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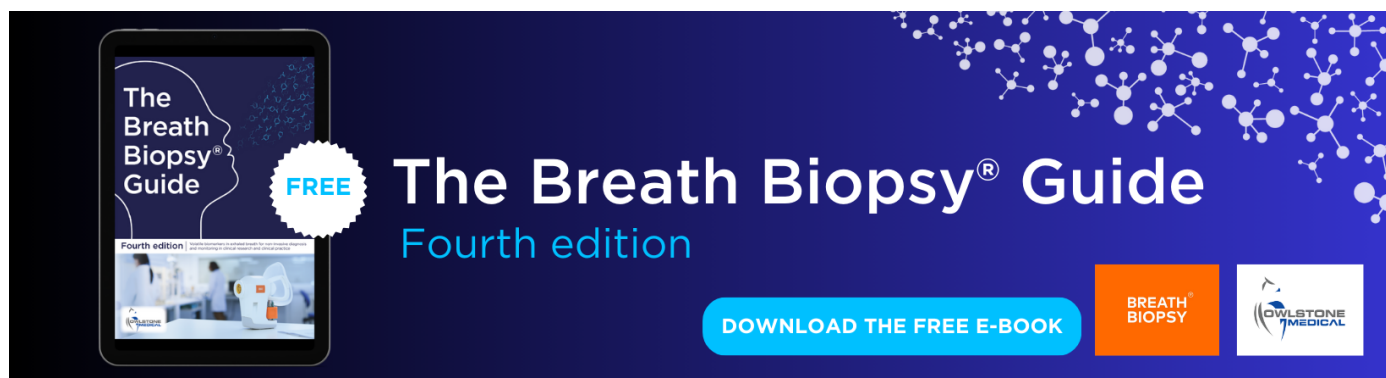
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Methods for the quantification of GHG emissions at the landscape level for developing countries in smallholder contexts

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Abstract

Landscape scale quantification enables farmers to pool resources and expertise. However, the problem remains of how to quantify these gains. This article considers current greenhouse gas (GHG) quantification methods that can be used in a landscape scale analysis in terms of relevance to areas dominated by smallholders in developing countries. In landscape scale carbon accounting frameworks, measurements are an essential element. Sampling strategies need careful design to account for all pools/fluxes and to ensure judicious use of resources. Models can be used to scale-up measurements and fill data gaps. In recent years a number of accessible models and calculators have been developed which can be used at the landscape scale in developing country areas. Some are based on the Intergovernmental Panel on Climate Change (IPCC) method and others on dynamic ecosystem models. They have been developed for a range of different purposes and therefore vary in terms of accuracy and usability. Landscape scale assessments of GHGs require a combination of ground sampling, use of data from census, remote sensing (RS) or other sources and modelling. Fitting of all of these aspects together needs to be performed carefully to minimize uncertainties and maximize the use of scarce resources. This is especially true in heterogeneous landscapes dominated by smallholders in developing countries.

Keywords: landscape, smallholder agriculture, greenhouse gas, climate change mitigation



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1. Introduction

There is potential for smallholder farmers in developing countries to gain benefits from carbon (C) friendly practices.

Landscape scale quantification can enable farmers to pool resources and expertise, which could in turn put participation in carbon markets and other funding sources within their reach. Therefore, funding agencies, governments and NGOs increasingly recognize the benefits of taking a landscape scale approach to GHG quantification (FAO 2010). Havemann and Muccione (2011) recently reviewed mechanisms for climate change mitigation for smallholders and point out that a minimum scale is necessary to be financially viable. Issues of complexity and cost associated with the aggregation of smallholders across a landscape are an issue for both the compliance and voluntary sectors. Despite our poor understanding of this complexity there are a large number of reducing emissions from deforestation and degradation (REDD+) projects and efforts that are currently monitoring carbon at a landscape scale (Angelsen *et al* 2012). Examples include initiatives from countries in UN-REDD or the FCPF (Forest Carbon Partnership Facility 2012) and the work carried out in Brazil both at the national scale, in the state of Amazonas or for the Juma REDD+ Project (IDESAM 2012). In the voluntary market, Plan Vivo probably provide the best examples of large scale assessments covering areas with multiple smallholdings and accounting for a variety of sources and sinks of GHGs and indeed other ecosystem services.

