International Journal of Agricultural
Science and Research (IJASR)
ISSN(P): 2250-0057; ISSN(E): 2321-0087
Vol. 5, Issue 6, Dec 2015, 31-44

LOW-COST QUANTIFICATION OF GREENHOUSE GAS EMISSIONS IN SMALLHOLDER AGRO-ECOSYSTEM: A COMPARATIVE ANALYSIS OF METHODS

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ABSTRACT

Quantification of greenhouse gas (GHG) exchanges between agricultural field and the atmosphere is essential for understanding the contribution of various production systems to the total emissions, develop mitigation options and policies, raise awareness and encourage adoption. But, GHG quantification from smallholder agricultural landscape is challenging primarily because of the heterogeneity of production systems. Various methods have been developed over years to quantify GHG fluxes between agricultural ecosystem and atmosphere. In this paper, we reviewed and analysed the common methods with regard to their scale and precision of quantification, cost effectiveness, prospects and limitations focusing mainly on smallholder production systems. As most of the quantification methods depend on ground data and due to data deficit for smallholder systems, field measurement must be an essential part of GHG emission inventories under such systems. Chamber-based method is a principal approach for field level quantification under smallholder production system mainly because of its cost effectiveness, portability and adoptability under diverse field conditions. However, direct measurement of GHG for all mosaics of smallholder production landscape is impractical and therefore use of models becomes imperative. Here, selection of suitable models and their rigorous parameterization, calibration and validation under various production environments are necessary in order to obtain meaningful emission estimation. After proper validation, linking dynamic ecosystem models to geographic information system (GIS) helps estimating GHG emission within reasonable time and cost. Integration of different approaches such as chamber-based measurement to generate field data, simulation modelling by using empirical as well as process-based models coupled with use of satellite imagery may provide a robust estimate of GHGs emission than use of a single approach.

KEYWORDS: Greenhouse Gas, Smallholder Production Systems, Agriculture, Climate Change, Modelling

Original Article

Received: Oct 02, 2015; **Accepted:** Oct 13, 2015; **Published:** Oct 18, 2015; **Paper Id.:** IJASRDEC20155

INTRODUCTION

Agricultural sector is one of the major emitters of GHGs accounting for 14% of total anthropogenic emission (Schaffnit-chatterjee, 2011).Developing countries currently account for about three-quarters of direct emissions and are expected to be the most rapidly growing emission sources in the future. Expansion of agricultural land also remains a major contributor of GHGs, with deforestation largely linked to clearing of land for cultivation or pasture, generating 80% of emissions from developing countries (Hosonuma et al., 2012). Unnecessary tillage for land preparation and planting, indiscriminate irrigation and fertilizer application are the main sources of GHG emission from agricultural production systems. Methane and nitrous oxide are the main agricultural GHGs accounting for 10%–12% of total global anthropogenic emissions (Smith et al., 2008)mainly through direct N_2O emissions from soils, CH_4 emission from enteric fermentation, biomass burning, rice production, and manure management (Vermeulen, Campbell, & Ingram, 2012). At the same time, agriculture is part of the solution in mitigating climate change: by reduction of GHG emission into the atmosphere as well asabsorption of atmospheric carbon into plant biomass and soil. Therefore, agricultural production system can be either a net sources or sinks of GHGs depending on the management practices.

Understanding the dynamics of fluxes between agricultural fields and the atmosphere is essential for knowing the contribution of various production systems to the total GHGs emission. This helps farmers, researchers and policymakers to understand how mitigation can be integrated into policy and practice. Quantification of GHG emissions from agricultural production systems is also important to guiding national planning for low-emissions development, generating and trading carbon credits, certifying sustainable agriculture practices, informing consumers' choices with regard to reducing their carbon footprints and supporting farmers in adopting less carbon-intensive farming practices (Olander, Wollenberg, Tubiello, & Herold, 2013). Better information on greenhouse-gas (GHG) emissions and mitigation potential in the agricultural systems also help manage these emissions and identify solutions that are consistent with the food security and economic development priorities of countries.

