Advancing national greenhouse gas inventories for agriculture in developing countries: improving activity data, emission factors and software technology

2013 Environ. Res. Lett. 8 015030

(http://iopscience.iop.org/1748-9326/8/1/015030)

OPEN ACCESS
IOP PUBLISHING ENVIRONMENTAL RESEARCH LETTERS
Environ. Res. Lett. 8 (2013) 015030 (8pp) doi:10.1088/1748-9326/8/1/015030

Advancing national greenhouse gas inventories for agriculture in developing countries: improving activity data, emission factors and software technology

Stephen M Ogle[1,2], **Leandro Buendia**[3], **Klaus Butterbach-Bahl**[4,5], **F Jay Breidt**[6], **Melannie Hartman**[1], **Kazuyuki Yagi**[7], **Rasack Nayamuth**[8], **Shannon Spencer**[1], **Tom Wirth**[9] and **Pete Smith**[10]

[1] Natural Resource Ecology Laboratory, Colorado State University, Fort Collins, CO, USA
[2] Department of Ecosystem Science and Sustainability, Colorado State University, Fort Collins, CO, USA
[3] 2113-A Pula Street, College Ville, Brgy. Putho-Tuntungin, Los Banos, Laguna, 4030, Philippines
[4] Institute for Meteorology and Climate Research (IMK-IFU), Karlsruhe Institute of Technology, Garmisch-Partenkirchen, Germany
[5] International Livestock Research Institute, Old Naivasha Road, Nairobi 00100, Kenya
[6] Department of Statistics, Colorado State University, Fort Collins, CO, USA
[7] National Institute for Agro-Environmental Sciences, Tsukuba, Japan
[8] Mauritius Sugarcane Industry Research Institute, Le Reduit, Mauritius
[9] United States Environmental Protection Agency, Washington, DC 20460, USA
[10] Institute of Biological & Environmental Sciences, University of Aberdeen, 23 St Machar Drive, Aberdeen AB24 3UU, UK

E-mail: stephen.ogle@colostate.edu

Received 11 September 2012
Accepted for publication 15 February 2013
Published 7 March 2013
Online at stacks.iop.org/ERL/8/015030

Abstract

Developing countries face many challenges when constructing national inventories of greenhouse gas (GHG) emissions, such as lack of activity data, insufficient measurements for deriving country-specific emission factors, and a limited basis for assessing GHG mitigation options. Emissions from agricultural production are often significant sources in developing countries, particularly soil nitrous oxide, and livestock enteric and manure methane, in addition to wetland rice methane. Consequently, estimating GHG emissions from agriculture is an important part of constructing developing country inventories. While the challenges may seem insurmountable, there are ways forward such as: (a) efficiently using resources to compile activity data by combining censuses and surveys; (b) using a tiered approach to measure emissions at appropriately selected sites, coupled with modeling to derive country-specific emission factors; and (c) using advanced software systems to guide compilers through the inventory process. With a concerted effort by compilers and assistance through capacity-building efforts, developing country compilers could produce transparent, accurate, complete, consistent and comparable inventories, as recommended by the IPCC (Intergovernmental Panel on Climate Change). In turn, the resulting inventories would provide

1748-9326/13/015030+08$33.00

the foundation for robust GHG mitigation analyses and allow for the development of nationally appropriate mitigation actions and low emission development strategies.

Keywords: national greenhouse gas inventory, agricultural greenhouse gas emissions, emission factors, activity data, soil nitrous oxide, rice methane, enteric methane, manure methane, soil organic carbon

1. Introduction

National greenhouse gas (GHG) inventories are essential for public policy planning to mitigate GHG emissions because it is not possible to develop an informed plan without first knowing the emissions. Inventories provide essential information and enhance environmental integrity in planning and development of GHG mitigation policy, such as baseline and mitigation scenarios for nationally appropriate mitigation actions (NAMAs), and low emission development strategies (LEDS). Furthermore, GHG inventories track the trends in emissions after actions and strategies are implemented, and can be used to assess the outcomes. While this is generally true for all countries and sectors of commodity production, our objective is to discuss ways of advancing GHG inventories in the agricultural sector for developing countries to support policy planning and assessment.

The 2006 IPCC National Greenhouse Gas Inventory Guidelines (IPCC 2006) describe the sources of emissions in livestock and crop production systems. Our discussion will focus on emissions directly from soils, animals, crops and forages, although this does not discount the importance of fossil fuel combustion and other sources of emissions associated with agricultural production. Emissions from livestock management include methane (CH_4) from enteric fermentation (mostly from ruminants such as cattle, buffalo, and sheep), and CH_4 and nitrous oxide (N_2O) from manure management. Burning of savanna and agricultural residues releases non-CO_2 greenhouse gases such as CH_4, N_2O, carbon monoxide, and oxides of nitrogen. Nitrogen fertilizer and other N-containing amendments when applied to agricultural soils are sources of direct and indirect N_2O emissions. Liming of agricultural soils is an activity leading to carbon dioxide (CO_2) emissions, while CH_4 is emitted from wetland rice production systems. Land use change and management can increase or decrease biomass, litter and soil carbon stocks (e.g., Houghton *et al* 1999, Bondeau *et al* 2007, Ogle *et al* 2010).

