Whole farm quantification of GHG emissions within smallholder farms in developing countries

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Received 31 January 2013, revised 31 January 2014
Accepted for publication 4 March 2014
Published 31 March 2014

Abstract
The IPCC has compiled the best available scientific methods into published guidelines for estimating greenhouse gas emissions and emission removals from the land-use sector. In order to evaluate existing GHG quantification tools to comprehensively quantify GHG emissions and removals in smallholder conditions, farm scale quantification was tested with farm data from Western Kenya. After conducting a cluster analysis to identify different farm typologies GHG quantification was exercised using the VCS SALM methodology complemented with IPCC livestock emission factors and the cool farm tool. The emission profiles of four farm clusters representing the baseline conditions in the year 2009 are compared with 2011 where farmers adopted sustainable land management practices (SALM). The results demonstrate the variation in both the magnitude of the estimated GHG emissions per ha between different smallholder farm typologies and the emissions estimated by applying two different accounting tools. The farm scale quantification further shows that the adoption of SALM has a significant impact on emission reduction and removals and the mitigation benefits range between 4 and 6.5 tCO₂ ha⁻¹ yr⁻¹ with significantly different mitigation benefits depending on typologies of the crop–livestock systems, their different agricultural practices, as well as adoption rates of improved practices. However, the inherent uncertainty related to the emission factors applied by accounting tools has substantial implications for reported agricultural emissions. With regard to uncertainty related to activity data, the assessment confirms the high variability within different farm types as well as between different parameters surveyed to comprehensively quantify GHG emissions within smallholder farms.

Keywords: smallholder agriculture, farm scale GHG quantification, mitigation, Kenya, sustainable agricultural land management

1. Introduction

Given the current projections on global population growth and food consumption patterns agricultural production will need to increase by at least 70% to meet demands by 2050. At the same time, the climate is being influenced by GHG emissions from the agricultural sector, which is responsible for an estimated 10–12% of total GHG emissions (Smith et al. 2007). Consequently, this sector holds significant climate change mitigation potential through the reductions of the major greenhouse gas (GHG) emissions (CO₂, N₂O and CH₄) as well as the sequestration of carbon in agricultural landscapes. The majority of emissions and the expected increase of agricultural emissions are in low- and middle-income countries, where smallholder farmers predominate (Smith et al. 2007). Smallholder farmers tend to have low absolute emissions per hectare, but high emissions per unit of food produced (`emissions intensity’). As with other sectors, the United Nations Frame-
work Convention on Climate Change (UNFCCC) formulates specific requirements for national performance and benefit systems for climate mitigation and adaptation actions in the Land Use, Land-Use Change and Forestry sector (LULUCF). The convention requires use of the IPCC guidelines to measure and report agricultural emissions at the national level. However, the country-specific emission factors and site-specific information required to develop national GHG accounting systems for the agricultural sector or respective nationally appropriate mitigation actions (NAMAs) often do not exist. Furthermore, the land-use categories used in national GHG inventories are very broad and do not consider the diversity of smallholders and their need for future increases in production.

### 2. Methods and concepts of agricultural emissions quantification

Typical mixed crop and livestock smallholder farming systems are characterized by different integrated production systems within one farm. In such systems, livestock provide draught power to cultivate land and manure to fertilize the soil, and crop residues feed livestock (Herrero et al. 2010). To date, most of the studies that have evaluated mitigation options in the agricultural context have explored them using a single method to mitigate a specific pollutant, including specific GHGs (del Prado et al. 2010). Given the complex nature of the interactions in such farming systems and between adaptation, food security and mitigation activities, using appropriate indicators and methods of analysis is essential to establish a baseline that captures all relevant information, as well as for meaningful monitoring and evaluation (FAO 2012).

The IPCC has compiled the best available scientific methods into published guidelines (IPCC 2006b) for estimating emissions and emission removals from the land-use sector. This guidance is designed for GHG accounting at the national level (IPCC 2006b). As the IPCC forms the mandatory basis for the national GHG emission accounting under UNFCCC and the Kyoto protocol, most of the project-based accounting standards and specific methodologies in the land-use sector have widely adopted this methodological guidance including the use of default emission factors. Along with this, numerous tools have been developed to support the quantification of GHG emissions from agricultural and forestry activities.