The term 'landscape' is used in different ways. Here we use a definition from landscape ecology of a more or less well defined and bordered piece of land (Antrop 2000) that is larger than a single farm and smaller than a region. Within the landscape, a mosaic of land cover and land use types can occur. These are dynamic, as are the relationships that connect them. A landscape analysis should be spatially integrated recognizing that the landscape as a whole is more than the sum of its parts. A landscape can refer to a watershed or any other geographic or ecological boundary. In addition, landscapes are usually defined by social aspects and involve a wide range of stakeholders especially where numerous smallholders are involved. In many instances, political and administrative boundaries may be used for practical reasons (The Sangha Group 2008).

Landscape scale quantification can allow stakeholders to establish critical patterns and connectivity within the landscape that influence carbon dynamics. These can be used to improve mitigation and manage resources more efficiently. For example, a landscape scale approach allows transhumance (the seasonal movement of people and livestock) to be included in a way that would not be possible in a farm level analysis. Landscape assessments can be more cost effective than multiple farm level analysis when employing sampling strategies which focus on emission hotspots. In addition, techniques such as eddy covariance can account for integrated flux from multiple sources. However, there are many challenges associated with landscape scale quantification. One striking example is the need to measure, monitor and model the five carbon pools (above ground biomass, below ground biomass, dead wood, litter and soil organic carbon) defined by the IPCC (IPCC 2003). These are usually requested by carbon market related projects not only under the Kyoto Protocol but also under the voluntary carbon market.

Defining landscape boundaries and attributing emissions to given areas can be problematic. Methods for detecting leakage have been developed (Gershenson *et al* 2011) but they are still lacking in the case of mixed landscapes with multiple land uses. Access to technical equipment and expertise is another challenge and is particularly pertinent in a developing country smallholder context.

Sources of uncertainty and acceptable levels of precision and accuracy differ when working at the landscape scale as opposed to the farm or national scale. Uncertainty results from three major sources: (i) activity data (inventory), (ii) year to year variability (due to climate and management practice variation) and (iii) emission factors (Gibbons *et al* 2006). Different combinations of these sources mean that there is no direct linear link between scale and uncertainties. For instance, it is easier to get reliable data for administrative regions, whatever the scale, rather than for watersheds or ecoregions. At farm level, most activity data can be provided by farmers whereas at landscape level, data is based on statistics, on regionally available data or expert knowledge, thus uncertainties can be quite important. Evaluating the impact of these uncertainties is often difficult. The best way to proceed is to go through an iterative process, ensuring a high level of accuracy for those activities with greatest impact on the result. Large uncertainties related to using simpler approaches can be accompanied by a 'discounting' of credits. Discounting provides a direct incentive to countries to upgrade their measuring and monitoring methods. Overcoming the methodological challenges in this way enables forest degradation to be realistically included in a REDD agreement, thus making REDD more effective by accounting for a wider range of forest GHG emissions. It also increases the international equity of the REDD mechanism by encouraging participation by a wider range of countries, many of them in Africa (Murdiyarso *et al* 2008).

The purpose of this paper is to analyse current GHG quantification methods that can be used in a landscape scale analysis, to consider the advantages and disadvantages of these in terms of relevance to areas dominated by smallholders in developing countries and to discuss potential innovations for overcoming the challenges.

2. Examples of methods to date

2.1. Landscape scale measurement approaches

Due to efficiency and cost, carbon (C) accounting frameworks will likely incorporate modelling for scaling up and projection. Nevertheless, measurements are an essential element of GHG assessments at any scale (Conant *et al* 2010). In addition to providing a direct assessment of C stock changes and GHG emissions, they underpin assumptions in models and the development of emissions factors, as well as providing verification of patterns estimated by models. Taking C/GHG measurements at the landscape scale presents practical problems:- (i) the cost and resource demands of field measurement campaigns, (ii) availability of cost efficient methods that allow holistic C/GHG accounting of

multiple activities in a given landscape and (iii) equipment and subsequent analytical processes constrain the extent of sampling. This is significant because nutrient stocks and fluxes are highly heterogeneous at the plot scale, not to mention at larger spatial extents (CBP 2011a, 2011b). Capturing heterogeneity in a diverse landscape can demand an impractical number of samples and significant investment in equipment. Landscape scale measurement approaches therefore always find themselves balancing the relationships between cost, scale and accuracy, integrating modelling with measurements (Conant *et al* 2010).