The hallmark of a high quality inventory is that it follows good practice according to the IPCC guidelines, and the key components of good practice is that the inventory is transparent to others including reviewers, government personnel, non-governmental organizations (NGOs) and others actively involved in GHG mitigation planning; has accurate and complete emissions estimates for all gases, sources and sinks; has consistent application of methods across a times series; and is comparable to inventories from other countries (IPCC 2006). While even developed countries struggle with implementation of good practice, most can produce reasonably high quality inventories (e.g., US-EPA 2012). However, the task is even more challenging in developing countries with few and sporadic surveys of agricultural production systems, lack of country-specific data on emission rates, and limited resources to complete the task. The following are more specific challenges commonly encountered by developing countries in preparing national GHG inventories:

- No clear roles and responsibilities of relevant ministries and agencies in preparing a national GHG inventory and lack of institutional arrangements;
- small teams with limited resources and multiple responsibilities;
- difficulty in retaining expertise;
- incomplete or non-existent activity data, and lack of experimental data for developing country-specific emission and stock change factors;
- insufficient documentation and absence of an archiving system from previous inventories;
- no quality assurance and quality control (QA/QC) plan; and
- no concrete plan to improve future national GHG inventory.

To some, these problems may seem insurmountable, but here we discuss several options that through a concerted effort by national inventory teams can lead to inventories that are produced with good practice. We focus on three main challenges, improving activity data compilation, producing more accurate country-specific emission factors, and application of advanced software systems to help manage the inventory data and conduct mitigation analyses. Moreover, if developing countries can produce high quality inventories, the governments would be able to more fully and effectively participate in the development of NAMAs and LEDS, as well as the negotiations for the United Nations Framework Convention on Climate Change (UNFCCC), which could ultimately provide the foundation for participation in incentive programs to reduce GHG emissions.

2. Activity data compilation: challenges and the way forward

To compile GHG inventories, a variety of data is needed about activities that influence GHG emissions (IPCC 2006). Activity data for agriculture includes a range of diverse information, such as the number of livestock in the country, quantity of nitrogen fertilizers applied to soils, and tillage practices used in field preparation for growing crops. These data can be obtained from one of several sources, including a census, survey, farmer interviews, field observations, remote sensing and other geospatial products, expert knowledge, or some combination of these sources.

Fortunately, most countries have some information on agricultural production from a census or survey. Other data sources also exist from organizations such as the International Fertilizer Industry Association (IFIA) (www.fertilizer.org/ifa/statistics.asp) and the Food and Agriculture Organization of the United Nations (www.faostat.fao.org/; IPCC 2010) that can be used in a national GHG inventory. 'Mining' of these data sources is the first step in compiling an inventory, but activity data gaps still exist in most countries, and represent a significant challenge to producing a complete inventory of GHG emissions.

In general, the challenge of filling activity data gaps may be achieved through a census or a probability survey, each of which seeks to make inference about an entire population, such as all farmers or fields in a region or country, or all experts in a group. The key distinction is that a probability survey selects a subset of the population to make inference about the entire population, while a census selects the entire population (e.g., Sarndal *et al* 1992, Lohr 2009). Both censuses and surveys are subject to non-sampling errors, including under-coverage errors (in which part of the population cannot be selected; e.g., unlisted farmers, unmapped fields or unidentified experts), non-response errors (in which not all selected population elements yield complete responses; e.g., cloud-covered pixels), measurement errors, and processing errors. Surveys are further subject to sampling error, which is due to the fact that the selected sample is not the entire population. However, sampling error is easily quantified using the sample itself and standard statistical techniques (Sarndal *et al* 1992, Lohr 2009). By enumerating only a subset of the entire population, surveys save resources that can then be devoted to reducing non-sampling errors, and therefore are preferable in situations where resources are limited. In addition, non-sampling errors are often larger and more difficult to quantify than sampling errors, and so surveys are often considered a better approach in practice for data collection than a census. Examples of probability surveys for agricultural resources include the US National Resources Inventory (Nusser and Goebel 1997, Nusser *et al* 1998) and the European Land Use and Cover Area Frame Statistical Survey (Gallego and Delince 2010).

Geospatial products for land use, land management, soils and climate are key datasets for an agricultural inventory; the availability of these data was recently reviewed by Smith *et al* (2012). Spatial data for soils and weather/climate are available at sufficient resolution for GHG inventories in developing countries. More specifically, soil data are available from the Harmonized World Soils Database (FAO, IIASA, ISRIC, ISSCAS and JRC 2012) and GlobalSoilMap.net project, which will likely provide an even better global soil map in the near future (Sanchez *et al* 2009). There are various sources of weather/climate data at fine resolutions, such as WorldClim, NEO and CRU (e.g., Dee *et al* 2011). However, one of the key gaps in datasets for agricultural GHG inventories are spatial data on land use change, which are adequate for some developed countries (e.g., Homer *et al* 2007), but are almost universally poor for developing countries (Smith *et al* 2012). Land cover databases include GLCC-IGBP, GLC2000, MODIS and other combined products reviewed in Smith *et al* (2012), but these data do not always provide information on land use change that is sufficient for GHG inventories. In addition, obtaining reliable activity data on agricultural management in developing countries remains one of the greatest challenges (Smith *et al* 2012). For example, estimating CH_4 emissions from wetland rice cultivation requires annual harvested area of rice by different ecosystems, water management regimes, type and amount of organic amendments, and other conditions that influence CH_4 emissions (IPCC 2006).

