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Working Title: Comparison of methods for the measurement and assessment of carbon stocks and carbon stock changes in terrestrial carbon pools.

Draft Review Protocol

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COVER SHEET

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1. Background

Land use and land cover changes, including legal and illegal deforestation, are amongst the most important factors that contribute to the social and environmental challenges facing mankind in the 21st century. Deforestation alone is responsible for about 12% of the world's anthropogenic greenhouse gas (GHG) emissions, whereas another 6% stems from peat oxidation and fires on degraded peatland areas (Van der Werf et al., 2009). The combined effects of logging and forest regrowth on abandoned land are responsible for 10-25% of global human-induced emissions (Achard et al., 2002; Gullison et al., 2007). Annual emissions from deforestation in Indonesia and Brazil equal four-fifths of the annual reduction target of the Kyoto Protocol (Santilli et al., 2005).

Under the United Nations Framework Convention on Climate Change, reducing emissions from tropical deforestation is currently not accountable. However, a future REDD-instrument (Reducing Emissions from Deforestation and Forest Degradation) will alter the situation for developing countries. REDD includes the implementation of policies and measures for reducing deforestation rates such as sustainable forest management (SFM) and reduced impact logging (RIL). For the implementation of REDD, it is crucial to determine the spatio-temporal variation of carbon stocks. Obtaining sufficient ground-data to do so is an expensive and time-consuming task.

This systematic review will compare methods of measuring carbon stocks and carbon stock changes in all primarily vegetated land use and land cover types, e.g., forest, croplands, wetlands, pastures, agroforestry systems (FAO, 2005), and all major terrestrial carbon pools (soil including peat, deadwood, litter, above and below-ground biomass).

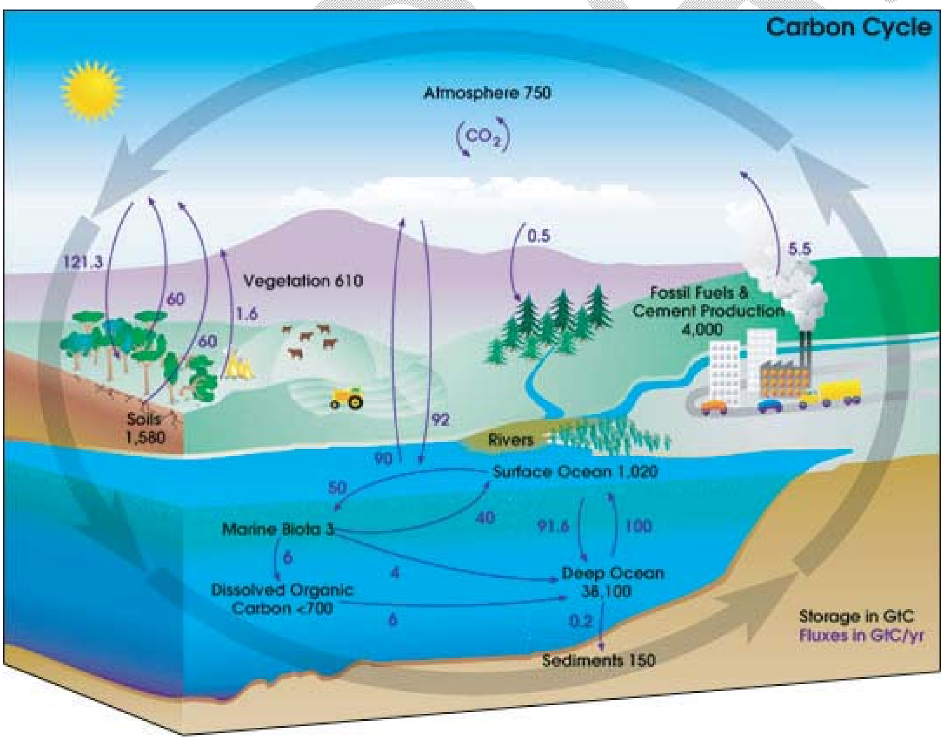

Figure 1 Major carbon pools and fluxes of the global carbon balance (FAO, 2004)

1.1. Forests and biomass

A key challenge for successfully implementing REDD and similar mechanisms is the reliable estimation of biomass carbon stocks in tropical forests. Biomass consists of approximately 50% carbon (Brown and Lugo, 1982; Malhi et al., 2004). Uncertain estimates of biomass carbon stocks of tropical forests (resulting from difficult access, limited inventory and their enormous extent, Baker et al., 2004a; Hansen et al. 2008; Malhi et al., 2004) prohibit the accurate assessment of carbon emissions as much as uncertainties in deforestation rates (Houghton, 2005).

A reliable estimation of above-ground biomass (AGB) has to take account of spatial variability, forest allometry and wood density (wood specific gravity or WSG). Many studies have been published on AGB estimates in tropical forests around the world (e.g. Baccini et al. 2008; Brown et al., 1999; Chave et al., 2001; Gaveau et al., 2003; DeWalt and Chave, 2004; Segura and Kanninen, 2005; Saatchi et al., 2007; Sales et al., 2007), whereas the volume of literature on below-ground biomass estimates is relatively small.

Most studies on tropical forest AGB have been conducted in the Brazilian Amazon and in Southeast Asia. Few studies have reported on AGB for forests in Africa (but see Baccini et al. 2008). The large number of published biomass equations (Baker et al., 2004b) indicates that there is a substantial variation in tropical forest biomass (Ramankutty et al., 2007).