With these realizations, quantification of GHGs from agricultural production systems has been the subject of intensive scientific investigation recently. This need has driven the development of different methods for measuring exchanges of GHGs between agricultural landscape and atmosphere. Denmead (2008) broadly classified them into two categories: chamber and micrometeorological methods. With rapid development of technologies, use of models and remote sensing for GHG quantification is increasing. This review focuses mainly on the methods applicable to the smallholder production systems with regards to their operations aspects along with their strengths and weaknesses. The aim is to provide users with helpful information for choosing the most appropriate methods based suitable for the objective, scale and cost.

CHAMBER METHOD

Chambers are classified as flow through or non-flow through i.e. closed chamber (Rochette & Eriksen-Hamel, 2008). In a flow-through chamber, a constant flow of outside air is maintained through the headspace of the chamber and the difference in gas concentration between the air entering and leaving the headspace is measured. In a closed chamber, on the other hand, there is no or a very small replacement of air in the headspace so that the gas concentration increases continuously. The closed-chamber method described by Rolston et al. (1978) is the most common method used for measuring gas exchange between the soil and the atmosphere. Close-chamber techniques have been used to estimate soil respiration for more than eight decades and still remain the most commonly used approach (Rochette & Eriksen-Hamel, 2008; Rochette & McGinn, 2004). This method permits measurement of very small flux, is relatively inexpensive and can be adapted to a wide range of field conditions and experimental objectives (Sapkota et al., 2014).With this method, flux measurements can be taken multiple times during the year for estimating seasonal or annual flux. This method is very useful for quantifying the impact of various treatments but their coverage is limited over space and time.

The operating principle of close chamber method is to restrict the volume of air with which gas exchange occurs so as to magnify changes in concentration of gas in the headspace (Denmead, 2008). The increase in gas concentration over time indicates the amount of flux from the soil. For this method, chambers are placed in specific locations on the agriculture field. At certain time intervals, air samples are physically extracted from the chamber headspace employing either manual or automated system. The concentration of GHGs in the air samples is quantified in a gas chromatograph. Soil flux is then determined through the relationship of headspace gas concentration with time.

More than 95% of the thousands of published studies on GHG emission used chamber methodologies (Rochette, 2011). Chamber-based method with manual system has particular advantage in smallholder production system of developing countries because they are low cost, portable, and require no power in the field. The drawbacks include its inability to capture all spatio-temporal variability of episodic emissions such as nitrous oxide due to limited replication and logistical (time and human labour) constraints. Further, chambers can alter the soil environment and microclimate, potentially introducing biases and artifacts to the soil fluxes(Glenn, Amiro, Tenuta, Stewart, & Wagner-Riddle, 2010). Nevertheless, given its cost-effectiveness, versatility and adoptability, chamber method is suitable for the smallholder system of developing countries. Adoption of this approach to quantify N_2O emission in irrigated rice(Kumar, Jain, Pathak, Kumar, & Majumdar, 2000; Majumdar, Kumar, Pathak, Jain, & Kumar, 2000; Malla et al., 2005)and leguminous crops (Ghosh, Majumdar, & Jain, 2002), to quantify methane emission from rice-wheat cropping system(Pathak et al., 2003) and to quantify GWP of rice-wheat system(Bhatia, Pathak, Jain, Singh, & Singh, 2005) are some of the examples of use of chamber-based method for GHG quantification in small-holder production systems.

MICROMETEOROLOGICAL METHODS

Micrometeorological approaches assume that fluxes are nearly constant with height and that concentrations change vertically not horizontally. The flux at particular height ‘z’ depends on whether the ground is source or sink. Various micrometeorological methods such as eddy covariance (Burba, Madsen, & Feese, 2013), flux gradient (Glenn et al., 2010; Pattey et al., 2007), eddy accumulation (Desjardins, Buckley, & Amour, 1984) and backward Lagrangian dispersion (Flesch, Wilson, & Yee, 1995) with various degree of complexity have been developed to determine the net exchange of GHGs between landscape and atmosphere. These methods have advantage of providing continual measurement and can take into account temporal and spatial variability of flux. But generally, they require large footprint area of similar landscape and depend on many assumptions, violation of which may result into serious errors in measurement and interpretation. Further, these methods are expensive; require sophisticated instrumentation and high technical capacity all of which may be prohibitive for its adoption in smallholder production system of developing countries.