Landscape estimates based on measurements will only be as reliable as the data that are used to derive them. A premium is thus placed on the sampling strategy. The sampling strategy must adequately characterize the magnitude or change in the pools/fluxes of interest and the relative frequency of occurrence throughout the landscape. Several steps are needed when defining the sampling approach including definition of the landscape boundary, landscape stratification and selection of the sampling methods and size (Ravindranath and Ostwald 2008). The latter being a function of expected heterogeneity, the stock or flux to be considered, the accuracy and precision demands of the intended use and the resources available. Consideration of all of these factors, in addition to the occurrence of 'hot spots' of C/GHG flux, should be accounted for to ensure efficient resource use and to improve estimates.

One approach is to use a nested sampling design. Measurement sites are nested in a spatially stratified hierarchical fashion across the landscapes. Sampling may include soil cores, biomass and tree parameters, as well as trace gas samples with chambers or tower-based approaches, amongst others. For example, nested designs are being used to estimate soil C stocks in 60 landscapes (10 km × 10 km) throughout sub-Saharan Africa with the Land Degradation Surveillance Framework (CBP 2011c). Nested designs provide broad spatial coverage with fewer samples required to deliver sensible characterization of landscape elements and their composite. Other successful approaches have relied on stratifying the landscape based on land cover type. Use of land cover to guide sampling patterns is logical given the relationships between land cover and nutrient stocks/fluxes. Tree growth habits differ depending on location, be it for forest, agroforestry, or perennial croplands such as fruit and nut tree stands. Contextually appropriate allometric equations are therefore needed for each variant (Kuyah *et al* 2012). In a grass ecosystem, chamber-based and eddy covariance measurements of CO₂ and CH₄ fluxes were shown to agree well when the areal extent of all source components were accounted for in the scaling equations (Schrier-Uijl *et al* 2010). Stratification, by spatial extent or land cover, is a fundamental component of efficient sampling design.

Sampling strategy cannot be separated from measurement method. Methods differ in their cost, sophistication and geographic and temporal coverage. Chamber measurements can measure soil gas fluxes and are relatively cheap and simple to use. However, since chambers cover a limited fraction of the soil surface (<1 m²) and measurements are taken at discrete time intervals, there are concerns over their

representativeness (Davidson *et al* 2002, Wolf *et al* 2010). In addition to chamber design, positioning and deployment of chambers can greatly influence flux estimates (Rochette and Eriksen-Hamel 2008). Up scaling from flux estimates may propagate measurement errors and thus must be done with caution to avoid biased estimates of landscape fluxes.

Recent development of novel technologies could help overcome some of the challenges. Mobile technologies such as GPS applications in mobile phones offer new ways of accurately reporting sampling sites and landscape boundaries. Advances in hand held video mapping devices linked to GIS and a GPS offer a means of reducing the necessary sample size (Stohlgren *et al* 2000, Skutsch 2005). Shifts in laboratory techniques may also help. Many laboratory methods to measure soil organic C can require significant sample preparation and analysis time (wet combustion, dry combustion), in addition to expensive equipment (LECO) further increasing costs. Increased use of diffuse reflectance infra-red spectroscopy, both in laboratory and field settings, provides the potential to greatly increase sample analysis without increasing analytical cost by comparisons to wet chemistry (Shepherd and Walsh 2007, Knadel *et al* 2011). This technique however relies on calibration libraries which, although being developed for many regions, are still far from comprehensive.

Measurements provide a collection of point data characterizing nutrient stocks and fluxes for various components of the landscape. Deriving landscape scale estimates will also rely on an integrated approach involving other methods such as remote sensing for stratification (section 2.2) and modelling for up scaling (section 2.3) (CBP 2011a, Goidts *et al* 2009).

2.2. Approaches using remote sensing

2.2.1. Introduction to remote sensing. There are a variety of sensors used in making earth observations that are either active or passive sensors. Active sensors include LIDAR (light detection and ranging) and RADAR (radio detection and ranging) that emit energy and measure attributes of the returned energy. Passive sensors detect reflected radiation from a landscape or radiation emitted by landscape features. Remote sensing (RS) has been used for the past several decades to monitor land cover and land cover change throughout the tropics (Skole and Tucker 1993). The magnitude and rates of tropical deforestation have been well documented through RS methods and techniques (FAO 2011). Remote sensing has also been used to document the various drivers of tropical deforestation including logging, fire, large scale commercial agriculture and small holder agriculture (Wang *et al* 2005, Matricardi *et al* 2010).