Chave et al. (2004) identified four types of uncertainty associated with AGB estimates of tropical forests:

- Inaccurate measurements of parameters
- Wrong allometric models
- Sampling uncertainty (related to the size of the study plot)
- Failing representativeness of the sample plot network.

Vieira et al. (2008) demonstrated the effect of inaccurate height measurement. A stem with a diameter at breast height (DBH) of 20 cm and a height of 13 m gave an AGB of 153.0 and 127.0 kg, respectively, when using models of Chave et al. (2005) and Scatena et al. (1993). With the same DBH but one meter more height, the estimated AGB become 164.1 and 136.6 Kg, i.e. an increase of around 7% and 5%, respectively.

The most important error is the wrong choice of allometric model (which is related to the representativeness of biomass sampling). Allometric equations relate easily-measured parameters of an organism (such as diameter and height) to attributes that are more difficult to assess (such as volume, leaf area, and biomass). They aim at facilitating large scale estimation of complex parameters (Zianis, 2008), e.g. providing ground reference for remote sensing or estimating regional biomass. Height and diameter are the most common dependant variables for assessing tree biomass, but as height of individual trees is difficult to measure, most allometric models for tropical forests are based only on tree diameter (Williams and Schreuder, 2000; Alder and van Kuijk, 2009).

Currently, allometric equations are almost entirely based on Southeast Asian and South American measurements. Some equations are available for African tree species or forest vegetation types (Hofstad, 2005), but there are no allometries based on destructively sampled trees for Central Africa

(Chave et al., 2005). Biomass equations for North America are listed in Ter-Mikaelian and Korzukhin (1997), for Europe in Zianis et al. (2005). Similar databases for other parts of the world would be of high value.

Furthermore the biomass stock of tropical forests and its distribution remain poorly resolved at the regional scale (Fearnside, 1996; Houghton et al., 2001; Houghton, 2005). Consensus has also yet to be reached on how much carbon is being emitted by changes in tropical land use (e.g., Malhi and Grace, 2000; Achard et al., 2004; De Fries et al., 2007, Malhi et al., 2002; Fearnside and Laurance, 2003; Ramankutty et al., 2007, Van der Werf et al., 2009). There is thus an urgent need for calibrating and improving the methods for determining tropical forest biomass and its spatial distribution (Goetz et al. 2009).

The accuracy of biomass estimation ultimately depends on the accuracy of the original measurements used to develop biomass assessment tools, such as allometric models, biomass expansion factors (BEFs), generic equations (Wirth et al. 2004, Wutzler et al. 2008) and species group specific volume-to-biomass models (Smith et al. 2003). BEFs, for example, strongly depend on stand age (Lehtonen et al. 2004, Lehtonen et al. 2007) and extrapolation with BEFs may lead to biased results when compared with local biomass equations (Jalkanen et al. 2005), indicating the importance of representativeness and the risks of extrapolation.

It is time consuming and costly to sample sufficient trees to acquire information on species and size distribution in a forest (particularly in a highly diverse tropical forest) and to determine the local or regional WSGs. Guidelines for measuring WSG in the field exist, but for tropical regions published WSG data are limited to a few commercial timber species that represent only a fraction of the forest biomass. WSG data on other species are scarce or lacking.

There is thus a clear need for country- and region-specific studies to address the validity and reliability of allometric models. Ideally, such studies would utilise good ecological plot data, but these are often of poor quality or lacking completely. Commercial inventory data gathered by private companies are therefore used as an alternative and rich source of site-specific data. These are necessary for improving methods for estimating forest carbon, but generally not available in the published literature.

1.2. Remote sensing

Remote sensing has considerable potential as a source of biomass data (Foody and Cutler, 2003; Goetz et al., 2009). Remote sensing (space-borne or air-borne) usually provides continuous spatial information over landscape-size areas (size depends on sensor characteristics) in contrast to field inventory where information is generally limited to plots or small areas. Direct measurements of AGB are limited to small forest areas, because site-specific allometric equations cannot be generalised for a forest or region and space-borne instruments cannot yet measure tropical forest biomass directly. The use of space-borne radar backscatter data is becoming increasingly accepted as a method for measuring woody biomass over large areas in the tropics because of its capability of penetrating through the forest canopy and all-weather acquisition.

Published studies very often use national forest inventory data to verify results of remote sensing estimates of carbon. Many claim to show strong correlation. However, limitations are reported in the literature, in particular the weak, or absent, relationship between radar backscatter and AGB associated with saturation, and errors in geo-location: for example, old Global Positioning System (GPS) instruments used in constructing inventories may introduce uncertainty in establishing the 'centre of plot' location, compass direction, etc. (Alder and van Kuijk, 2009).

There are a number of approaches to estimating AGB from remote sensing data, including multiple regression analysis, nonparametric k-nearest neighbour technique (k-NN), neural networks, or indirect relationships between forest attributes, determined by remote sensing, and biomass. An increasing number of studies use fine resolution imagery such as Quickbird, aerial photographs or IKONOS for modelling tree parameters or forest canopy structures, though these are not applied to large areas owing to cost and technical demand. Medium spatial resolution imagery such as Landsat is widely in use. Where optical sensors have limitation, radar and light detection and ranging (LiDAR) data are being used. Most studies on AGB estimates have not provided accuracy assessments with respect to ground data (Lu, 2006). Rosenqvist et al. (2003) undertook a qualitative review of remote sensing techniques for use under the Kyoto Protocol but did not provide an assessment of their operational status for use at national scales. For the UK and countries with similar reporting requirements, Patenaude et al. (2005) made quantitative assessments of the accuracy and comparative costs of optical, radar and LiDAR techniques for reporting deforestation through land-cover classification analyses and quantification of forest above-ground carbon stocks.