Within the land-use sector, the GHG emissions sources and sinks are disaggregated into the following components: non-CO₂ emissions: enteric fermentation (CH₄), manure management (CH₄ and N₂O), rice cultivation (CH₄ and N₂O), agricultural soils (N₂O), burning of biomass (N₂O); and CO₂ emissions or emission removals: carbon stock changes in biomass (above- and below-ground biomass, litter, deadwood, harvested wood products) and carbon stock changes in soil organic carbon (SOC). The IPCC protocols require estimating GHG emissions and change in carbon stocks within these categories providing detailed guidelines and equations for calculating any changes (IPCC 2006b). Thereby, the IPCC uses the concept of key source or sink category which is an activity or carbon pool that has a significant influence on the estimate of GHGs with respect to the absolute level trend, or uncertainty in emissions and removals. Fundamental to the IPCC guidelines is the concept of hierarchical tiers (tiers 1, 2, 3) for estimating GHG emissions and removals. The three tiers are a function of methodological complexity, regional specificity of the emission factors, and the extent and spatial resolution of the activity data. The tiers progress from least to greatest level of certainty (IPCC 2006b).

### 2.1. Testing smallholder farm scale quantification in Western Kenya

To compare different approaches, we tested farm scale quantification with real data in smallholder conditions. According to Denef et al. (2012), accounting tools can be divided in three main categories: (1) calculators, (2) protocols and guidelines, and (3) process-based models. Basically, calculators and protocols use models (process-based and/or empirical models) often in combination with IPCC default values as emission factors. GHG results produced by calculators and protocols predominantly provide an area-based output, such as tCO₂ ha⁻¹, per project or per region. Only few provide the results on a product-based output.

The applied dataset was derived from the Activity Base-line and Monitoring System (ABMS) of the Kenya Sustainable Agricultural Land Management Project in Western Kenya. This project is developed and implemented by the NGO, Vi Agroforestry, and is validated against the Verified Carbon Standard (VCS). The project covers 60 000 farmers, organized in 3000 registered farmer groups on approximately 45 000 ha of agricultural land. It is breaking new ground in designing and implementing climate finance projects in the agricultural sector. While increasing agricultural productivity and enhancing resilience to climate change, smallholder farmers will receive benefits for greenhouse gas mitigation based on the adoption of sustainable agricultural land management (SALM) practices. The project is achieving its goal using a holistic and focused farm-enterprise extension approach. It strongly supports the development of farmer groups and local advisory service providers, provides high-quality advisory services to farmer groups to strengthen democratic principles, introduce loan and saving schemes to provide farmers with access to credit, and supports farmers to adopt site- and context-specific SALM practices. Therefore, the array of different SALM practices is very large. However, among the most widely adopted practices with a particular focus on those relevant for understanding greenhouse gas emissions and removals and increase of agricultural productivity include:

- **Residue management**: residues from crops such as maize, beans, cowpeas, sweet potatoes as well as deciduous tree litter are left on the soil. This organic matter creates favourable microclimatic conditions that optimize decomposition and mineralization of organic matter (‘surface composting’), and protect soil from erosion.
- **Composting** entails controlled biological and chemical decomposition that converts animal and plant wastes to humus. It is an organic fertilizer made from leaves, weeds, manure, household waste and other organic materials from the farm.

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- Cover crops are planted on bare or fallow farmland to reduce erosion and mineralization of organic matter. Green manure is a fast growing cover crop sown before the main crop and then ploughed into the soil.
- Agroforestry is a major project activity to increase tree cover that contributes to increased biomass above-and below-ground including soil carbon. Several agroforestry practices are part of this project activity: Agro-silviculture comprises selected species of trees (e.g. *Sesbania sesban*, *Markhamia lutea*, *Grevillea robusta*) grown on the cropland in a mixed spatial system. Boundary and hedge tree planting of trees along field boundaries, borders and roadsides creating micro-climates for crops, and serve as a windbreak, thus stabilizing the soil. Woodlots serve as biomass pool for the farmers and are established near homesteads and separately from cropland. Tree shading of perennial crops involves trees grown in combination with other perennial crops such as coffee, sugarcane and tea. These systems potentially increase productivity of the soils through increased litter inputs, enhanced microclimatic conditions and soil nutrient availability. Silvo-pastoral systems combine trees and pastures to produce green manure and improved fallowing practices. Finally, tree fodder banks provide essential and improved feeds to livestock and are an integral part of the whole livestock feeding and management system. Fodder trees usually include *Calliandra* spp., *Sesbania sesban*, *Gliricidia sepium*, *Moringa oleifera* and *Cajanus cajan*.