One way forward is to obtain the required activity data on land use and management by applying well-developed statistical methods that combine censuses and surveys (e.g., Sarndal *et al* 1992). In particular, relatively inexpensive remote sensing data, which is analogous to a census with fully-processed 'wall-to-wall' coverage, can be combined with more expensive field measurements or surveys of land use and management practices to optimize resource use (e.g., Nusser *et al* 1998, Gallego and Delince 2010). The National Resources Inventory in the United States is a good example of this approach (Nusser *et al* 1998). Land use is classified using aerial photography in this survey. In subsequent special studies of tillage, irrigation, or other management practices, a subset of locations is visited by field crews to collect additional data. For example, sampling can be targeted toward rare but important environmental conditions, such as highly erodible land. Similarly, in the Land Use/Cover Area frame Survey (LUCAS) conducted by Eurostat, remotely-sensed data are used to partition a large initial sample into preliminary classes, allowing efficient selection of subsequent sample sites for field visits (Gallego and Delince 2010).

Alternatively, expert knowledge could be used to acquire activity data. While expert knowledge may seem inadequate to some, it is a type of data collection recommended by the IPCC (2006) when other sources of data are not available. Use of expert knowledge to obtain data for estimating emissions from a GHG source is a better option than for a country to have no estimate for reporting. An example is provided in a Brazilian study evaluating soil carbon stock changes in lower Amazon that utilized an expert knowledge survey to compile information on crop rotations and tillage practices in the region (Maia *et al* 2010). Surveys were given to experts in the extension service, and responses were combined to produce not only estimates for the use of various management practices, but also uncertainty based on the variability in responses. By combining remote sensing data, farm surveys and/or expert knowledge, data gaps can be filled for the required information related to management of crops and livestock.

Capacity-building efforts could focus on assisting national inventory compilers and associated government agencies and ministries with data collection by providing guidance on the design, implementation and interpretation of data from farmer interviews, field observations, remote sensing and other geospatial products, and expert knowledge. For example, regional centers could assist with development and application of remote sensing products, such as the Regional Center for Mapping of Resources for Development in Africa (www.rcmrd.org/). Such centers would assist remote sensing experts in the countries with acquisition, processing, classification, and evaluation of remote sensing products. Assisting the compilers through this entire process will allow them to learn by 'doing' and potentially provide a more valuable experience than only generalized training on the methods for data collection. It is important to note that activity data are likely to be useful for more than just GHG inventories, and so activity data collection should consider the broader set of policy and resource management needs when compiling this information.

3. Country-specific emission factors: challenges and the ways forward

Emission factors are the rate of emissions associated with the different environmental conditions (e.g., climatic and soil variation) and practices for managing livestock and crop production systems. The emission factors are essentially multiplied by the activity data, discussed in section 2, to estimate the total GHG emissions in a country. The IPCC (2006) provides default factors for all emission source categories (e.g., enteric methane) in a national GHG inventory. The purpose of the default factors is to ensure that every country can conduct an inventory and report emissions. However, these factors are not very precise or possibly even accurate for application in certain countries or regions due to unique conditions that are not always represented by the default factors. For example, default enteric CH_4 emission factors are identical for all countries within large continental-scale regions (IPCC 2006). There is more variation in emissions from livestock production across a continent, or even a country, due to differences in environmental conditions, as well as the specific livestock breeds and management practices that are used (e.g., US-EPA 2012). In general, assigning factors that differ across the range of variability in a country for both livestock and crop production would improve the accuracy of the GHG inventory. As such, the IPCC (2006) considers it good practice to develop country-specific emission factors for key sources of GHG emissions (i.e., the emission sources that account for 95% of total emissions in a country), and this is another critical challenge for inventory compilers.

The least expensive way forward is for compilers to obtain emission factors that are more appropriate for their country through the IPCC Emission Factor Database (EFDB) (www.ipcc-nggip.iges.or.jp/EFDB/main.php). The EFDB provides emission factors and other parameters with background documentation and technical references. However, the EFDB is not a comprehensive database, and will not provide alternative factors that are appropriate for all conditions under which human activities are influencing GHG emissions in a country or region of a country.

Similar to activity data, the next option in developing country-specific emission factors is 'mining' of existing emissions data. In particular, there are regional research centers which have conducted GHG measurements and produced results that can be used to derive emission factors. For example, the International Rice Research Institute (IRRI) has conducted more than 10 years of CH_4 emission measurements, using automated chamber techniques to collect hourly data for rice growing seasons from major rice producing countries, including China, India, Indonesia, Thailand, and the Philippines. The data are applicable to different rice ecosystems, water regimes, and organic amendments, and to specific countries or regions with similar environments as described in the experiments (Wassmann *et al* 2000a, 2000c, 2000b). The IRRI studies have also produced sampling strategies, which are analyzed through regression equations, and can be applied to improve the estimates of CH_4 emissions when using manual sampling techniques (Buendia *et al* 1998).