The accurate assessment of above-ground forest biomass and carbon stock over large areas requires a grid of ground sample plots (with very precise location or a nested sampling) together with a map of vegetation types and/or cover classes. Classification and mapping can be done on the basis of satellite imagery or aerial photography. More precise vegetation classification and a denser network of sample plots will give more precise estimates at higher costs.

The spatial extrapolation of biomass density measurements from ground sample plots can be improved by (satellite-based) radar and (airborne) laser assessments. The latter can cover complete areas or transects. Radar can penetrate clouds while laser (LiDAR) cannot. Radar measurements saturate at biomass densities around 100 tons per hectare, whereas LiDAR shows no evidence of saturation (Figure 2).

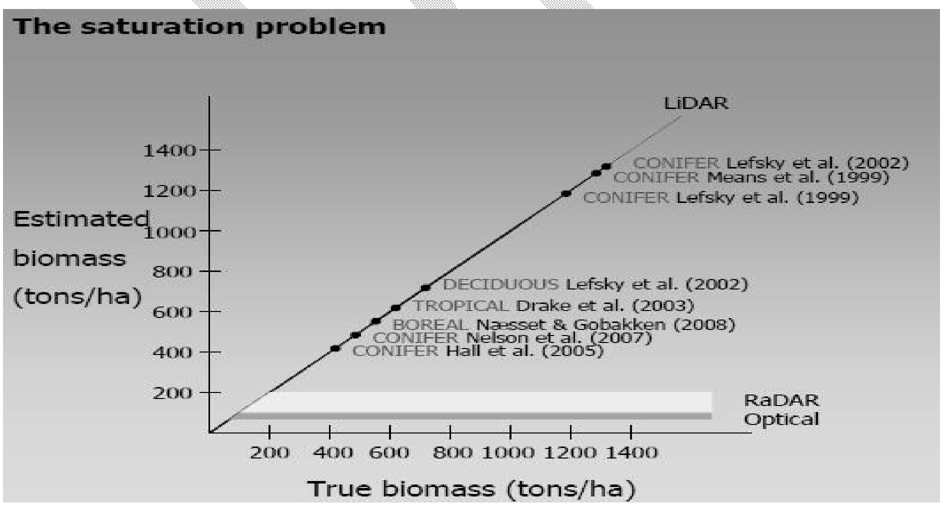

Figure 2. The saturation problem (after Hofstad, 2005)

There is clearly a need to critically review the accuracy, precision and cost of various remote sensing techniques against ground observation and among methods, and their applicability in geographically varied regions.

1.3. Carbon stocks in soils

Soils are the largest carbon reservoir of the terrestrial carbon cycle. Worldwide they contain three/four times more organic carbon (1500 Gt to 1 m depth, 2500 Gt to 2 m) than vegetation (610 Gt) and twice or three times as much carbon as the atmosphere (750 Gt, see Figure 1) (Batjes and Sombroek, 1997). Carbon storage in soils is the balance between the input of dead plant material (leaf and root litter) and losses from decomposition and mineralization of organic matter ('heterotrophic respiration'). Under aerobic conditions, most of the carbon entering the soil rapidly returns to the atmosphere by autotrophic root respiration and heterotrophic respiration (together called 'soil respiration' or 'soil CO_2 efflux'). Under anaerobic conditions, resulting from constantly high water levels, part of the carbon entering the soil is not fully mineralized and accumulates as peat.

Guo and Gifford (2002) conducted a meta-analysis of 74 publications on the influence of land use changes on soil carbon stocks. They acknowledge the possible bias in their findings as most data drew from only four countries (Australia, Brazil, New Zealand, and USA) and a limited number of studies. They point to the need for a more comprehensive analysis of some hypotheses generated in their study: soil carbon stocks decline after land use changes from pasture to plantation (-10%), native forest to plantation (-13%), native forest to crop (-42%), and pasture to crop (-59%). Soil carbon stocks increase after land use changes from native forest to pasture (+ 8%), crop to pasture (+ 19%), crop to plantation (+ 18%), and crop to secondary forest (+ 53%). Most land use on peat soils requires drainage and is associated with a continuous loss of soil carbon stock.

1.3.1. Mineral soils

Estimates of soil organic carbon (SOC) stocks are applied to determine long-term carbon fluxes and to design carbon sequestration strategies. Several approaches to estimating these stocks are currently in use and may provide conflicting results. One method for estimating SOC stocks of different ecosystems is a regression approach in which regional SOC densities (mass SOC/area) are related to temperature, precipitation, age class, and land-use history. An updated methodology applies a geographic information system (GIS) to calculate SOC densities for each forest type within a region from soil databases and satellite-derived land cover information. Campbell et al. (2008) showed large differences in the outcomes of both approaches and identified the need to use direct measurements of SOC in order to determine absolute errors in both approaches. The fact that the methods have been used interchangeably in the past indicates that errors will have been perpetuated in the literature. Both methods are valuable for estimating soil carbon stocks but not for carbon stock changes, because the predictors of both parameters are different.

