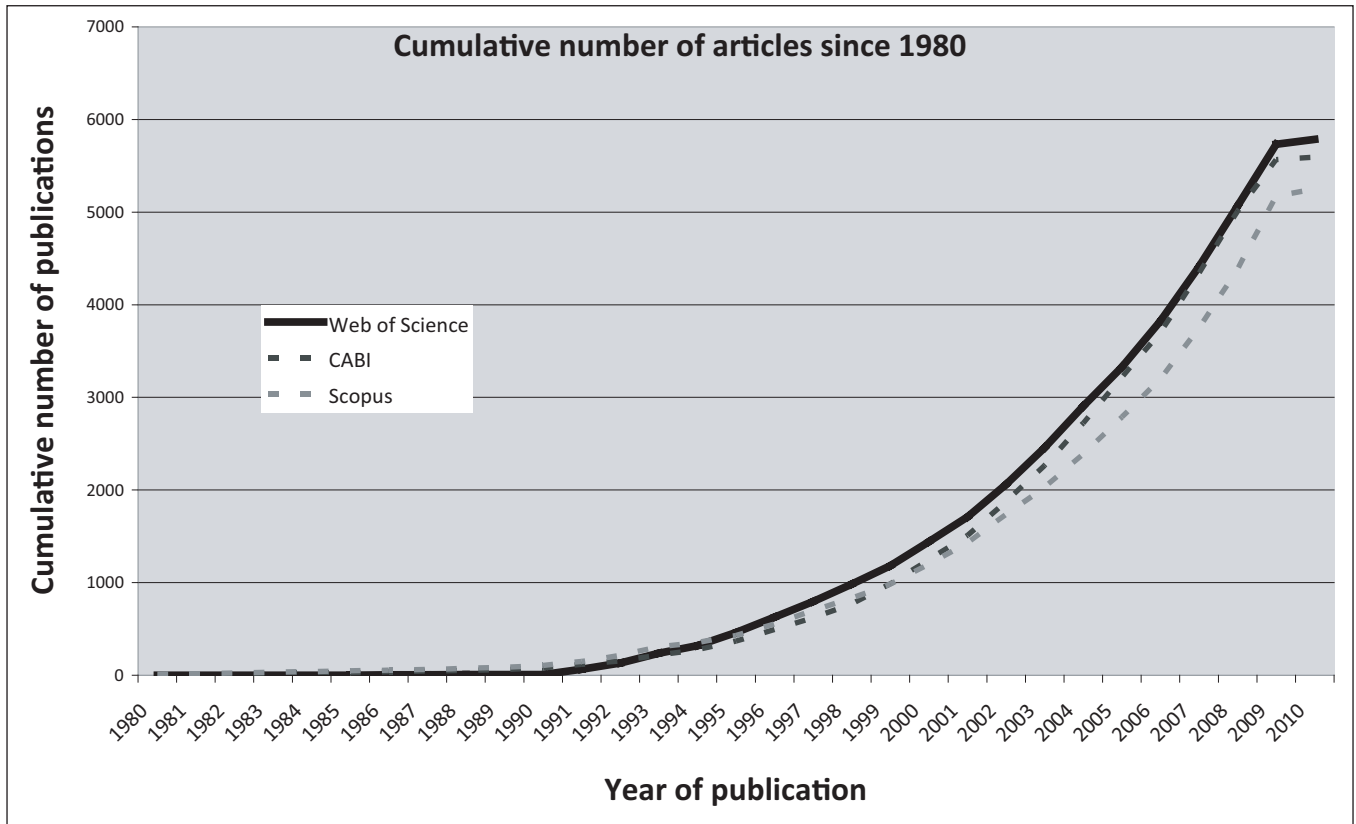
A prime example of these problems is the lack of consensus on how much carbon is being emitted by tropical land use changes (Malhi and Grace 2000, Malhi *et al.* 2002, Fearnside and Laurance 2003, Achard *et al.* 2004, De Fries *et al.* 2007, Van der Werf *et al.* 2009). It is rarely clear what the source of such discrepancies and inconsistencies is. It could be attributable to uncertainties about the amount of carbon in tropical forests or uncertainties in deforestation rates (Houghton 2005).