MODELLING

Direct measurement of GHG emissions for all landscape types in smallholder production systems is impractical as it would require many measurements to be made over large areas and for long periods of time. Therefore, development and use of model to predict GHGs emission is imperative. The models not only allows the simulation of agricultural GHGs emission at a range of scales i.e. from field through landscape to national and regional scale, but also the exploration of potential mitigation strategies. They are particularly essential for landscape scale assessments (Conant, Ogle, Paul, & Paustian, 2010; Eggleston, Buendia, Miwa, Ngara, & Tanabe, 2006). Considering these needs, a number of models have been developed for assessing GHG emissions from agricultural production systems besides IPCC’s work and progress on methodological issues. Different authors have classified modeling approaches differently. For example Babu et al. (2006) classified GHG quantification models into empirical, semi-empirical, regression and process-based models whereas Denef et al. (2012) have broadly classified them into calculators, protocols, guidelines and models. Based on the approach taken for GHG quantification, we categorize them into three groups i.e. a) guidelines, b) empirical models, tools & calculators and c) process based models. The former two groupsare based on the emission-factor associated with activities whereas third group takes into account interaction between different processes within the systems. Each group has its own advantage and disadvantage with regards to time taken for the study, data requirement, cost effectiveness as well as accuracy and reliability of the estimates.

Intergovernmental Panel on Climate Change (IPCC) Guidelines

In order to meet United Nations Framework Convention on Climate Change (UNFCC) reporting requirement for 37 industrialized countries, IPCC published guidelines for calculating national inventories in 1996(Houghton et al., 1997). These were subsequently revised in 2000, 2003 and 2006 and allowed for quantification of national emissions based on readily available activity data such as power usage, fossil fuel consumption, fertilizer use, animal number, land use change, as well as associated emission factor for each activity (Crosson et al., 2011). IPCC classifies GHG accounting systems into three i.e. Tier 1, Tier 2 and Tier 3 approaches. Tier 1 is a general approach with average emission factors provided for large eco-regions of the world. To estimate CO_2 emission from energy consumption and all N_2O and CH_4 emission, this method considers multiplying activity data by its specific emission factor for each source (Colomb et al., 2012). Tier 2 is also similar to Tier 1 but use state or region specific data, with more accurate emission factors when available. Tier 3, on the other hand, is a very detailed approach usually including biophysical modelling of GHG processes. IPCC methodologies provide set of generalized guidelines for estimating GHG emissions at various time also under smallholder production system but use of too generalized emission factor may mask the considerable variability which occurs among the smallholder farms (Crosson et al., 2011).

Empirical Models, Tools and Calculators

These are automated web-, excel-, or other software-based tools and mathematical equations developed for estimating GHG fluxes or emission reduction from agricultural and forest activities. These models are less complicated and require less amount of dataset as input to predict GHG emission from a product, production system and management practices. Most of them are based on the activity data (inventory) and associated emission factors developed elsewhere but some of them also take into account pedo-climatic condition. Various organizations and individuals have developed these models or calculators with diverse objectives such as raising awareness, GHG inventory, product footprint calculation, project evaluation and so on and they are suitable for defined geographical coverage. Therefore, users should choose the appropriate calculator based on the objective of the study and major factors contributing to the total emission. Further, direct comparison between studies done using different calculators is impossible. Detailed review of major GHG calculators in agriculture and forestry sector can be found in Colomb et al. (2012).

EX-ACT (Ex-Ante Carbon balance Tool), Holos and CBP (Carbon Benefit Project) are useful tool to evaluate GHG emission of various development and sustainable land use project. For example, EX-ACT has been widely used including a large scale ex-ante assessment of two rural development projects in Brazil dominated by smallholder farmers (Branca, Lipper, McCarthy, & Jolejole, 2013). EX-ACT allows the user to analyse any mosaic of land as the inputs and outputs are not spatially explicit. The CBP tool allows 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., 2013). Some calculators such as carbon calculator NZ, CALM (Carbon Accounting for Land Manager) are specifically developed to increase climate change awareness to farmers and land managers and to test the impact of various environmental schemes from the perspective of GHG emission. Few calculators (e.g. CFT, CoolFarmTool) are product oriented to calculate environmental footprint a production system or product. The result coming from such calculators contains three types of uncertainties i.e. uncertainties related to farm inventory, uncertainties related to climate induced variation and uncertainties due to emission factors. Together, these uncertainties can be very high particularly in the mosaic landscape of small-holder production systems. Therefore, the results out of these calculators should also include these uncertainties and interpreted accordingly.