According to Mäkipää et al. (2008) a reliable carbon stock change inventory for Finland with repeated soil carbon sampling would take 10 years and cost 8 million euros. This high cost would almost certainly prevent more than a few countries investing in adequate soil carbon inventories; the reality is that a combination of models and additional measurements is needed. Regardless of the methodology applied there is a clear need to identify the uncertainties associated with current understanding of SOC stocks and stock changes (Peltoniemi et al. 2006). It is important to pay particular attention to changes in soil carbon stock, through direct measurements and soil carbon modelling (Peltoniemi et al, 2007), as well as to regional variation of soil carbon stock.

Soil carbon models can be used for estimating carbon stocks and stock change estimation, but it is important to note that local measurements are needed to validate the applied models. Soil carbon models also face the initialization problem. Most soil carbon models assume that at the beginning of the simulation period equilibrium conditions apply, i.e., that plant input and soil carbon stock are in balance given the local climatic conditions. In order to simulate land cover or land use change under constant or changing climatic conditions the model needs a so-called 'spin up' period to reach equilibrium condition before any transition takes place. There are a number of problems and uncertainties related to this assumption and alternative methods are discussed. It is therefore essential to quantify these effects in any soil carbon accounting (Peltoniemi et al. 2006, Wutzler and Reichstein 2007, Yeluripati et al. 2009, Zimmermann et al. 2007).

1.3.2. Organic (peat) soils

Only recently has science recognized the importance of organic (peat) soils for greenhouse gas emissions and climate change. With some 500 Gt of carbon stored on only 4 million km^2 (= 3 %) of land, peatlands constitute the world's most dense terrestrial carbon stocks (Joosten and Couwenberg, 2008). In the case of peat swamp forest, emissions from peat oxidation and peat fires following drainage may be significantly larger and longer lasting than above-ground emissions from clearing or burning forest vegetation. Peat oxidation currently leads to worldwide emissions of some 1.3 Gt CO_2 per year, whereas peat fires contribute another 0.6 Gt CO_2 per year on average (Joosten, 2009). During the 1997-1998 El Niño drought peat fires in Southeast Asia emitted some 1.8 Gt CO_2 (Page et al., 2002; Van der Werf et al., 2008; Couwenberg et al., 2009), which is equivalent to 10% of the total global anthropogenic emissions for the same year.

Many variables linked to peat oxidation are not well understood and few reliable measurements exist for many of them. Uncertainty begins with the extent of peatlands worldwide and especially in the tropics and with the amount of carbon stored in the peat layer. The degree of peat humification has strong influence on the mass of peat and carbon per volume, the hydraulic conductivity and the moisture retention capacity. Knowledge of the 3D topology of peatlands is important for hydrology and modelling, but peat depth and peatland shape have been measured only in a few locations. Sampling sufficient locations to allow for spatial modelling is a time-consuming and costly exercise. New technologies may be capable of reducing time and effort.

Even less is known about emissions factors, which are essential for reliably estimating GHG emissions. Emission estimates from peat fires have large uncertainties, because of the highly variable mass of peat combusted and the various gases emitted depending on fire severity, water table, peat moisture and fire history. Data on most of these parameters are scarce or lacking. Long-term GHG emissions from biological oxidation of peat are even more significant than the emissions from peatland fires (Couwenberg et al., 2009; Joosten, 2009). Very few long term (> 1 year) measurements exist to assess emission rates under different water management regimes. A recent review shows that drained peatlands emit in the range of 9 CO_2 t/ha/yr from peat oxidation for each

10 cm of additional drainage depth (Couwenberg et al., 2009). The role of tropical peat swamps is crucial not only in terms of GHG emissions but also for REDD, as their peat carbon stock is on average 10 times larger than their above-ground biomass stock (Joosten & Couwenberg, 2008) and significant amounts of carbon are released by fire and bacterial decomposition. Emissions from drained peatland occur worldwide. The largest emitters include Indonesia, the European Union, Russia, China, USA, Malaysia, Mongolia, Belarus and Uganda (Joosten, 2009).

1.4. Deadwood and litter

Biomass of deadwood and litter could be as large as above-ground biomass. A variety of methods to measure deadwood and litter needs to be reviewed. Deadwood pools, including both standing dead trees and fallen woody debris, are of particular interest in projecting carbon losses from decomposition. They are also often used as an indicator of carbon losses from degradation due to logging (Palace et al 2007) or fire (Barlow 2003). Data collection regarding standing dead trees frequently follow the same protocols as those for AGB inventories but ideally should also include data on levels of decay. Woody debris is most often estimated using the line-intercept method which measures only debris which crosses a transect (e.g., Palace et al 2007) or through rectangular plots wherein the dimensions of each piece of debris is measured (e.g., Rice et al 2004). Although some studies have addressed the densities of woody debris of different decay classes (Keller et al 2004, Palace et al 2007), more regionally and biome specific studies would help refine estimates of carbon content of this pool.