2.2.2. Remote sensing of land cover and land cover change.

The primary uses for remote sensing in quantifying landscape GHG emissions/removals in the agriculture, forestry and other land use (AFOLU) sector are to measure the extent of land cover and changes in land cover, and stratification of the landscape prior to conducting ground inventories (Hairiah *et al* 2011). The IPCC refers to the land area parameter in

GHG emissions calculations as a type of activity data, which are the human actions or consequences of those actions that influence GHG emission rates (IPCC 2006). Remote sensing techniques are well established to classify land cover and to measure changes in area between different land covers through time series analysis of historical remote sensing data (GOFC-GOLD 2011).

2.2.3. Remote sensing of carbon stocks. Remote sensing techniques are increasingly being used to estimate landscape carbon density and carbon stocks—a type of IPCC emissions factor that is also required for calculations of landscape GHG emissions (Goetz *et al* 2009). Remote sensing methods using both active and passive sensors are maturing for the estimation of above ground biomass stocks by measuring forest greenness, forest height, canopy attributes, or other biophysical parameters. Low (200 m) or moderate (30 m) resolution satellite data can be used to measure the fractional cover of large scale closed canopy forests and then correlated with ground measurements of forest carbon density to map carbon stocks across large area landscapes. Analysis of multiple date satellite data can then estimate GHG emissions or sequestration from land cover change. Fine (<1 m) resolution satellite data can be used to directly measure crown attributes of individual trees in open forests or in non-forest land covers (Palace *et al* 2008). The above ground biomass (AGB) of these individual trees can be determined through allometric relationships between crown characteristics and AGB to map landscape C in open land covers such as woodlands, savannahs, agroforestry systems, and human settlements (Brown *et al* 2005). Allometric equations are freely available for all continents, including Africa with its first open-access database that contains more than 850 equations (Henry *et al* 2011). Airborne or space borne LIDAR sensors can directly measure forest height in closed canopy forests which correlates to AGB of various forest types (Saatchi *et al* 2011). Radar data are also being used to map low density woodlands and agricultural landscapes in Africa (Ryan *et al* 2012). Remote sensing analysis is in early development for estimating soil organic carbon stocks in agricultural landscapes where bare soil is visible to the satellite sensors. Soil reflectance values from satellite imagery can be correlated with laboratory measured reflectance values from near infra-red spectroscopy of SOC to map these SOC stocks across large agricultural landscapes (Betemariam *et al* 2011).

2.2.4. Remote sensing indices. Carbon offset markets and national inventories for the UNFCCC typically require the monitoring, reporting and verification of GHG emissions in units of tonnes of carbon dioxide equivalents (tCO₂eq) (VCS 2012). This level of measurement and monitoring requires a large financial expense. A field-based carbon inventory is needed for the five carbon pools in the six IPCC land use categories within the project boundaries and this may become cost prohibitive in complex smallholder landscapes. However, there are other related metrics that could provide insightful analysis into the carbon benefits resulting from smallholder

investments and activities on their lands. Monitoring and evaluation efforts for development projects might utilize remote sensing indices of biophysical parameters as a lower cost option to measure the impacts of their investments on smallholder landscapes. The Carbon Benefits Project (CBP) proposes several categories of project assessments and indices that are built upon RS analysis of coarse, moderate and fine resolution satellite imagery that are cost effective for large scale projects involving many smallholders across heterogeneous landscapes (CBP 2011d). Parameters such as hectares of land cover change, tree or forest canopy cover, Tier 1 carbon stocks, topography, and fire occurrence could be integrated with satellite data and analysis to develop simple but robust indices that illustrate landscape carbon benefits. These indices offer a low cost means of monitoring and evaluating the impacts of development efforts and changes in agricultural and forested landscapes.

2.2.5. Access to remote sensing data. Although the high cost of satellite RS data has historically been a barrier for researchers in both developed and developing countries, there are now multiple data sources that provide free or low cost satellite data including both MODIS and Landsat satellite data from the National Aeronautics and Space Administration (NASA). Even though these data are now readily available, technical capacity to store large data sets and process complex remote sensing data sets still remains as a barrier for smallholders, researchers and government agencies in developing countries. While government agencies have been the primary early developer of satellites and sensors for remote sensing, private commercial companies are now providing fine resolution satellite data (< 1 m pixels) although costs around \$15 USD km⁻² may still be a barrier. Aerial LIDAR flights and data collection are also available from commercial vendors but costs are again a barrier in developing countries.