Good part of using empirical tools or calculators in smallholder production system is they require less data and almost all data are available at least at farm level. The accuracy level is sometime questionable but active research is on-going and most developers are frequently updating their calculators. Given the level of information that is available, these calculators can be promising tools for quantification GHG emission under smallholder farming condition of developing countries. Further, almost all the calculators are available on their website or asking the developer free of cost. Many also provide detailed guidelines on how to use them and related assumptions. Although, there is a huge prospect of using GHG calculators in developing countries, most available calculators are developed in economically well-off countries; about 80% of the commonly used calculators are developed in USA and Australia. So, more calculators should be developed taking into account the smallholder production environments of developing countries.

Process-Based Models

One distinction between emission factor-based calculators and process-based models is that the former are stock-taking approaches whereas the latter are based on flows between different compartments of the system. This allows process-based 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. Process-based models are dynamics and take into account many management practices such as tillage, fertilizer, irrigation, crop protection etc. as well as their interaction with soil, climate and other management practices. Inclusion of these processes in modelling can enhance extrapolation reliability making it possible to model at ecosystem level.

Over the time, a number of process-based models have been developed to quantify GHG emission from agricultural production systems. For example, DAISY (Hansen, Jensen, Nielsen, & Svendsen, 1990) and CENTURY (Parton et al., 1993) describe the soil carbon dynamics in detail. The DayCent model is the daily time-step version of the CENTURY which reliably simulates fluxes of C and N between atmosphere, vegetation and soil under various native and managed systems (Del Grosso et al., 2002). The denitrification-decomposition (DNDC) model, originally developed to simulate biogeochemical cycling of nitrogen, also simulates C and N dynamics from agricultural landscapes (Giltrap, Li, & Saggar, 2010; Li, Frolking, & Frolking, 1992; Li, 2000). Cao, Gregson, & Marshall (1998) developed a process-based CH_4 emission model to predict CH_4 emission from rice fields. Matthews, Wassmann, & Arah (2000) simulated CH_4 emission from rice fields in China, India, Indonesia, Philippines and Thailand by using process-based 'Methane Emission from Rice Ecosystem' (MERES) model.Aggarwal, Kalra, Chander, & Pathak (2006) developed InfoCrop to simulate the effect of weather, soils, agronomic management practices such as planting, nitrogen, residue and irrigation and major pests on crop yield as well as C, N and water dynamics. Some researchers in South Asia(Pathak, Saharawat, Gathala, & Ladha, 2011; Saharawat et al., 2011) are using the InfoRCT (Information on Use of Resource-Conserving Technologies) simulation model to estimate GHGs emission fromrice-wheat production system. This model integrates biophysical, agronomic, and socioeconomic factors to estimate GHG emission by establishing input-output relationship related to water, fertilizer, labour and biocide uses.

Process-based models have the advantage of describing the underlying dynamics of a system. For example, process-based models use complex functions to describe the temporal dynamics of SOC through different pools and include sub-models of plant productivity, water movement and the turnover of plant nutrients. A major benefit of using processed-based models for scaling purposes is their ability to estimate several measurable variables at the same time (Turner, Ollinger, & Kimball, 2004) . Each model has its own strategy and philosophy. The extrapolation reliability and simulation power of the model depend on the mechanistic understanding and sub-modeling of the individual processes and driving variables involved. These models, when parameterized correctly, have been shown to decrease uncertainties in estimates, compared to estimations made using the IPCC equations and empirical models(Del Grosso, Ogle, & Parton, 2011)

The use of process-based ecosystem models linked to GIS for landscape scale GHG assessment involves a certain level of expertise in ecosystem modeling and GIS. This can prohibit the use by farmers' groups or extension workers in developing countries, making many of the calculators, based on simple computational methods, more accessible. Although most models can estimate GHG emission at one site with reasonable accuracy, their potential for simulating emissions at other sites with different management practices remains unknown. This requires large number of validation test across different mosaics of the landscape before such models can be used for landscape level quantification.