Several governments in Southeast Asia have used rice methane emissions data to derive country-specific emission factors, such as the Philippines, Indonesia and Thailand. In the Philippines, country-specific emission factors were developed using experimental data collected by IRRI (Corton *et al* 2000, Wassmann *et al* 2000b). The emission factor for continuously flooded systems with no organic amendment was estimated at 1.46 kg CH_4 ha^{-1} d^{-1} for the dry season, and 2.95 kg CH_4 ha^{-1} d^{-1} for the wet season. The country-specific factors reduce bias associated with the IPCC default value of 1.3 kg CH_4 ha^{-1} d^{-1} (IPCC 2006), which under-estimates emissions in the Philippines and does not incorporate the differences between the wet and dry seasons.

If a country has identified that a category is a key source of emissions, and there are insufficient research or other emissions data in the literature or EFDB to support development of country-specific emission factors, then it will be necessary for a county to undertake a measurement programme. In doing this, the compilers have to take into consideration the available resources and methodologies to perform measurements in an effective and robust manner.

For example, soil N_2O emissions are a key source of GHG emissions in many countries, largely due to the use of mineral fertilizers in agriculture. It is estimated that the amount of N_2O present in the atmosphere has been increasing at the rate of 0.2–0.3% per annum (Granli and Bockman 1994), and these rates are expected to further increase as more developing countries use fertilizers to enhance agricultural production and achieve food security. However, N_2O emissions from soils are notoriously variable, and flux differences between observational points in time and space may span several magnitudes (Stehfest and Bouwman 2006). The huge variability of fluxes mirrors the complexity of the underlying microbial processes involved in the formation and consumption of N_2O, predominantly the oxidative process of nitrification and the reductive process of denitrification, which in turn, depend on microbial activities and nitrogen turnover in the soil (Butterbach-Bahl *et al* 2011a). Significant pulse emissions of N_2O are largely driven by abrupt changes in soil

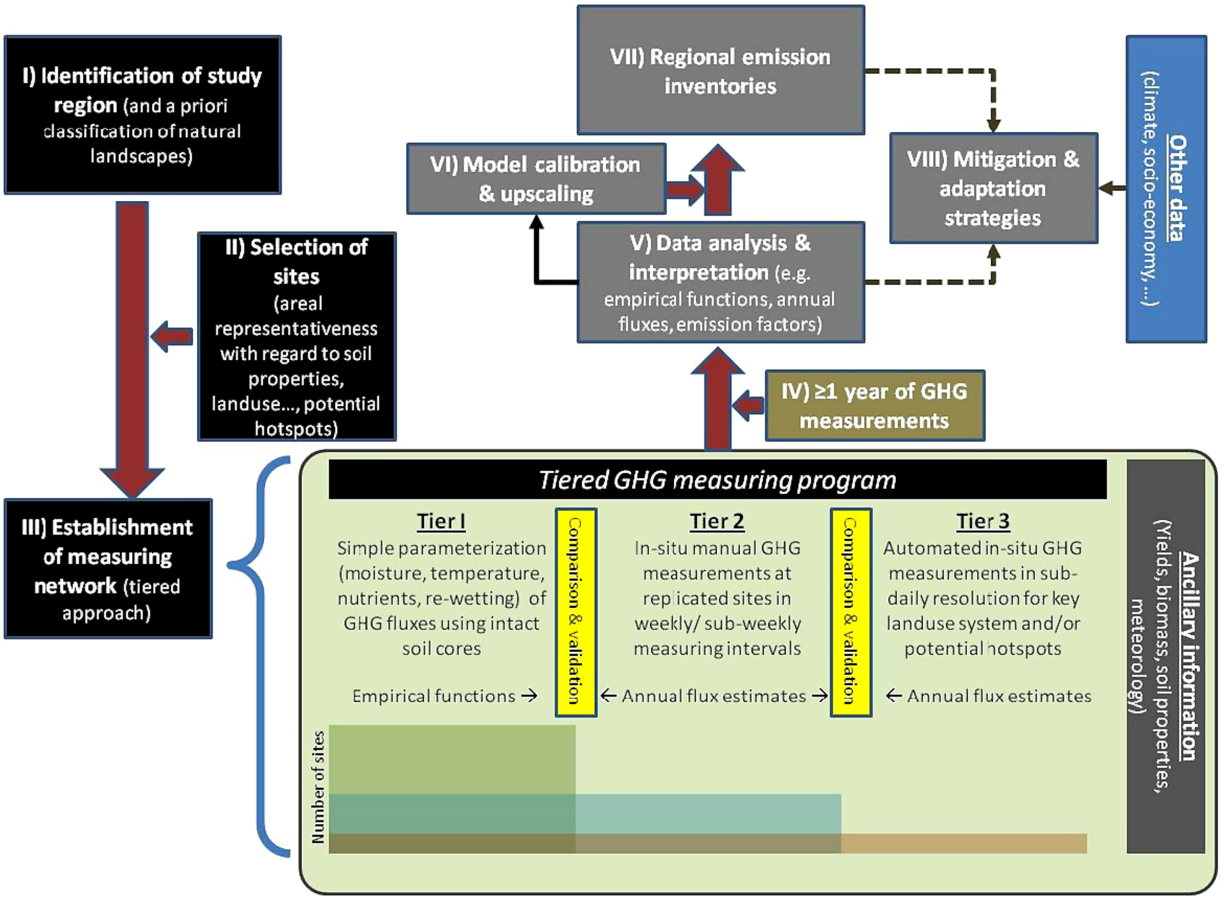

Figure 1. Measuring/modeling strategy for producing country-specific emission factors for N_2O and other GHG fluxes from agroecosystems in developing countries.