For this study, data from 103 smallholder farms in the Kisumu project location were used. These so-called ABMS farms are representative farm households which are interviewed periodically throughout the project’s lifetime (20 years) based on a structured questionnaire. Questions refer to general farm structure, current and future management practices, cropping systems, use of biomass within the farms, crop yields, livestock management, tree biomass and general socio-economic farm parameters. The sample unit is the whole farm. The data gathered from the ABMS farms always refer to two cropping seasons. The first season is from April to September and corresponds to the long rains period. This is the main season and usually has a higher productivity. The second season is from October to March in the following year and corresponds to the short rains period.

For this study the data representing the baseline conditions in the year 2009 are compared with 2011 where farmers adopted sustainable land management practices (SALM). Over four consecutive seasons farmers have adopted SALM such as mulching with crop residues, cover crops, applying composted manure and planting of soil fertility and biomass agroforestry trees on their cropland.

For this whole farm testing first a cluster analysis was conducted using SPSS (SPSS Inc. 2005) to identify different farm typologies in the project. The selected approach was to perform a hierarchical method to define the number of clusters and then use the *k*-means procedure to actually form the clusters of different farms. The variables selected to perform the analysis include:

- Maize yield in kg ha$^{-1}$.
- Area under SALM practices in ha.
- Area under crop residue burning in ha.
- Area under N-fertilizer use in ha and total units of fertilizer applied per year in kg.
- Area under mulching in ha.
- Area under application of direct manure in ha.
- Area under application of composted manure in ha.
- Area under cover crops in ha.
- Total number of trees planted.
- Total farm land in ha, and
- Total agricultural land in ha.

The Ward’s method was applied on the variables to produce an agglomeration schedule using SPSS. The number of clusters was determined by identifying the step in the agglomeration schedule where the ‘distance coefficients’ makes the biggest jump (also known as ‘elbow rule’ using a scree diagram). This resulted in 7 defined clusters. During the second step, the *k*-means method is used with the defined number of 7 clusters. The analysis revealed that three clusters are represented only by one to four farms which are outlier farms in terms of large farm areas and very high yields of maize. The remaining four farm clusters of farm typologies are used for the whole farm quantification analysis in this study (figure 1).

Table 1 compares the four farm clusters showing the average values for each cluster under baseline conditions in 2009 and after 2 years of project implementation. With regard to tree biomass, the average carbon stocks of long-living biomass trees are presented in the baseline whereas only the increase of additional carbon as a result of trees planted in the project is presented.

Table 2 illustrates the change of farm management practices within the farm clusters in the project as a result of extension, training and capacity building in SALM. Promoted practices include more than the ones listed, however, mulching and composting is explicitly shown since these practices are accounted for soil carbon benefits in the project. Again, average values for each cluster are presented.

For each of the farm clusters, farm scale quantification was exercised using first the VCS SALM methodology\(^1\) which combines activity monitoring of agricultural practices and process-based modelling. This methodology proposes to use a modelling approach by parameterizing a soil carbon model with existing datasets and to run the model with input values derived from the farm survey (ABMS). The soil model proposed is the Rothamsted carbon model RothC—Version 26.3 (Coleman and Jenkinson 1996, 2007). The model calculates soil carbon stock changes due to changes of inputs of crop residues and manure in the soil. The increase or decrease of soil organic matter (SOC) is the result of the decomposition of the added organic materials.

\(^1\) The VCS SALM methodology is available at [http://v-c-s.org/SALM_methodology_approved](http://v-c-s.org/SALM_methodology_approved).
Figure 1. Location of smallholder ABMS farms in Western Kenya classified into four farm clusters (OpenStreetMap 2013).