LIFE CYCLE OR WHOLE FARM APPROACH

Environmental analysis of product using life cycle assessment (LCA) takes into account the entire production system. The most specific characteristics of the LCA methodology is the "life cycle thinking" i.e. to consider the entire network of main and sub-processes relevant to the production(Brentrup, Küsters, Kuhlmann, & Lammel, 2001). Because of the integrated nature of the agricultural production system, whole farm and life-cycle approach can be used focussing on GHG quantification until farm gate of the production system. Here, emissions from the different components are summed up to total GHG budget. The main phases of LCA are goal and scope definition, life cycle inventory analysis, life cycle impact assessment and life cycle interpretation. Here, carbon footprint of the production system or farm can be calculated on per unit of area as well as per unit of final product. One can define the system boundary of the analysis at the beginning which generally includesproduction of agricultural inputs, field production processes and soil processes leading to change in soil C and N pool (Fig. 1;Brentrup et al., 2001). In this approach, production inputs such as fertilizer, compost, manure, machinery and other chemicals as well as management information such as tillage, cover crops, and residue are obtained from within the pre-defined system boundary. The emission factor associated with these inputs and management practices can be obtained from published literature. Similarly direct and indirect emission of GHGs can be estimated following published literature(e.g. Eggleston et al., 2006). As many agricultural production systems produce more than one product, it is necessary to attribute environmental impact to each product from the system using appropriate allocation approach. Based on the availability of activity data this approach can be applied in smallholder production system with varied degree of detail.

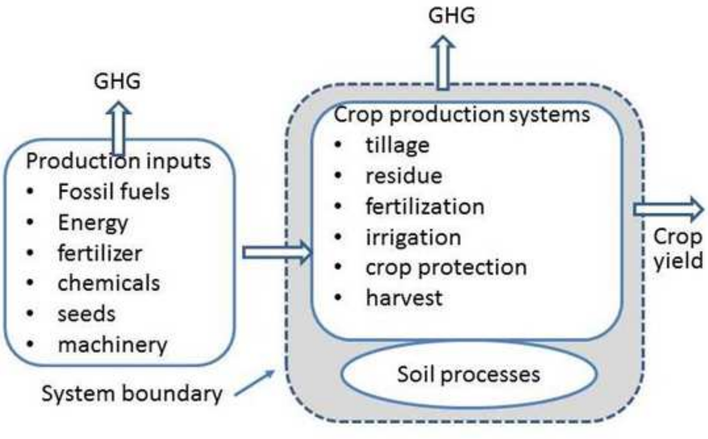

Figure 1: Basic Elements Estimating GHG Emission by Life Cycle or Whole Farm Approach in a Crop Prodution System

REMOTE SENSING

Remote sensing (RS) has been used for the past several decades to monitor land cover and land cover change throughout the tropics (Skole & Tucker, 1993). 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. 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 its changes, and stratification of the landscape prior to conducting ground inventories (Hairiah et al., 2011). The land cover changes due to human actions or consequences of those actions influence GHG emission rates(Eggleston et al., 2006). The availability of fine resolution satellite data allows for determination of heterogeneous landscape in smallholder production system. Crown attributes measured by satellites can then be related directly to above ground biomass through specialized allometric equations.

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). Here, 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 (Aynekulu, Sherpherd, & Winowiecki, 2011). A field-based carbon inventory of heterogeneous landscape in smallholder production systems requires a large financial expenses and this may become cost prohibitive in many developing countries. In such contexts, use of remote sensing could be a low-cost option to quantify carbon stock and its change over time at landscape level. These inventory data can be uploaded into an online GIS that calculates C stocks and emissions associated with current land cover and potential land cover changes.

Historically, high cost of satellite remote sensing data has been a barrier to adoption for researchers in both developed and developing countries. But, with the availability of multiple data sources (e.g. MODIS, NASA) which provide free or low cost satellite data, use of remote sensing for carbon stock studies may be particularly important in the smallholder production systems of the developing countries. However, technical capacity to store large datasets and process them still remains as a barrier for researchers and government agencies working in smallholder production systems.