environmental conditions due to re-wetting of soils following a drought period (Borken and Matzner 2008), thawing of soils (Groffman *et al* 2009, Wolf *et al* 2010), or changes in the nutrient status of soils following organic or mineral fertilizer applications (McSwiney and Robertson 2005). Given the large variability of N_2O fluxes, the planning and implementation of a measurement programme to develop country-specific emission factors is challenging.

So what is the way forward in developing country-specific emission factors for N_2O fluxes from measurements in a region with variable conditions and management practices influencing the rate of emissions? One way forward is coupling modeling with a measurement network of monitoring sites based on *a priori* spatial analysis and stratification of the country according to key environmental and management practices variables influencing emissions, such as existing land use, nutrient and water management regimes, climate, and soil properties. While advanced micrometeorological techniques are available for measuring N_2O across sites (Kroon *et al* 2010), it is more likely that a measurement network would use the closed chamber techniques (Hutchinson and Mosier 1981) due to costs and maintenance. With the closed chamber technique, fluxes are typically calculated from the temporal changes in headspace gas concentration with time using preferable non-linear approaches (Butterbach-Bahl *et al* 2011b).

To address both temporal as well as spatial variability of N_2O fluxes, a tiered measuring approach is likely needed consisting of (a) experiments for identifying emission potentials and driving factors with intact soil cores taken from various sites or *in situ* measurements, (b) manual chamber measurements for different land uses and management practices associated with the spatial stratification of the country, (c) automated chamber measurements for a few selected potential hotspot sites; and (d) ancillary data collection for characterizing the biophysical environmental conditions for assignment of the new factors to the country (e.g., yields, biomass, soil properties) (figure 1). N_2O measurements from experiments (a) and additional monitoring sites based on the spatial stratification (b) and (c) are complementary and allow the inventory compiler to estimate emission factors across a wide variety of land uses and/or test biogeochemical models for deriving emission rates across a larger region. It is important to recognize that the *in situ* N_2O measurements are only done at a restricted number of sites, and moreover it may be necessary for compilers to collaborate with other countries to implement the network of measurements given the resource needs. Research institutes, universities and staff from NGOs could facilitate measurement and modeling activities. Furthermore, this approach has been realized in recent studies for quantifying the regional soil GHG emissions of livestock systems in steppe environments (Yao *et al* 2010a, 2010b, Wolf *et al* 2010).

Similar to soil N_2O, recognized methods for measuring methane emissions from rice paddies include the closed chamber, open chamber and micrometeorological methods. The selection of the optimum method is dependent on the objective of the measurement (IAEA 1992, IGAC 1994), but ultimately a tiered approach with a network of sites is likely the most feasible and robust way forward, as discussed for soil N_2O. A tiered approach could also be used in livestock and manure management systems, with a focus on methods that are appropriate for livestock production systems (e.g., Johnson and Johnson 1995), and ancillary data related to key variables in these systems (e.g., types of livestock and breeds, age and gender classes, feeding situation, forage quality, manure handling and storage).

Lokupitiya and Paustian (2006) found that few countries estimate soil organic C (SOC) stock changes in agricultural systems, even though the potential for carbon sequestration in agricultural lands has been considered the most cost-effective method for reducing emissions from agriculture (Smith *et al* 2007). While there are global datasets with default stock change factors for SOC (Ogle *et al* 2005, Smith *et al* 2008), the coverage of experiments from which these factors were derived is patchy, with the poorest coverage over developing countries (Smith *et al* 2012). The uncertainty associated with some agricultural management practices is large, and the 95% confidence interval can, in some cases, cross the line between gains to losses of SOC (Ogle *et al* 2005). 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* 2008, 2012), while the stock change factors are more robust at larger scales (Ogle *et al* 2006).

An integrated framework combining a network of measurement sites with modeling is arguably the most efficient and feasible way forward to improve estimates of SOC stock changes in developing countries (Conant *et al* 2011, Spencer *et al* 2011, Smith *et al* 2012). A case of a country combining measurement with modeling to reduce uncertainty is provided by Del Grosso *et al* (2011) who compare the use of default and country-specific factors to the same SOC inventory. In this example, the Century process-based model was used to estimate SOC stock changes in croplands of the United States after evaluation with SOC measurements from about 50 experimental sites with over 800 treatments (Ogle *et al* 2010). Uncertainty was reduced by 43% as a result of advancing beyond the default factors with a method combining measurements and modeling (Del Grosso *et al* 2011). In some cases, compilers may want to develop regional cooperatives and pool resources to facilitate the development of a measurement network that could underpin a model analysis. As with N_2O and CH_4, research institutions, universities and NGOs could facilitate these activities.