2.2.6. Remote sensing applications for smallholders. Smallholder agricultural systems are typically more complex than industrial agricultural systems and may also incorporate more above ground woody biomass on their land through the use of agroforestry systems (Henry *et al* 2009). The availability of fine resolution satellite data, where single pixels (0.5 m) are smaller than individual tree crowns, allows for measurement of trees in agricultural landscapes (even trees as small as 10 cm in diameter at 1.3 m often have crown projection areas >10 m²). Crown attributes measured by satellites can be related directly to above ground biomass through specialized allometric equations or simply to diameter at breast height (DBH) for input into standard allometric equations that predict above ground biomass from DBH. Landscape carbon in complex smallholder agricultural systems can then be mapped by integrating RS analysis and basic tree inventory methods in the field. For example, the CBP is developing remote sensing methods and integrating them with online carbon management tools to enable smallholders to measure and monitor carbon in trees outside forests, agroforestry systems and other non-forest land covers (CBP 2011a).

Although smallholder farmers would not be involved with RS analysis, they certainly can contribute basic tree measurement or forest inventory data from their land. These inventory data can be uploaded into an online geographic information system that calculates C stocks and emissions associated with current land cover and potential land cover changes. Regardless, availability of the RS data may be a longer term challenge for implementing this type of accounting system.

2.3. Modelling

Models have an essential role to play in landscape scale assessments and GHG accounting in general (IPCC 2006, Conant *et al* 2010). They can be used to scale-up information from measurements of C stock changes and GHG emissions and make future projections. The majority of models are based on large data sets and a variety of assumptions about a system which give an approximation of the actual situation. They therefore have an inherent level of uncertainty which can be quantified with appropriate methods. The purpose for which a GHGs assessment is being carried out (e.g. a report to funding agency, an inventory or to gain certification) and the associated level of accuracy and precision, should determine the type of model that is used.

2.3.1. IPCC models and existing calculators. The Intergovernmental Panel on Climate Change (IPCC) developed a series of mathematical equations for estimating GHG fluxes that uses both data on land management activities and factors that describe emissions and removals from these activities (IPCC 2003, 2006). The method can be employed using default information (a Tier 1 approach) or, if available, country, region, landscape or even project specific data (a Tier 2 approach). Benefits of the approach are that it uses a lot of information farmers may already have. Drawbacks are if a Tier 1 approach is used, much of the data originate from North America and Europe and is highly aggregated.

The method forms the basis of several GHG accounting tools which can be used at the landscape scale in developing country areas (ALU, USAID AFOLU Carbon Calculator, The CBP Simple and Detailed Assessments and EX-ACT). Most of these allow the user to input their own emission and removal factors. The EX-ACT tool has been widely used including a large scale ex-ante assessment of two rural development projects in Brazil dominated by smallholder farmers (Branca *et al* 2013). Several watersheds covering over 800 000 ha were analysed. All land use in the area and transitions between them were accounted for in these projects. EX-ACT allows the user to analyse any mosaic of land as the inputs and outputs are not spatially explicit. A different approach is taken by the USAID AFOLU Carbon calculator which carries out analysis of specific administrative units, although data for a different scale can be entered by the user (Harris and Casarim 2010). The CBP's tools allow a more spatially explicit approach as the user can divide a landscape into numerous adjacent sub-units and enter detailed land management information for each of these before carrying out an integrated analysis which gives spatially explicit output (Milne *et al* 2010).

2.3.2. Dynamic ecosystem models. One distinction between emission factor-based calculators and ecosystem models is the former are stock-taking approaches whereas the latter are based on flows between different compartments of the system. This allows ecosystem models to simulate emission pathways and make predictions about the future for a variety of cases whereas other instruments often treat the time between two stock-taking exercises as black boxes and can only make predictions that are based on past emission trajectories. Ecosystem models such as Century (Parton *et al* 1988) and DNDC (Li *et al* 1992) have the advantage of describing the underlying dynamics of a system. They use complex functions to describe the movement of SOC through different pools and include sub-models of plant productivity, water movement and the turnover of N, P and K. A major benefit of using processed-based models for scaling purposes is their ability to estimate several measurable variables at the same time (Turner *et al* 2004). They do however need to be parameterized for the conditions they are used in. Such ecosystem models are designed for site scale application and although there are some drawbacks to using them at the larger scale (Paustian *et al* 1997), they have successfully been used for landscape scale assessments. Moreover, dynamic ecosystem models (when parameterized correctly) have been shown to decrease uncertainties in estimates, compared to estimations made using the IPCC equations (Del Grosso *et al* 2011).