INTEGRATED APPROACH

Quantification of GHGs from mosaic of smallholder production landscape is challenging because of variable conditions and management practices influencing the rate of emission. Selection of the suitable method depends on the type of production system, availability of database, desired precision of estimate and resources available. Unavailability of field-scale data from smallholder production conditions necessitates the use of plot-based measurement techniques (such as chamber) not only to develop emission factor for inventory preparation but also to calibrate and validate suitable models for landscape level quantification. However, field-based measurement of GHGs from heterogeneous landscape in smallholder production systems requires a large financial expenses and this may become cost prohibitive in many developing countries. Therefore, integration of different approaches may provide better, reliable and cost-effective estimates of GHGs emission than by adopting a single approach. An integrated framework coupling modelling with a measurement in key monitoring sitesis a way forward in smallholder quantification of GHG in developing countries(Ogle et al., 2013; Smith et al., 2012). The key measurement sites or ‘hotspots’ of such measurement should be determined based on *a priori* spatial analysis and stratification of landscape according to key environmental and management practices influencing emissions. Identification of hotspots based on what matters for emission, at what scale and boundaries help targeting the most important source of emission rather than measuring everywhere thereby making it cost-effective yet providing meaningful data. The results coming out of the measurement are fed into the model to improve the assumptions and emission factors of the model while the output of model can also help improve the process studies. It has also been widely recognized that the efficacy of mitigation practices are very site specific, and that application of default IPCC stock change factors at fine spatial scales is not advisable (Smith et al., 2012). The use of process-based ecosystem models linked to GIS may be the future of landscape scale GHG quantification. With the availability of multiple sources of satellite data at low or no cost, integration of remote sensing with modelling efforts could also be low cost quantification approach under smallholder production condition.

Critical Analysis and Comparison GHG Quantification Methods with Regards to Cost, Scale and Accuracy

A multitude of approaches are available for quantification of GHG from agricultural production systems with potential to use under smallholder conditions. A choice of method depends on the objective and desired level of precision, scale of estimation and available resources. Advantages and disadvantages of common method under smallholder crop production systems along with their cost effectiveness and scale of estimation is summarized in table 1. Chamber-based method permits measurement of very small flux, is relatively inexpensive and adapted to wide range of production environment. However, they cover small soil surface area and many chambers are required for a representative emissions estimate. Further, it is not possible to have continuous measurement with chamber based method possibly missing some peaks of episodic emission (e.g. N_2O) unless automatic chambers are used. IPCC developed guidelines for calculating national GHG inventories in a consistent and standard framework. Although appropriate for national level accounting purposes, Tier 1 and Tier 2 methodologies lack the farm level resolution (Crosson et al., 2011) and use of too generalized emission factor may mask the considerable variability, a typical characteristics of smallholder production systems. Micrometeorological methods offer the possibility of continuous measurement and achieving spatial integration of fluxes, but they are generally expensive and require large footprint area of homogeneous landscape. Therefore, use of micrometeorological approaches has limited scope under smallholder production systems from practical, technological and financial perspective. Life-cycle or whole farm approach of GHG quantification provide the overall footprint of a particular product, production system or whole farm which can be useful not only for understanding the wider consequences but also for raising awareness, demonstration and encouraging adoption. Considering the integrated nature of smallholder production systems, this can be useful tool to take into account various processes within the system boundary. However, the precision of the output from this approach depends on the degree of details of the activity data.

Since direct measurement of GHGs for inventory purpose is impractical as it would require many measurements to be made over large areas and for long, use of simulation models become essential component of smallholder quantification. Empirical models and calculators are relatively simple to build and develop and may be considered as decision support tools for farmers and policy makers at field and farm level. Various calculators and tools have been developed with different objectives and assumptions and many of them may be location specific. Therefore, users should choose the appropriate calculators based on objectives and major factors contributing to the emission. Use of empirical model can be a cost-effective approach to estimate GHG emission from smallholder production system where minimum datasets are available to run the model. Process-based models have the advantage of describing the underlying dynamics of a system. They take into account many management practices and their interaction with soil and climate. Inclusion of these processes in modelling can enhance extrapolation reliability making it possible to simulate at ecosystem level. However, they are very complex and require huge amount of data input. Further, the extrapolation reliability and simulation power of these models depend on the mechanistic understanding and sub-modelling of the individual processes and driving variables involved. Therefore, they are more oriented to research and refining emission factors. Remote sensing techniques are increasingly being used to estimate landscape carbon density and carbon stocks. Sampling based carbon inventory may be cost prohibitive in many developing countries. In such context and with the availability of low-cost or free satellite data, use of remote sensing could be a cost effective option to quantify carbon stocks under smallholder production systems. However, the resolution of available satellite imagery (pixel size) may not be sufficient to capture possible variabilities in smallholder production systems.