4. Advancing software systems for inventory compilation

One of the decisions from the UNFCCC Conference of the Parties meeting in Durban (Decision 2/CP17) revises the national GHG inventory reporting requirements for non-Annex 1 countries (developing countries) to a biennial cycle (Least Developed Countries and small island developing states may submit biennial update reports at their discretion), and includes monitoring, reporting, and verification components (MRV). These requirements pose a challenge to developing countries and require effective data management to facilitate biannual reporting. Advanced inventory software systems are a way forward to assist compilers with overcoming this challenge.

A variety of software systems exist than can be used to estimate GHG emissions, and these tools operate across a range of scales with different capabilities (Crosson *et al* 2011, Colomb *et al* 2012, Cowie *et al* 2012). It is important to note that these GHG emission software systems are designed for managing activity data and emissions factors, but not the equally important component of establishing a sustainable GHG inventory system. Other guidance tools have been developed for this purpose such as the US-EPA inventory management template workbook, 'Developing a National Greenhouse Gas Inventory System' (US-EPA 2011).

For national inventories, compiling and managing large amounts of data over time is probably the most important capability of an advanced software system for the estimation of GHG emissions, particularly with agriculture and land use, which arguably require more data and inter-relationships among those data than found in other emission reporting sectors (e.g., energy). A relational database structure is an efficient approach for storing large volumes of data. Another key feature of an advanced software system is a graphical user interface that allows compilers to extract and enter data into the database without the need to develop computer programming code. Such a system can guide compilers through the process of activity data compilation, emission factor assignment and emission calculations through the interface, while storing, processing, and analyzing data, in addition to producing reports. An example of a tool developed for this purpose is the Agriculture and Land Use National Greenhouse Gas Inventory (ALU) Software (www.nrel.colostate.edu/projects/ALUsoftware/).

Consequently, advanced software systems have advantages over the spreadsheet approaches that are commonly used by national inventory compilers in developing countries (e.g., UNFCCC software, http://unfccc.int/resource/cd_roms/na1/ghg_inventories/index.htm). Spreadsheets certainly provide the basic functionality for completing an inventory, but with the technology available today, more advanced systems can be developed to manage the inventory data.

An advanced software system can promote the use of good practice from the IPCC guidelines, ensuring transparency, accuracy, completeness, comparability, and time series consistency (IPCC 2006). Transparency and comparability of results is provided through detailed reports on calculations that show all activity data and emission factors, and associated documentation about data sources and emission factors. Accuracy is promoted by an integrated QA/QC process and range checking of data during entry. Furthermore, accuracy is improved through the use of country-specific factors, and therefore software should accommodate new factors and associated documentation with multiple levels of stratification to allow variation in assignment of emission factors for different conditions in a country. Facilitating stratification will complement the tiered design for developing country-specific emission factors (figure 1) (e.g., Yao *et al* 2010a, 2010b, Wolf *et al* 2010). Completeness of data can be reinforced by data validation at each data entry step in the software, such as ensuring all land area is included, assigned to a land use, and that the management is described. Completeness can also be achieved by allowing compilers to 'track and check' the completeness of activity data and emission factor assignments in each GHG emissions category and sub-category. Using an advanced inventory system promotes consistent time series where all inventory years are calculated using the same method and data sources in all years. In addition, multi-year reports can be compared by the software system to identify inconsistencies within a time series of activity data or anomalies in annual GHG emission trends.

While an inventory is an important component to meet reporting requirements to the UNFCCC, the inventory is also the means to analyze mitigation potentials and consider options for NAMAs and LEDS in developing countries (i.e., how these data will be used in development of domestic policy and international programs promoting mitigation in developing countries). Consequently, mitigation potentials can be estimated using the inventory data as a baseline for projecting emission trends associated with 'business as usual' practices and management alternatives. An advanced software system could be informed by various drivers of emissions, including population growth, mitigation technologies and economic trends, and by integrating mitigation into the system, the tool will be of more utility for the compiler than a simple calculation of emissions.

5. Conclusions

National GHG inventories are an essential component of climate change policy development and negotiations among party countries to the UNFCCC. Developing countries will be able to more fully participate in the UNFCCC climate change negotiations as well as develop more effective policies for their agricultural sector with inventories that follow good practice as defined by the IPCC (2006). Good practice will ultimately lead to transparent, accurate, complete, consistent and comparable inventories. More importantly the resulting inventories can be used with confidence in development of NAMAs and LEDS. In turn, the proposed strategies and actions can form the foundation for incentive programs to reduce GHG emissions in developing countries through international cooperation, and improve practices in the agricultural sector from the small stakeholder to the commercial farmer.

Acknowledgments

The lead author is grateful to the US Environmental Protection Agency for funding to support preparation of the manuscript and journal page charges (Agreement No. EP-W-08-013/0014). We thank Mausami Desai for comments on the manuscript. The contribution of Pete Smith is part of his research on the Defra GHG Platform Projects AC0114 and AC0116 and the EU-funded project GHG-Europe. Pete Smith is a Royal Society-Wolfson Research Merit Award holder.