Litter is another pool that must be taken into consideration when estimating carbon losses and movement between pools (litter -> soil) (Ostertag et al 2008). Litter includes leaves and other fallen plant material (including fine woody debris of diameter < 2cm). Litter may be equivalent to only a small fraction of AGB in some ecosystems (e.g. 2% for montane forests in Mexico (Ordóñez et al 2008)) whereas it can be substantially higher in others (e.g. 30% in sugarcane fields). Some estimates of the litter pool in forests use quadrats to assess the litter mass per unit area at a given point in time (Ordóñez et al 2007). However, this method may suffer from imprecision due to the difficulty of distinguishing between litter and soil organic matter. Litterfall traps, which can monitor the input of litter falling over time, may be more accurate in distinguishing between pools. Several studies are available which address decomposition rates and the implications for carbon cycles (Tuomi et al 2009, Wieder et al 2009).

1.5. Need to synthesise studies from different disciplines

It is clear that a wide range of efforts have been and are being undertaken in public and corporate research to provide methods and data for carbon stock assessments in different pools. There is a huge body of knowledge collected over decades. There has been a proliferation of scientific and technical papers. But still monitoring of forests is 'insufficiently accurate or precise for an international protocol that would administer finances based on monitoring results of forest area or forest carbon storage' (Holmgren and Marklund, 2007) and there is no reason to suppose that the situation for other pools is any better. The adequacy of current or potential systems for reliably assessing carbon stocks at national, regional or local levels (under the REDD framework or elsewhere) has not been systematically evaluated, nor has the scientific underpinning of these approaches been properly examined. It has been argued that a REDD system must allow and account for variability in methodologies and accuracy. The latter is inevitable with such wide differences between countries and assessment methods. But flexibility must come with knowledge of the limits of confidence in these variable approaches if REDD is to be credible, transparent and fair. It is timely to undertake a systematic review of methods and approaches to carbon stock assessments.

2. Object of the review

2.1. 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?

2.2. 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?
2. How accurate, precise and repeatable are methodologies for generating carbon stock estimates for larger geographical areas (landscape level) from site-level data?
3. How accurate, precise and repeatable are direct remote sensing methodologies for estimating carbon stocks?

2.3. Components of the questions

The subject for all sub-questions will be the 5 terrestrial carbon pools identified by the Intergovenmental Panel on Climate Change (IPCC):

- Above-ground biomass
- Below-ground biomass
- Deadwood
- Litter
- Soil (including peat)

Applicable spatial scales of methodologies will be explicitly reviewed for each question. For soil, depth and mass will be taken into consideration.

Land-cover categories will include the following:

- Forest (including agroforestry)
- Cropland and grassland
- Wetland

Peatland is a carbon pool and can be found under any land-cover categories.

The term “methodologies” is used to include methods (including direct measurements, sampling design, remote sensing and models) and systems that aggregate methods to measure and assess carbon stocks.

Sub-question 1 reviews direct measurements in the field (*in situ*) and methodologies that convert them into carbon stock estimates at the site level. Sub-question 1 also looks at 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.

The term "landscape level" in sub-question 2 encompasses the spatial scales from site to sub-national and national levels through forest inventories, stratification, other sampling schemes and modelling. Sampling and stratification by remote sensing are also dealt with under sub-question 2. Sub-question 2 also looks at methodologies to assess changes in soil carbon with land use conversion.

Sub-question 3 includes direct carbon stock estimates from measurements by remote sensing instruments, coupled with field measurements and methodologies to convert measurements into stock estimates. Ground-based measurements such as terrestrial LiDAR will be included, and field biomass components will be identified when available from the source material.

2.4. Outcomes

Outcomes will assess accuracy, precision and repeatability against gold standard methodologies that are generally agreed to have the highest accuracy, precision and repeatability. Recognizing that there may not be a single gold standard for any of the carbon pools and land types, the methodologies that convert *in situ* measurements into carbon stock estimates at the site level, reviewed under sub-question 1, will be treated as the gold standard for sub-questions 2 and 3. Consideration will be taken of the frequency requirements built into the methods and systems (e.g. necessity for annual measurements, etc.)

3. Methods

3.1. Search strategy and resources

3.1.1. Published material

The following computerised information resources will be searched for published studies and resources in organisational libraries:

1. CAB Abstracts http://www.cabi.org
2. Google Scholar http://scholar.google.com
3. ISI Web of Knowledge (including Web of Knowledge with Conference Proceedings, BIOSIS Previews) http://apps.isiknowledge.com
4. Scopus http://www.scopus.com
5. SCIRUS http://www.scirus.com/
6. AGRICOLA http://agricola.nal.usda.gov
7. Scielo http://www.scielo.org
8. GeoRef database http://www.ovid.com/
9. ScienceDirect http://www.sciencedirect.com
10. ProQuest Dissertations and Theses http://www.il.proquest.com/
11. Science.gov http://www.science.gov
12. US Department of Agriculture Forest Service Treesearch http://www.treesearch.fs.fed.us/
13. Australian Government Department of Climate Change website http://www.climatechange.gov.au/index.html
14. Tropical forest conservation and development database http://forestry.lib.umn.edu/bib/trps.html