Use at the landscape scale involves the linkage of the ecosystem model to a geographical information system (GIS). For example, extensive work has been carried out linking the Century model to a GIS to make state and regional scale estimates (Paustian *et al* 1995, 2001, 2002). Climate, soils and land use data sets associated with specific geographic areas are overlain in a GIS to create a unique set of polygons that define driving variables needed to run Century. This approach formed the basis of the development of the GEFSOC Modelling system, a scalable system which allows the user to estimate the impacts of varying land management practices on C stocks in soils and biomass (Easter *et al* 2007, Milne *et al* 2007). Paustian *et al* (1995) point out the need to evaluate model performance in the conditions particular to the region under investigation as most ecosystem models have been developed in North America and Europe. Therefore, a large part of the development of the GEFSOC system involved parameterization and evaluation of Century using data from four developing country test cases (Bhattacharyya *et al* 2007, Cerri *et al* 2007, Kamoni *et al* 2007). The system is therefore suitable for use in a wide range of developing country situations.

Use of ecosystem models linked to GIS for landscape scale GHG assessment involves a certain level of expertise in ecosystem modelling and GIS. This can prohibit use by farmer groups or those representing them, making many of the simpler calculators based on computational methods more accessible (USAID AFOLU, CBP SA, EX-ACT). An example of a US-based calculator is COMET-VR, which involves multiple Century runs linked to a database of soils climate and land use for the USA (Paustian *et al* 2009). The user needs knowledge of current and historical land management

in his/her parcel of land to be able to estimate landscape scale changes in C stocks in soils. The output also includes a rigorous estimate of uncertainty using an empirically based method (Ogle *et al* 2007). Although COMET-VR is restricted to estimates of SOC changes in the USA, this type of approach has potential for estimates of net GHG balance in agricultural landscapes around the World.

A slightly different approach is taken by the APEX model (Gassman *et al* 2009). Rather than using overlain layers of GIS to create unique polygons, the user has to divide a given watershed into sub-units. Each sub-unit has homogeneous soils, climate and land use. Users can then link these units to model the flow of water and nutrients between them. Lateral flows become important where slope induces mass transport out of one compartment into the next. For instance, when nitrogen leaches into groundwater and is then transported off-site, it can be emitted as N₂O from an adjacent compartment. However, whether such emissions will be of a significant order of magnitude remains unclear. The APEX model is a multi-unit version of the soil erosion model EPIC and as such, its primary focus is impacts of land use/management on water and nutrient loss. However it does model C and N cycling, providing emissions of CO₂ and N₂O in its output.

The calculators and models which cover developing countries and can be applied at the landscape level have been developed for a range of purposes and therefore have different strengths and weaknesses (see Colomb *et al* 2013, for calculators). Some key aspects include analysis of uncertainty, non-land use GHG emissions and availability in multiple languages. A review of these attributes is given in Milne *et al* (2012).

2.4. Integrated resources

All measurement-based approaches build on models that allow the observable datasets to inform target variables (in this case GHGs or C stocks); and all modelling approaches build on observable metrics (e.g. management practices; activity data) that feed into the models, whether they use simple regressions that link EFs to activity data such as those of the IPCC Tier 1 and 2 approaches or derive the target values from complex interrelationships in mechanistic ecosystem models such as CENTURY or DNDC. Therefore landscape scale assessments of GHGs require a combination of ground sampling, use of data from census, RS or other sources and modelling to upscale results and make forward projections. Fitting all these aspects together needs to be done carefully to minimize uncertainties and maximize use of scarce resources. This is especially true in heterogeneous landscapes dominated by smallholders in developing countries. However, examples of integrated resources that provide guidance on all of these aspects, in particular collecting data for all of the parameters needed to run specific calculators and models, are few and far between. The CBP toolset is an early example of a resource that provides online calculators, guidance tools and protocols for collecting data for specific calculators and is tailored to the needs of developing countries.