References

Bondeau A *et al* 2007 Modelling the role of agriculture for the 20th century global terrestrial carbon balance *Glob. Change Biol.* **13** 679–706

Borken W and Matzner E 2009 Reappraisal of drying and wetting effects on C and N mineralization and fluxes in soils *Glob. Change Biol.* **15** 808–24

Buendia L V *et al* 1998 An efficient sampling strategy for estimating methane emission from rice field *Chemosphere* **36** 395–407

Butterbach-Bahl K *et al* 2011a Nitrogen processes in terrestrial ecosystems *The European Nitrogen Assessment: Sources Effects, and Policy Perspectives* ed M A Sutton, C M Howard, J W Erisman, G Billen, A Bleeker, P Grennfeldt, H Van Grinsen and B Grozetti (Cambridge: Cambridge University Press) pp 99–125

Butterbach-Bahl K, Kiese R and Liu C 2011b Measurements of biosphere–atmosphere exchange of CH_4 in terrestrial ecosystems *Methods Enzymol.* **495** 271–87

Colomb V, Bernoux M, Bockel L, Chotte J-L, Martin S, Martin-Phipps C, Mousset J, Tinlot M and Touchemoulin O 2012 *Review of GHG Calculators in Agriculture and Forestry Sectors: A Guideline for Appropriate Choice and Use of Landscape Based Tools, Version 2.0 (ADEME, IRD, FAO)* p 43 (www.fao.org/tc/exact/exact-publications/papers-mentioning-ex-act/en/)

Conant R T, Ogle S M, Paul E A and Paustian K 2011 Measuring and monitoring soil organic carbon stocks in agricultural lands for climate mitigation *Front. Ecol.* **9** 169–73

Corton T M, Bajita J B, Grospe F S, Pamplona R R, Asis C A Jr, Wassmann R, Lantin R S and Buendia L V 2000 Methane emission from irrigated and intensively managed rice fields in Central Luzon (Philippines) *Nutr. Cycl. Agroecosyst.* **58** 37–53

Cowie A, Eckard R and Eady S 2012 Greenhouse gas accounting for inventory, emissions trading and life cycle assessment in the land-based sector: a review *Crop Pasture Sci.* **63** 284–96

Crosson P, Shalloo L, O'Brien D, Lanigan G J, Foley P A, Boland T M and Kenny D A 2011 A review of whole farm systems models of greenhouse gas emissions from beef and dairy cattle production systems *Anim. Feed Sci. Technol.* **166/167** 29–45

Dee D P *et al* 2011 The ERA-Interim reanalysis: configuration and performance of the data assimilation system *Q. J. R. Meteorol. Soc.* **137** 553–97

Del Grosso S J, Ogle S M and Parton W J 2011 Soil organic matter cycling and greenhouse gas accounting methodologies *Understanding Greenhouse Gas Emissions from Agricultural Management* ed L Guo, A Gunasekara and L McConnell (Washington, DC: American Chemical Society) chapter 1, pp 3–13

FAO, IIASA, ISRIC, ISSCAS, JRC 2012 *Harmonized World Soil Database, Version 1.2* (Rome: FAO) (www.iiasa.ac.at/Research/LUC/External-World-soil-database/HTML/)

Gallego J and Delince J 2010 The European land use and cover area-frame statistical survey *Agricultural Survey Methods* ed R Benedetti, F Piersimoni, M Bee and G Espa (New York: Wiley) pp 149–68

Granli T and Bockman O C 1994 Nitrous oxide from agriculture *Norw. J. Agric. Sci.* **12** 7–17

Groffman P M, Butterbach-Bahl K, Fulweiler R W, Gold A J, Morse J L, Stander E K, Tague C, Tonitto C and Vidon P 2009 Challenges to incorporating spatially and temporally explicit phenomena (hotspots and hot moments) *Biogeochemistry* **93** 49–77

Homer C, Dewitz J, Fry J, Coan M, Hossain N, Larson C, Herold N, McKerrow A, VanDriel J N and Wickham J 2007 Completion of the 2001 national land cover database for the conterminous United States *Photogramm. Eng. Remote Sens.* **73** 337–41

Houghton R A, Hackler J L and Lawrence K T 1999 The US carbon budget: contributions from land-use change *Science* **285** 574–8

Hutchinson G L and Mosier A 1981 Improved soil cover method for field measurements of nitrous oxide fluxes *Soil Sci. Soc. Am. J.* **45** 311–6

IAEA 1992 *Manual on Measurements of Methane and Nitrous Oxide Emissions from Agriculture* (Vienna: International Atomic Energy Agency) pp 1–91

IGAC 1994 *Global Measurement Standardization of Methane Emissions from Irrigated Rice Cultivation* ed R L Sass and H U Neue (Cambridge, MA: International Global Atmospheric Chemistry)

IPCC 2006 *2006 IPCC Guidelines for National Greenhouse Gas Inventories* ed H S Eggleston, L Buendia, K Miwa, T Ngara and K Tanabe (Hayama: Intergovernmental Panel on Climate Change, IGES)

IPCC 2010 Datasets for use in the IPCC guidelines *Meeting Report of the IPCC–FAO–IFAD Expert Meeting on FAO Data for LULUCF/AFOLU (Rome, Oct. 2009)* ed H S Eggleston, N Srivastava, K Tanabe and J Baasansuren (Hayama: Intergovernmental Panel on Climate Change IGES)

Johnson K A and Johnson D E 1995 Methane emissions from cattle *J. Anim. Sci.* **73** 2483–92