15. EuroForest portal http://forestportal.efi.int/
16. EDIS (Electronic Data Information Source) http://edis.ifas.ufl.edu/
17. Forests in flux http://www.unep-wcmc.org/forest/flux/index.htm
18. ATROFI-UK ; Archive of Tropical Forestry Inventory http://www.rdg.ac.uk/ssc/atrofi/
19. NRCAN Library Catalogue http://catalogue.nrcan.gc.ca
20. World Environment Library http://www.nzdl.org/fast-cgi-bin/library?a=p&p=about&c=envl
21. CGVlibrary http://vlibrary.cgiar.org
22. UNFCCC REDD Web Platform http://unfccc.int/methods_science/redd/items/4531.php
23. FAO Online Catalogues http://www4.fao.org/faobib
24. CIFOR Publications http://www.cifor.cgiar.org/Publications
25. ISRIC http://www.isric.org/
26. UNEP Publications http://www.unep.org/publications
27. World Agroforestry Centre Publications http://www.worldagroforestry.org
28. Columbia Earth Institute – International Research Institute for Climate and Society - http://portal.iri.columbia.edu/portal/server.pt
29. European Space Agency Earth Observation Projects Department http://www.esa.int
30. Tropical Soil Biology and Fertility Institute of CIAT (TSBF-CIAT): Conservation and Sustainable Management of Below-Ground Biomass project http://www.bgbd.net
31. Global Forest Resources Assessment (FRA) 2005 of FAO and its country reports http://www.fao.org/forestry/fra
32. National Forest Monitoring and Assessment (NFMA) of FAO and its reports http://www.fao.org/forestry/nfms/en/

3.1.2. Unpublished and grey literature

As a large proportion of material has not been digitised and requires hand searching through organisational resources, the search strategy and list of searchable resources will be further developed iteratively during the early phases of the review. A large volume of work on systems and methods of measurement and assessment has not been published formally. Recognised experts, authors and people who have used these techniques as practitioners will be contacted to contribute further ideas on resource identification and invited to share relevant publications or data. A large database of potential contacts has already been established in the scoping phase of this project and will be made available to the reviewers for this systematic review. The review will utilise the expertise of members of the International Directory of Forest Information Services (Libraries, Documentation Centres, and Subject Specialists), launched by IUFRO in 2002 and hosted by Forintek in Canada, which contains details of 152 forestry libraries and information centres in 49 countries (http://iufro.forintek.ca). Collaboration with agricultural information professionals and librarians will be canvassed through the International Association of Agricultural Information Specialists (http://www.iaald.org), whose members are drawn from research and development institutes, international agencies, universities and colleges, government departments, information providers, non-governmental organisations and the private sector. Logging companies with significant inventory resources will be pursued during the early stages of the review for information resources of relevance to the review questions. For peat the members of the International Peat Society and the International Mire Conservation Group will be consulted.

3.1.3. Search Terms

1. (Carbon near/2 stock*) AND (aboveground OR ‘above ground’ OR above-ground OR belowground OR ‘below ground’ OR below-ground OR forest OR forests OR terrestrial OR land OR soil OR peat OR yield OR harvest OR crop OR grass* OR meadow)
2. Carbon AND (forest near/2 inventor*)
3. Biomass AND (aboveground OR ‘above ground’ OR above-ground OR belowground OR ‘below ground’ OR below-ground OR forest OR forests OR terrestrial OR land OR yield OR harvest OR crop OR grass* OR meadow)
4. Carbon and (deadwood OR dead wood OR necromass OR litter OR litterfall OR residue OR stubble* OR humus OR soil* OR peat OR peatland*)
5. (estimate* OR asses* OR measure* OR monitor* OR method*)
6. Carbon and (Remote near/2 sens* OR Aerial near photo* OR LiDAR OR AVHRR OR MODIS OR MERIS OR VGT OR Landsat- OR ASTER, OR LISS OR AwiFs OR CBERS OR PALSAR OR IKONOS OR QuickBird)

((1 OR 2 OR 3 OR 4) AND 5) OR 6

A wide range of papers that address the main question will be captured by the search terms above but a large number of hits suggested by preliminary searches on major databases may prevent reviewers from conducting an effective review. There are several tiers of search terms as summarized below and the best strategy to combine these terms will be determined in iterative processes at the literature search phase. We aim to have a standardized search approach across all sub-questions but there can be multiple sets of search terms for each sub-question to carry out an efficient search.

1. Subject for measurement:
   - carbon or biomass
   - “peat depth” or “peat thickness” or “peat bulk density” or “carbon density”

2. Land type:
   - *forest* or *wood* or *tree* [for forest]
   - crop* or pasture* or graz* or grass* or savanna* [for cropland and grassland]
   - wet* or peat* or swamp* or marsh* [for wetland and peatland]

3. Carbon pool:
   - (aboveground or "above ground" or above-ground) or (belowground or "below ground" or below-ground) or (deadwood or "dead wood" or dead-wood) or (litter or root* or shoot* or necromass* or AGB* or BGB* or live or dead or branch* or leaf* or leaves) [for forest biomass]
   - (*soil* and *organic*) and (stock or pool or storage or mass or content) [for soil carbon]
   - “peat carbon”
   - (yield or harvest or residue or fodder or silage or straw or hay or stubble or litter) [for croplands]

4. Methodologies
   - (method* or technique* or approach* or model* or simulat* or estimat* or assess* or *measure* or calculat* or allometr* or biometr* or "expansion factor*" or "conversion factor*" or BEF* or formula*) [for methodologies in forest except for remote sensing]