Table 1. Quantitative description of the four farm clusters using average values.

| Cluster | No of farms | Farm land/agricultural land (ha) | Main crops; % of cropland; crop yields (t ha$^{-1}$ yr$^{-1}$) | % farms with livestock and types | % farms with trees; trees ha$^{-1}$; carbon (tCO$_2$ ha$^{-1}$) |
|---------|-------------|----------------------------------|---------------------------------------------------------------|---------------------------------|--------------------------------------------------|
|         |             |                                  |                                                               |                                 |                                                  |
| Baseline conditions 2009 |             |                                  |                                                               |                                 |                                                  |
| 1       | 39          | 0.67/0.49                        | Maize; 50%; 0.8 Sorghum; 7%; 0.7 Beans; 6%; 0.6              | 95%; 1 calve; 3 cows; 2 goats; 11 chicken; 2 sheep | 54%; 46; 6.1 |
| 2       | 12          | 0.71/0.36                        | Maize; 72%; 1.8 Beans; 35%; 0.6                            | 100%; 1 calve; 3 cows; 2 goats; 10 chicken | 50%; 103; 7.1 |
| 6       | 8           | 0.88/0.57                        | Maize; 46%; 2.1 Beans; 21%; 0.2                            | 100%; 1 calve; 4 cows; 3 goats; 11 chicken; 2 sheep | 75%; 56; 6.9 |
| 7       | 38          | 0.76/0.53                        | Maize; 55%; 1.2 Beans; 21%; 0.3 Sorghum; 7%; 1.6           | 95%; 1 calve; 3 cows; 3 goats; 8 chicken; 1 sheep | 55%; 46; 6.3 |

| Project conditions 2011 |             |                                  |                                                               |                                 |                                                  |
| 1       | 39          | 0.64/0.48                        | Maize; 52%; 1.7 Sorghum; 8%; 1.2 Beans; 11%; 0.7            | 87%; 1 calve; 2 cows; 2 goats; 12 chicken | 77%, 131; +1.5 |
| 2       | 12          | 0.78/0.48                        | Maize; 60%; 2.5 Beans; 38%; 0.9 Sorghum; 13%; 1.3           | 92%; 3 cows; 1 goat, 17 chicken | 92%; 136; +1.6 |
| 6       | 8           | 0.80/0.56                        | Maize; 55%; 2.9 Beans; 29%; 1.2 Sorghum; 16%; 0.5         | 88%; 2 calves; 4 cows; 2 goats; 7 chicken; 3 sheep | 88%; 202; +2.4 |
| 7       | 38          | 0.78/0.63                        | Maize; 58%; 2.6 Beans; 22%; 0.7 Sorghum; 12%; 1.1 Vegetables; 6%; 1.7 | 95%; 4 cows; 2 goats; 10 chicken; 1 sheep | 76%; 190; +2.2 |

Table 2. Average areas per farm under different management practices in the baseline and adoption areas in 2011 for each farm cluster.

| Cluster | Residue burning—area per farm (ha) | N-fertilizer use—area per farm (ha) | Total SALM area per farm (ha) (%) change | Mulching—area per farm (%) change | Composting—area per farm (%) change | Wood/charcoal consumption (h day$^{-1}$) (%) change |
|---------|------------------------------------|------------------------------------|----------------------------------------|---------------------------------|---------------------------------|---------------------------------------------|
|         |                                     |                                    |                                        |                                 |                                 |                                             |
| 2009/2011 |                                     |                                    |                                        |                                 |                                 |                                             |
| 1       | 0.18/0.01                          | 0.04/0                             | 0.43/0.90 (+53%)                       | 0.03/0.30 (+90%)                 | 0.01/0.25 (+95%)                 | 3.0/3.1 (-15%)                            |
| 2       | 0.12/0.03                          | 0.12/0                             | 0.42/1.02 (+59%)                      | 0.06/0.43 (+86%)                 | 0.03/0.44 (+94%)                 | 4.4/3.3 (-34%)                            |
| 6       | 0.22/0                             | 0.11/0                             | 0.52/0.81 (+36%)                     | 0.03/0.46 (+94%)                 | 0.02/0.29 (+95%)                 | 4.1/3.1 (-34%)                            |
| 7       | 0.18/0                             | 0.11/0                             | 0.41/0.79 (+48%)                     | 0.02/0.41 (+96%)                 | 0.08/0.35 (+76%)                 | 3.8/3.3 (-15%)                            |
Table 3. Soil information and input parameters for the RothC soil modelling of different management practices for each farm cluster. The organic inputs are given for 2009 and 2011.