There is substantial variation in published estimates of the total carbon content of tropical forest (Ramankutty *et al.* 2007). These variations are attributed to a number of factors, which can be considered in terms of the three independent but interlinked components defined in the framework for carbon measurement (Figure 4):

1. Problems of direct measurements of biomass variables including difficulties of access and limited number of ecological studies that measure biomass directly (Brown *et al.* 1989, Baker *et al.* 2004a, Malhi *et al.* 2004).
2. Problems converting biomass estimates into C stock estimates including the large number of published

<sup>5</sup> Details of the search strategies are included in the Appendix.

FIGURE 5 Number of articles of relevance to carbon in forest indexed in three major databases



biomass equations (Baker *et al.* 2004b) and the spatial extent of tropical forests (Malhi *et al.* 2004, Hansen *et al.* 2008). Grainger (2008) points to uncertainties in values derived from remote sensing for extent of forest area and rates of deforestation. These values significantly affect estimations of carbon stocks.

3. Problems of scale and extrapolation. Laumonier *et al.* (2010) caution against calculating carbon stocks in a given forest type or a region by extrapolating data from small plots to larger spatial scales and demonstrate considerable variation in values obtained sometimes from very small sample plots and replicated in reports with no regard for applicability. The same study specifically highlights considerable variance from the IPCC biome default value for 'tropical wet forest' (Eggleston *et al.* 2006) reported in their results and in the literature, but the point is a general one: using values derived for one ecological or landscape type and applying them to another is likely to result in errors.

Difficulties in comparing results of carbon estimates is not confined to research in tropical areas. Bradshaw *et al.* (2009) describe a situation of considerable uncertainty in boreal forest zones, pointing out discrepancies between methodologies of estimating biomass and applying carbon modelling projections.

The scoping project produced clear evidence of a large knowledge base that had not been subjected to systematic

or transparent synthesis. The group concluded that greater rigour could be brought to a review of reliable forest carbon monitoring methods through adoption of an evidence-based framework of the type widely used in medicine.

#### A SYSTEMATIC REVIEW OF METHODS OF CARBON MEASUREMENT AND ASSESSMENT

The final output of the first phase of the project to scope an evidence-based approach to carbon monitoring was a collaborative document produced as a draft systematic review 'Protocol'. This was posted in July 2009 for peer-review on the website of the Collaboration for Environmental Evidence (<http://www.environmentalevidence.org/SR77.html>). These protocols describe the set of steps to be followed in systematic reviews: the rationale for the review, the objective(s), and the methods that will be used to locate, select and critically appraise studies, and to collect and analyse data from the included studies. They are written collaboratively with a considerable element of iteration and peer-reviewed in order to reduce bias of the final systematic review, which is also peer-reviewed. The concept for peer-review developed by the Cochrane Collaboration and followed in this project, involves direct approaches to expert reviewers (mirroring practice in many academic journals), and inviting feedback from interested parties through direct emailing and, more 'informally', using internet discussion groups and fora to draw attention to

the work as it progresses. The Protocol remained open for review until the end of 2010. Twenty-two people reviewed the protocol and provided feedback. The level of detail varied greatly among reviewers, as is not uncommon with peer-review in academic journals, but was generally well-informed and useful.

The scoping exercise had considerably widened the extent of the review to include carbon pools in all terrestrial biomes and not just those connected with forest.

The draft protocol received no adverse feedback and the decision was taken to fund a full-scale systematic review using review authors with expertise in the terrain and topic areas identified by the scoping project: forest, soil and peat land, agricultural land, remote sensing technology for carbon assessment. The review authors met in November 2009 for three days to frame the review questions with very precisely defined terms and start a discussion to agree the basis on which evidence from the literature would be included in the review and how findings from these papers would be analysed in accordance with 'Cochrane-style' systematic review methodology (<http://www.cochrane.org>). Those discussions are ongoing and will be reported in due course when the systematic review has been completed.