- (method* or technique* or approach* or model* or simulat* or estimat* or assess* or *measure* or calculat* or allometr* or biometr* or formula*) [for methodologies in cropland and grassland]
- (method* or technique* or approach* or model* or simulat* or estimat* or assess* or *measure* or calculat* or formula*) [for methodologies in peatland and wetland]
- (remote near/2 sens*) OR (aerial near photo*) OR LiDAR OR AVHRR OR MODIS OR MERIS OR VGT OR Landsat- OR ASTER, OR LISS OR AwiFs OR CBERS OR PALSAR OR IKONOS OR QuickBird or Radar [for remote sensing]
- "basal area*"or "wood volume*" or "diameter at breast height*" or DBH* or "growing stock*" or stem* or diameter* or densit* or height* or crown* or trunk* or "specific gravit*" or (structure near/5 tree) or (stand* near/5 tree) or timber [for direct measurements]

5. Comparison of methodologies
   (accura* or uncertaint* or precis* or repeat* or confiden* or cost* or variat* or reliabl* or better or best or worse or worst or statist* or robust* or discrepanc* or error* or deviat* or compar* or improve* or capab* or trasparen* or timel* or credib* or practical or *consisten* or sensitiv* or *appropriat* or *agree* or evaluat* or "metaanaly" or "meta-analy" or "meta analy")

In a separate exercise, language experts familiar with the subject will be used to advise on the extent to which it will be practical to retrieve documents in other languages using searches comprising translated terms from the list above. If this is considered practical and beneficial for the review as a whole, and if the means at our disposal for carrying out this exercise will not add additional bias into the process, it is envisaged that important collections of literature will be retrieved from French, Spanish, and Portuguese, sources of forestry information, and, additionally for peat, German, Finnish, Swedish, Russian, Polish and Czech. The review team will consider the advice of language experts before the stage of data extraction and synthesis and will update the Protocol accordingly.

3.2. Knowledge management

The bibliographic details of all studies retrieved by this search strategy will be captured in a RefWorks bibliographic library. Studies will be coded to indicate which of the sub-questions they have been retrieved for. Many studies will be relevant to more than one sub-question. In order to reduce replication of effort retrieved studies will be coded for all sub-questions before being entered in the bibliographic library. Full texts will be retained on a secure site and will be coded with the unique ID taken from the RefWorks bibliography.

3.3. Study inclusion criteria

Studies will first be assessed for inclusion on the basis of title only, followed by assessment on the basis of abstract, and finally, full-text. Preliminary studies during the scoping phase have revealed the difficulty of assessing relevant studies on the basis of either title or abstract alone; studies will therefore be included unless there is clear information to justify exclusion.

To reduce the effects of between-reviewer bias, two reviewers will apply the inclusion criteria for a random sample of 20% of the studies retrieved (up to a maximum of 200 studies) to assess repeatability of the selection criteria. Kappa analysis will be performed, with a rating of substantial (0.6 or above) being required to pass the assessment (Cohen 1960). Disagreement regarding inclusion or exclusion of studies will be resolved by consensus, or following assessment by a third reviewer. If the Kappa value is low, the reference list will be reassessed against adjusted inclusion and exclusion criteria. The same subset of references will be re-assessed by a second reviewer with Kappa analysis. Reviewers will then consider articles viewed at full text for relevance, either excluding them from, or admitting them to, the review. Relevant studies are required to discuss all three elements: **X [name of method] method** to measure **Y [what is measured]** in **Z [where].**

3.3.1. Relevant subjects

The list of methods to assess carbon stocks/changes (across all 3 sub-questions) that are considered relevant for the review, i.e., X [name of method], is provided in Annex A.

Relevant papers must also present methods to assess carbon stocks/changes in the following land uses, types, and terrestrial ecosystem components, i.e., **Z [where]**:

All land uses and types (forest, terrestrial system, agricultural land, cropland, pasture, grazing land, savanna (woody and herbaceous), grassland, wetland, meadow, swamp, marsh, agroforestry, agroecosystem, bog, shrubs, trees, biomes, peatland, fen, and all other land) in the form of:

- Above-ground biomass
- Below-ground biomass
- Deadwood
- Litter
- Soil (incl. peat)

including necromass, litterfall, residue, stubble, humus, harvest, , yield, grain, harvest, tuber, live roots, roots, shoot, branch, leaves, fodder, silage, straw, hay, timber, lumber, stands, stem wood, stem bark, living and dead branches, fallen trees, fallen braches, fragmented wood, standing dead trees (snags), needles, stump, foliage, downed wood, woodlot, plantations, biomes, dissolved organic matter, dissolved gases.

3.3.2. Types of outcome

All types of outcome measures that relevant papers should contain (i.e. what was being measured), i.e., **Y [what is measured]**, are listed in Annex B. This could also contain measures of processes (if this is relevant), such as litter decomposition rates, etc.

3.3.3. Comparators

Studies comparing either one methodology of carbon stock/carbon stock change measurement or assessment over time or space or one methodology against another methodology. It is possible there will be a prohibitively large number of single methodology papers. At the study quality assessment stage it will be determined whether it is feasible to include single methodology papers in the review,

3.3.4. Types of studies

Any primary study that compares methods of assessment or estimation or attempts to assess the effectiveness of the method against clear criteria.

3.3.5. Potential for heterogeneity in outcomes

Differences in terrain/vegetation, spatial scale, temporal scale, technical and/or personnel limitations.

3.4. Study quality assessment

To assess the possible systematic errors or bias, each study will be assessed at full-text using a simple list of desirable study characteristics based on a hierarchy of evidence developed for other systematic reviews in medicine and conservation.