Table 1: Comparison of Different Methods of GHG Quantification for Smallholder Production Systems

Approaches	Cost effectivenes s	Scale of estimation	Precision	Limitations	References
Chamber Method	Cost effective, Labour intensive	Plot level, sometime field level	Possible to measure very small flux.	Difficult to take into account temporal and spatial variability. Disturbs the system being measured.	(Denmead 2008; Glenn et al. 2010; Rochette 2011)
Micrometeor ological approaches	Very expensive	Field to landscape level	Gives precise estimation and also accounts for temporal and spatial variability.	Requires high technical skills and uniform landscape. Not suitable for smallholder condition.	(Pattey et al. 2007; Denmead 2008; Burba et al. 2013)
Life cycle or whole plot approach	Moderately cost effective	Whole farm or production system	Precision depends on the type of sub-modules for different sub-systems	Time consuming. Requires large amount of data from different sub-systems of farm or production system.	(Brentrup et al. 2001; Knudsen et al. 2014)

Table 1 – Cond.,					
Modelling	Cost effective	Plot, field and landscape level	Moderately precise if adequately parameterized and validated across different production environments. Its accuracy depends on model and input data. For example, it can be low while using Tier 1 Approach	Requires technical expertise. Process-based models need detailed input data.	(Conant et al. 2010; Del Grosso et al. 2011; Colomb et al. 2012)
Remote Sensing	Moderately cost effective.	Landscape level	Its accuracy is variable depending on land cover. Chances of errors if high resolution images are not available	Requires expertise for data processing.	(Goetz et al. 2009; Aynekulu et al. 2011; Hairiah et al. 2011)

CONCLUSIONS AND WAY FORWARD

Here, we presented various approaches for quantification of GHG from smallholder production systems along with their comparative analysis of cost effectiveness, scale of estimation and precision. Quantification of GHGs from mosaic of smallholder production landscape is challenging because of variable pedo-climatic conditions and management practices influencing the rate of emission. Use of generalized emission factor for GHG estimation for such production system will mask the variability occurring amongst the farms. Chamber methods are cheap, simple and easy to operate but they fail to take into account spatial and temporal variability of emission and also pose disturbance on the system being measured. Micrometeorological methods offer the possibility of undisturbed and continuous measurement but they are expensive, technologically complex and require large footprint area. Use of models allows simulation of agricultural GHG emission under wide range of conditions and makes it possible to scale up estimation to landscape, national, regional and global level. However, choice of appropriate model and its parameterization as well as validation under different production systems is necessary for the model to adequately simulate GHGs under variable production environment of smallholder systems. With the advancement of technology, linking dynamic ecosystem models to GIS and development of user friendly tools can make quantification of environmental footprint of product and production system cost-effective and reliable. At the moment, two main barriers to extending such tools to smallholder areas in developing countries are: a) a lack of default data with relevance to the land management systems in smallholder areas and b) lack of accessible systems which are comprehensive enough to allow smallholders to input their own data. Therefore, considering the dependence of quantification approaches on data and the current data deficit for smallholder systems, it is clear that *in-situ* measurement must be the core part of initial and future strategies to improve GHG inventories and develop mitigation measures for smallholder agriculture. Many a times, integration of different approaches such as chamber-based measurement, modelling and use of satellite imagery can provide better and reliable estimates of GHGs emission from smallholder production systems than by adopting a single approach. Quantification of GHGs and its mitigation from certain production system should, however, be assessed taking into account the household benefits such as resilience led-productivity enhancement and input use efficiency.

ACKNOWLEDGEMENTS

This review was carried out as part of pro-poor mitigation program of CGIAR's research program (CRP) on Climate Change Agriculture and Food Security (CCAFS) in CIMMYT.

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