Kroon P S, Schrier-Uijl A P, Hensen A, Veenendaal E M and Jonker H J J 2010 Annual balances of CH_4 and N_2O from a managed fen meadow using eddy covariance flux measurements *Eur. J. Soil Sci.* **61** 773–84

Lohr S L 2009 *Sampling: Design and Analysis* 2nd edn (Boston, MA: Brooks/Cole)

Lokupitiya E and Paustian K 2006 Agricultural soil greenhouse gas emissions: a review of national inventory methods *J. Environ. Qual.* **35** 1413–27

Maia S M F, Ogle S M, Cerri C E P and Cerri C C 2010 Soil organic carbon stock change due to land use activity along the agricultural frontier of the southwestern Amazon, Brazil between 1970 and 2002 *Glob. Change Biol.* **16** 2775–88

McSwiney C P and Robertson G P 2005 Nonlinear response of N_2O flux to incremental fertilizer addition in a continuous maize (Zea mays L) cropping system *Glob. Change Biol.* **11** 1712–9

Nusser S M, Breidt F J and Fuller W A 1998 Design and estimation for investigating the dynamics of natural resources *Ecol. Appl.* **8** 234–45

Nusser S M and Goebel J J 1997 The National Resources Inventory: a long-term multi-resource monitoring programme *Environ. Ecol. Stat.* **4** 181–204

Ogle S M, Breidt F J, Easter M, Williams S, Killian K and Paustian K 2010 Scale and uncertainty in modeled soil organic carbon stock changes for US croplands using a process-based model *Glob. Change Biol.* **16** 810–20

Ogle S M, Breidt F J and Paustian K 2005 Agricultural management impacts on soil organic carbon storage under moist and dry climatic conditions of temperate and tropical regions *Biogeochemistry* **72** 87–121

Ogle S M, Breidt F J and Paustian K 2006 Bias and variance in model results associated with spatial scaling of measurements for parameterization in regional assessments *Glob. Change Biol.* **12** 516–23

Sanchez P A *et al* 2009 Digital soil map of the world *Science* **325** 680–1

Sarndal C-E, Swensson B and Wretman J 1992 *Model Assisted Survey Sampling* (Berlin: Springer)

Smith P *et al* 2007 Agriculture *Climate Change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* ed B Metz, O R Davidson, P R Bosch, R Dave and L A Meyer (Cambridge: Cambridge University Press)

Smith P *et al* 2008 Greenhouse gas mitigation in agriculture *Phil. Trans. R. Soc.* B **363** 789–813

Smith P *et al* 2012 Towards an integrated global framework to assess the impacts of land use and management change on soil carbon: current capability and future vision *Glob. Change Biol.* **18** 2089–101

Spencer S, Ogle S M, Breidt F J, Goebel J and Paustian K 2011 Designing a national soil carbon monitoring network to support climate change policy: a case example for US agricultural lands *Greenhouse Gas Manag. Meas.* **1** 167–78

Stehfest L and Bouwman L 2006 N_2O and NO emission from agricultural fields and soils under natural vegetation: summarizing available measurement data and modelling of global annual emissions *Nutr. Cycl. Agroecosyst.* **74** 207–28

US-EPA 2011 *Developing a National Greenhouse Gas Inventory System* EPA-430-K-11-005 (Washington, DC: US-Environmental Protection Agency)

US-EPA 2012 *Inventory of US Greenhouse Gas Emissions and Sinks: 1990–2010* (Washington, DC: US-Environmental Protection Agency) p 481

Wassmann R, Neue H U, Lantin R S, Buendia L V and Rennenberg H 2000a Characterization of methane emissions from rice fields in Asia: I. Comparison among field sites in five countries *Nutr. Cycl. Agroecoyst.* **58** 1–12

Wassmann R, Neue H U, Lantin R S, Buendia L V, Corton T M and Lu Y 2000b Characterization of methane emissions from rice fields in Asia: III. Mitigation options and future research needs *Nutr. Cycl. Agroecoyst.* **58** 1–12

Wassmann R, Neue H U, Lantin R S, Makarim K, Cahreonsilp N, Buendia L V and Rennenberg H 2000c Characterization of methane emissions from rice fields in Asia: II. Differences among irrigated, rainfed, and deepwater rice *Nutr. Cycl. Agroecoyst.* **58** 13–22

Wolf B, Zheng X, Brüggemann N, Chen W, Dannenmann M, Han X, Sutton M A, Wu H, Yao Z and Butterbach-Bahl K 2010 Grazing-induced reduction of natural nitrous oxide release from continental steppe *Nature* **464** 881–4

Yao Z, Wolf B, Chen W, Butterbach-Bahl K, Brüggemann N, Wiesmeier M, Dannenmann M, Blank B and Zheng X 2010a Spatial variability of N_2O, CH_4 and CO_2 fluxes within the Xilin River catchment of Inner Mongolia—a soil core study *Plant Soil* **331** 341–59

Yao Z, Wu X, Wolf B, Dannenmann M, Butterbach-Bahl K, Brüggemann N, Chen W and Zheng X 2010b Soil–atmosphere exchange potential of NO and N_2O in different land use types of Inner Mongolia as affected by soil temperature, soil moisture, freeze-thaw, and drying–wetting events *J. Geophys. Res.* **115** D17116