3.5 Data extraction strategy

The volume and quality of information available to address the review sub-questions are not known at this stage. Methods for data extraction and synthesis will be refined during the early phases of the review. The protocol will be amended as this process is undertaken. If information is too limited to perform meta-analysis of methodology comparisons, studies will be categorised according to subject, comparator and outcome, and a detailed qualitative summary will be produced. Where information is sufficient meta-analysis or other quantitative analysis will be used to provide a summary of quantified differences in methods.

4. Potential conflicts of interest and sources of support

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Annex A. List of methods to assess carbon stocks/changes (across all 3 sub-questions): X [name of method]

Broad methods:

Remote sensing, modelling, survey, inventories, conversion, field sampling, measurements

All approaches within these broad methods:

Remote sensing
aerial photography
infrared imagery
microwave radiation
Lidar (light detection and ranging)
optical
Radar
airborne laser scanning, ALS
airborne mapping
GLAS
satellite imagery
earth observations
satellite laser altimetry
SRTM
decision tree approach
regression tree model

Modelling
digital canopy height model, DCHM
eddy correlation
footprint modelling
soil organic matter models,
GIS
Up-scaling
gap filling strategies
surface energy exchange models
process based simulations
grassland ecosystem model
ecosystem flux techniques
ecosystem demography model (height structured ecosystem model)
RothC (a soil carbon model)
CENTURY
DNDC
Q model
CANDY model
CERES model
Crop growth model
Crop yield model

DGVM, digital global vegetation models
pedotransfer model
pedotransfer function
process based model
pipe model theory
peat growth model
peat accumulation model
peat decomposition model

Survey
random forest

Inventories
biomass classification approach
inventory plots

Conversion
biomass expansion factors, BEF
biomass equations
biomass assessment
biomass functions
continuous biomass expansion factor method, CBM
allometric equations
allometric relationship
allometric regression equations
biometric equations (function)
biometric approach
conversion factor
mean biomass density method, MBM
mean ratio method, MRM
LORCA or LARCA (LOng term Rate of Carbon Accumulation)
ARCA (Actual Rate of Carbon Accumulation)
RERCA (REcent Rate of Carbon Accumulation)

Field sampling
line intersect sampling (method) of CWD
prism sweeps
diameter relascope sampling of CWD, DRS
fixed area sampling (plots) of CWD
point relascope sampling of CWD
soil sampling
soil organic carbon sampling
soil organic matter sampling

Measurements
FLUXNET
tower eddy flux network

AIR-based estimation
flask-based estimation
bulk density correction
network theories
flux chamber techniques
carbon accounting
closed dynamic chambers
gas analyzers
dendrometers
litterfall traps
Litterbags
Litter traps
microcosm experiment
mesocosm experiment
Marcocosm experiment
FACE – free air carbon enrichment
SOMNET
soil cores

Annex B. List of types of outcome measures that relevant papers should contain: Y [what is measured].

All types – outcome measures
biomass
biomass saturation values
biomass density
biomass stock
biomass accumulation
biomass turnover rates
biomass increment
carbon
carbon density
carbon credits
carbon source
carbon sink
carbon sequestration
carbon balance
carbon stock
carbon flux – if it is in remote sensing papers, not relevant
carbon surface flux
carbon cycling – if it is in remote sensing papers, not relevant
carbon emission
carbon storage
carbon accumulation
carbon estimate
carbon monitoring
carbon pool
carbon uptake
carbon stock change
C pool
C stock
net primary production, NPP
gross primary production, GPP
emission factors
net ecosystem production, NEP
net ecosystem exchange, NEE
gross ecosystem production
net biome production, NBP
terrestrial organic carbon
implied emission factor

Soil – outcome measures
soil carbon
soil carbon transit times and age distribution
peat depth

peat thickness
peat bulk density
peat volume
CO_2 exchange
CO_2 efflux
soil organic matter, SOM
soil organic carbon
CH_4 efflux
DOC (dissolved organic carbon)
DIC (dissolved inorganic carbon [includes dissolved CO_2])
POC (particulate organic carbon)

Soil – measures of processes
litter input
decomposition
heterotrophic respiration
Microbial activity
Decomposition rate
Q10 temperature sensitivity
soil autotrophic respiration
soil heterotrophic respiration
DOC/DIC/POC loss

Forest – outcome measures
forest cover [not an inclusion keyword for forestry subgroup but it is one for remote sensing subgroup]
stem volume [an inclusion keyword for remote sensing subgroup as it is a proxy for carbon but not used as an inclusion keyword for forestry subgroup]
stem density
stem biomass
root [not an inclusion keyword for forestry subgroup but it is one for remote sensing subgroup]
root biomass (density)
root:shoot ratios (R/S)
total forest plant mass
wood density
wood specific gravity

Deadwood and Litter – outcome measures
coarse woody debris, CWD
down and dead woody (DDW) materials
transect length
litterfall
dead organic matter (DOM)

Deadwood and Litter – measures of processes
litter decomposition
litter input

litterfall / litter fall
respiration
decomposition

Crop and grassland – outcome measures
yield
grain
straw
residue
stubble
litter
tuber
root
cut
silage
fodder
seeds
forage
foliage
leaf
manure
slurry
grass

Crop and grassland – measures of processes
biomass decay rates
senescence rate
crop growth rate
aboveground autotrophic respiration rate
ecosystem respiration rate
rate of photosynthesis