### The review question

After extensive discussion, a question was agreed as a strong candidate for a systematic review, which commenced in December 2009. The scope of the question is extremely broad and it has been broken down into three sub-questions, which will be the focus of the reviewed literature. Several competing suggestions had emerged during the group discussions, notably a suggestion to limit the scope of the review to forest carbon only, which had been the starting point of the project, or to concern the review only with economic comparators of methods, or to abandon the idea of assessing above-ground carbon altogether in favour of the much less well researched below-ground carbon, which all had validity, but were rejected finally on two principal grounds. Firstly, it is clear that a review of studies on carbon stocks within one biome type or one carbon pool would suffer from precisely the sort of methodological bias the review was aiming to overcome. Second, the scope of REDD+ is broad and requires an equally broad evidence base of robust science, which was one of the driving forces behind the project to validate the evidence base in the area of carbon monitoring.

The framework for measuring forest carbon discussed above, was key to framing the wording of these questions, and will inform the inclusion criteria for the literature under review.

#### (iii) Primary question

How do current methodologies compare in their ability to measure and assess terrestrial carbon stocks and changes in carbon stocks with accuracy, precision and repeatability?

- 'methodologies' is defined to include methods (direct measurements, sampling design, remote sensing and

models) and systems that aggregate methods to measure and assess carbon stocks.

#### (iv) Sub-questions

1. How accurate, precise and repeatable are methodologies used for the conversion of in situ measurements into carbon stock estimates at the site level?
  - reviews direct measurements in the field (*in situ*) and methodologies that convert them into carbon stock estimates at the site level. Also reviews the geographical validity of methodologies developed at the site-level and examines the applicability of methodologies to different land use categories in different environments, ecosystems and countries.
2. How accurate, precise and repeatable are methodologies for generating carbon stock estimates for larger geographical areas (landscape level) from site-level data?
  - 'landscape level' encompasses the spatial scales from site to national levels through forest inventories, stratification, other sampling schemes and modelling.
3. How accurate, precise and repeatable are direct remote sensing methodologies for estimating carbon stocks?
  - reviews direct carbon stock estimates from measurements by remote sensing instruments, coupled with field measurements and methodologies to convert measurements into stock estimates.

The challenge of defining, *a priori*, which studies to include in the review to answer each question has necessitated extensive discussions about the diverse terminology which is used in the literature to describe concepts of direct relevance to the study. These terms will be used to construct a transparent literature search strategy, which can be replicated by other researchers. This clarity of content is one of the most important facets of the systematic reviews that contributes to reduced bias compared with traditional, 'narrative' reviews. Chalmers (2003) discusses 'bluntly' clear evidence of bias in narrative reviews which have used different methods to review the literature and arrived at different conclusions.

## DISCUSSION

It is too early for a scholarly analysis of the Cancun Agreement on REDD+ taken at COP16 in December 2010, but what is certain is that there will now be progress towards mechanisms which can reward carbon mitigation and that this will drive demand for high quality carbon monitoring systems. REDD+ can potentially act as the elusive catalyst for sustainable forest management by providing what could be unprecedented financial opportunities for developing countries for mitigating climate change through sound natural resources management. The very substantial amount of money that will be available for REDD+ implementation will focus attention on the need to adopt monitoring and assessment systems that are underpinned by good science.



Although there is a very large, and growing, body of scientific and technical information on methods of carbon measurement, there has been no systematic review of the literature which would meet the high standards of evidence review which are demanded as prerequisites for decision making by disciplines such as medicine and social policy. This does not mean that current decisions on methods are wrong, simply that they cannot be said to have been taken on the basis of evidence which has been analysed in a manner that is readily repeatable and as free from bias as possible. These criteria are the minimum for original scientific work but they have not been widely adopted in forestry or natural resource management as minimum standards for analysing the knowledge base prior to taking key decisions of global importance. Researchers are very familiar with the discipline of designing robust experiments, often in international teams of collaborators, from which high quality data can be generated. Systematic reviews utilise the same discipline, and encourage international, multidisciplinary teams of scientists, information professionals and decision-makers to work collaboratively on providing a high-quality evidence base. Collaboration is recognised as an important element in systematic reviewing, building partnerships between researchers and promoting stronger linkage between the science and policy communities (Turner, pers comm., Turner and Nye 2007).

The earlier scoping phase of the carbon assessment project and early results of the ongoing systematic review have demonstrated the strength of working in a multidisciplinary group to reach a shared understanding of the precise nature of the questions which need to be answered and to define very precisely a method of interrogating and analysing the existing evidence in the knowledge base.