| Cluster | Clay content of the topsoil (%) | Inputs—crop residues 1st season (tC ha\(^{-1}\)) | Inputs—crop residues 2nd season (tC ha\(^{-1}\)) | Inputs—composted manure per application (tC ha\(^{-1}\)) | Inputs—soil fertility trees per year (kg C ha\(^{-1}\)) |
|---------|---------------------------------|------------------------------------------|------------------------------------------|------------------------------------------|------------------------------------------|
| 1       | 44                              | 0.53/0.82                               | 0.50/0.72                               | 0.65/0.55                               | 0/0.4                                   |
| 2       | 49                              | 0.82/1.12                               | 0.69/1.17                               | 0.93/0.64                               | 0/7.2                                   |
| 6       | 40                              | 0.88/1.12                               | 0.69/0.95                               | 0.76/0.75                               | 0/30.1                                  |
| 7       | 39                              | 0.77/1.00                               | 0.71/1.14                               | 0.62/0.63                               | 0/2.3                                   |

Table 4. Carbon pools and GHG emission sources selected in this study for the two quantification tools.

| IPCC carbon pools                          | Selected under SALM methodology | Selected under cool farm tool |
|--------------------------------------------|---------------------------------|-------------------------------|
| Aboveground woody biomass                  | Yes                             | Yes                           |
| Below-ground woody biomass                 | No                              | No                            |
| Dead wood                                  | No                              | No                            |
| Litter                                     | No                              | No                            |
| Soil organic carbon                        | Yes                             | Yes                           |
| Wood products                              | No                              | No                            |
| Emission sources                           | GHGs included under SALM methodology | GHGs included under cool farm tool |
| Use of fertilizers                         | \(N_2O—\)emissions from N-fertilization effects \(N_2O—\)emissions from N-fertilization and N-emissions from crops (indirect) | \(CO_2—\)from fertilizer production |
| Direct and indirect field \(N_2O\)         | \(N_2O—\)emissions from N-fixing species\(a\) \(N_2O—\)emissions from burning and mulching | \(CH_4, N_2O—\)emissions from burning |
| Residue management                         | \(CH_4, N_2O—\)emissions from burning | \(CH_4, N_2O—\)emissions from burning and mulching |
| Burning of fossil fuels\(b\)              | \(CO_2, CH_4, N_2O\)           | \(CO_2\)                     |
| Livestock enteric emissions                | \(CH_4—\)initially not included under SALM methodology | \(CH_4\)                     |
| Livestock manure management                | \(N_2O, CH_4—\)initially not included under SALM methodology | \(N_2O, CH_4\)               |
| Livestock feed                             | No                              | \(CO_2\)                     |

\(a\) Not included in this study due to lack of data.

\(b\) Not included since no machinery is used in agricultural management within the sample farms.

The inputs required by the model are clay content in the soil (%); climate parameters such as monthly temperature (\(^\circ\)C), monthly precipitation (mm), monthly pan evaporation (mm); additional residue inputs due to crop management changes (tC ha\(^{-1}\)); additional manure inputs due to manure management changes (tC ha\(^{-1}\)); and soil cover in each month. The data to parameterize the model where compiled from local weather stations and from online databases such as the harmonized world soil database (FAO/IIASA/ISRIC/ISSCAS/JRC 2012).

The calculation of organic inputs is based on the data collected from the ABMS farms and on equations from the volume 4 of the 2006 IPCC guidelines. For instance, the harvested fresh yield of crops in t ha\(^{-1}\) season\(^{-1}\) is converted to amount of residues produced on the basis of the equations reported in table 11.2 in volume 4 of the 2006 IPCC guidelines (IPCC 2006a). Table 3 displays the average weighted organic inputs for each farm cluster for the RothC modelling.

In addition to the SALM methodology, IPCC emission factors were used to estimate emissions from manure management. To account for emissions from enteric fermentation, Kenya-specific emission factors were applied (e.g. Herrero et al. 2008).