3. Conclusions—research gaps and looking forward

There are advantages and constraints associated with different quantification methods (table 1). A constraint common to all methods is the issue of accurately defining a landscape boundary. Innovations in hand held GPS, mobile phone applications and video mapping linked to GPS are making this easier, along with free access to RS images through applications such as Google Earth and geographic data through initiatives such as Open Street Map. The same technologies are also aiding sampling design for measurement approaches. This can be a hindrance in developing countries where reaching randomly predefined sites for sampling can be challenging. For large scale ground measurement campaigns, RS technologies can be used to aid sampling designs that identify hotspots to minimize sampling costs.

Techniques such as eddy covariance could be useful in the future; however use is limited to flat relatively homogeneous areas making applicability to smallholders limited. Cost is also a major barrier. Investment is needed in landscape scale measurement techniques such as near infra-red spectral reflectance. This technique relies on calibration libraries of soil samples, which are lacking for many areas of the developing world. For approaches based on RS, high resolution RS data is becoming more accessible and costs are coming down but both can still be a barrier to use in developing countries.

There are a number of models that can make landscape scale assessments. These have different demands in terms of expertise and data inputs. Over time, measurements of land use systems with clear distinctive features will eventually allow improvement of modelling tools. However, currently, far too few examples exist from developing countries, particularly from Africa and Southeast Asia to calibrate the existing regression and mechanistic models to reflect tropical soils from low input farming systems.

There is also a need to include landscape specific analysis of uncertainty in most of the models currently available. Most tools that provide guidelines or estimates of uncertainty build on the IPCC best practice guidance (2006) which relies mainly on error propagation. It is well established that uncertainties in environmental modelling are scale dependent (Heuvelink 1998), with some source of uncertainty gaining or losing significance as one moves from the farm to the landscape scale. Therefore, tools that aggregate farm level data to produce a landscape scale assessment could produce misleading estimates of uncertainty if the same summation approach is applied to sources of uncertainty.

Advances in linking dynamic ecosystem models to GIS, and increased computing power, have led to the development of user friendly tools that can be used online by land managers (COMET-VR, COMET Farm). At the moment the two main barriers to extending such tools to smallholder areas in developing countries are; (1) a lack of default data with relevance to the land management systems found in smallholder areas in developing countries and (2) a lack of accessible systems which are comprehensive enough to allow smallholders to input their own data. Investment is needed to

Table 1. Methods for the quantification of GHG emissions at the landscape level for developing countries in smallholder contexts (Note: l = low, m = medium, h = high.)

Approach	Suitability to landscape approach in general			Relevance to landscapes dominated by smallholders			Accessibility for developing countries				Stocks and fluxes covered
	Defining boundaries	Managing integrated data	Accuracy	Dealing with multiple land use classes	Accounting for changes in land management	Account for small heterogeneous sources and sinks	Specialist expertise needed	Specialist equipment needed	Cost	Labour	
Large scale ground sampling	Time consuming to define boundary	Generates large data sets that need to then be integrated	High	Yes with good stratification and sampling strategy	Yes	Can do with appropriate sampling strategy but costly	Can be low or high tech	Can be low or high tech	H	H	All
Remote sensing approaches	Good way of defining boundaries	Data from large areas on C in AGB and soils but flux has to come from other methods	Variable depending on land cover	Most useful for land with trees but techniques for other land classes being refined	Only if they result in a significant change in AGB	Costly if small scale detail is required	Yes	Yes especially for data processing	H/M	M	C stocks
Modelling	Some models spatially explicit others no spatial element	Several models available that integrate data from many sources over large areas	Depends on model and input data. Can be low if using Tier 1 approach	Several models deal with emissions from multiple sources from multiple land classes (CBP SA, EX-ACT)	Yes	Difficult at the landscape scale as long model runs with large data sets required	For some online calculators no	No	L	L	All

bring existing sources of this data together. In addition, more research is needed into the development GHG accounting models that deal with interaction of multiple activities which promote GHG emissions/removals and with lateral flows of nutrients, water and carbon thereby presenting an integrated approach. Likewise more resources which provide specific protocols and guidance on how to use different methods in an integrated way (collecting measurements to run specific models) would improve accessibility to smallholders in developing countries.

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