## CONCLUSIONS

Measuring forest carbon accurately and reliably is an absolute requirement if REDD+ is to be accepted and implemented successfully. At present, however, there is insufficient capacity in almost all potential REDD+ countries and potentially costly investments will need to be made in national forest monitoring systems. But which systems should impoverished countries invest in and are recommendations for these systems based on sound science? For REDD to be credible, the methods used by different national systems for forest carbon measurement need to be evidence based.

It is clear from the preliminary scoping work described in this paper that the underpinning science for measuring forest carbon has not been systematically reviewed using the sort of robust evidence-based frameworks which are considered to be essential in other science-informed areas which develop evidence-based policy and practice.

Working towards the development of a systematic review for forest carbon measurement has successfully engaged members of the science community in a process which has clear benefits for other policy problems that require analysis of complex and often contradictory science.

REDD+ is at a critical stage of development which coincides with a time of increased public scepticism in science. A systematic review of carbon measurements, using the standards set in medicine, will provide a transparent and readily-repeatable evidence base which can support decision-making in an important area of climate mitigation.

## ACKNOWLEDGEMENTS

The project was supported by the UN-REDD programme.

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## APPENDIX

Search strategy developed to determine the number of articles published each year in the three main bibliographic databases which index global natural resources publications. It should be noted that this search strategy is for very preliminary scoping purposes; the complete strategy published in the systematic review Protocol for the systematic review which emerged as a result of this work is available on the CEE website (<http://www.environmentalevidence.org/SR77.html>).

### Scopus

limited to Agriculture and environment subsections  
 ((TITLE-ABS-KEY(carbon W/5 sink\*)) OR ((TITLE-ABS-KEY(carbon W/5 emi\*)) OR (((TITLE-ABS-KEY(carbon W/5 assess\*)) OR (TITLE-ABS-KEY(carbon W/5 measur\*)) OR (TITLE-ABS-KEY(carbon W/5 sequest\*)))))) AND (TITLE-ABS-KEY(forest\* OR wood\* OR scrub\* OR browse)) AND (LIMIT-TO(SUBJAREA, "ENVI") OR LIMIT-TO

(SUBJAREA, "AGRI") OR LIMIT-TO(SUBJAREA, "MULT"))

### CAB Abstracts

A database specializing in agriculture, natural resources and forestry, which defines the subject coverage.

((carbon adj5 assess\*).ti,ab OR (carbon adj5 emi\*).ti,ab OR (carbon adj5 sequest\*).ti,ab OR (carbon adj5 sink\*).ti,ab) OR ((carbon sequestration).de OR ((carbon).de AND (measurement).de OR (assessment).de OR (emission).de)) AND ((forest\* OR wood\* OR scrub\* OR browse OR agroforest\* OR rainforest\* OR tree\*)),ti,ab,de)

### Web of Science

Subject coverage limited by choice of subject area.

Subject Areas=(environmental sciences or ecology or forestry or meteorology & atmospheric sciences or soil science or geosciences, multidisciplinary or plant sciences or agronomy or biodiversity conservation or energy & fuels or environmental studies or multidisciplinary sciences or remote sensing or agriculture, multidisciplinary or agricultural engineering or imaging science & photographic technology or biology or geography).

(TS=(carbon SAME assess\*) OR TS=(carbon SAME measur\*) OR TS=(carbon SAME sink\*) OR TS=(carbon SAME emi\*) OR TS=(carbon SAME sequest\*)) AND TS=(forest\*) OR TS=(wood\*) OR TS=(scrub\*) OR TS=(browse) OR TS=(tree\*) OR TS=(agroforest\*) OR TS=(rainforest\*))

### Field descriptions for Scopus/CABI

title: TITLE (Scopus); /.ti (CABI)

abstract: ABS (Scopus); /.ab (CABI)

Keywords: KEY (Scopus); /.de (CABI)

TS (topic search) – searches in title, abstract and keyword fields in Web of Science

The Boolean operator 'W' in Scopus is 'Adj' in CAB. W/5= search for the two terms up to 5 words apart, in either order.

The number 5 is suggested to limit occurrence to words in a phrase. Adj5 is the same in CAB. In Web of Science, the Boolean operator 'SAME' searches for occurrence of two words in one sentence. This is the closest equivalent to the W or ADJ operators. The search strategies have taken account of the different ways searches operate within each database architecture.