As a comparison, the cool farm tool (CFT) calculator was used for the same farm clusters being a user-friendly farm-level greenhouse gas calculator for estimating net GHG emissions from agricultural management. Methodologically, the CFT sits between calculators using simple emission factor approaches (IPCC tier 1) and process-based models (tier 3) providing tailored emission estimates without the need for data beyond farmer common knowledge and a deeper understanding of the interactions between land use, biophysical processes and management operations (Hillier et al. 2011).

Table 4 summarizes all carbon pools and GHG emission sources included in the comparison study.
3. Results

3.1. Cluster analysis

The four farm clusters studied differ in various aspects. Clusters 1 and 7 with 39 and 38 farms respectively are quite similar in the baseline in terms of land holdings, average livestock per farm as well as existing woody biomass. The yields of the main crop maize are slightly higher in cluster 7. Cluster 2 (12 farms) is characterized by smaller agricultural land, but with higher dependency on maize and beans and with significantly higher yields in the baseline. Although only 50% of the farms grow long-term trees, these farms on average have the highest tree carbon density. The 8 farms of cluster 6 have the largest land holdings (0.88 ha) as well as the highest maize yield in the baseline. 75% of these farms grow trees.

After 4 seasons of project implementation in 2011 the farmers in all clusters significantly increased their crop yields, cluster 1 is lower than the other farm clusters in this respect. All farms increased the tree cover while the number of farms possessing livestock slightly decreased except for cluster 7.

With regard to farm management practices, all farms reduced the burning of crop residues and ceased using N-fertilizers. The total adoption of different SALM practices ranges around 50% of the farm land with cluster 6 being an exception with only 36%. Taking a closer look at the two soil carbon relevant practices mulching and composting, the adoption rates are quite constant up to 95% except for cluster 7 where 75% of the crop land is under composting. With regard to the consumption patterns of firewood and charcoal, it is interesting to observe that the consumption is decreasing within the project in three farm clusters. This can be explained by the promotion of energy efficient stoves and the quality of firewood producing tree species on-farm which is promoted as part of the project. In cluster 1, on the other hand, the consumption increased slightly which might be a cause of the trade-off between crop residues and manure normally used by the farms for cooking prior to the project. This trade-off needs to be carefully studied over time in order to avoid leakage effects in such conditions.

3.2. Whole farm quantification

The whole farm quantification results in 2009 and 2011 represent annual emissions and emission removals (sequestration)
Figure 3. (a) and (b) Average annual GHG emission and removal profile of each farm cluster in tCO$_2$e ha$^{-1}$ representing the baseline (2009) and the project scenario (2011) using the cool farm tool.

The existing carbon stocks of long-living trees on agricultural land in 2009 are very low ranging between 1.4 and 3 tCO$_2$e ha$^{-1}$, because only 50–75% of the farms actually have these long-living biomass trees on their cropland. Since baseline trees have already reached equilibrium state, no carbon stock changes are assumed for 2009.

After two years of project implementation 72–92% of the farms now grow such trees contributing to annual carbon stock changes of 0.8–1.1 tCO$_2$e ha$^{-1}$.

The modelled soil carbon stock changes increased significantly as a result of the adoption of SALM practices from around 0.2 tCO$_2$e yr$^{-1}$ in 2009 to 1.2 ha$^{-1}$ yr$^{-1}$ in 2011. The difference between the four clusters is in the range of 27%. There is a direct relationship between the crop yield and residues produced and the soil carbon stock changes if the residues are added to the soil as organic matter (mulch or compost). The crop yield increase is reflected by higher organic input factors and higher modelled SOC changes.

The main source of emissions is attributed to livestock and the differences between the four clusters result from the different livestock units per ha of agricultural land, in particular the difference in the number of cows. For example, farm cluster 2 with the highest amount of enteric emissions (8.2 tCO$_2$e ha$^{-1}$ yr$^{-1}$) in the baseline has on average 9 cows ha$^{-1}$ of agricultural land while cluster 1, having low enteric emissions, has 5 cows. In 2011, the farms in cluster 2 have reduced this number to 5 cows ha$^{-1}$.

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CFT includes emissions from fertilizer production; fertilizer induced field emissions (N$_2$O) and background N$_2$O field emissions which are combined under direct and indirect N$_2$O field emissions; burning of crop residues and N$_2$O emissions from residues is referred to as emissions from crop residue management. Emissions from livestock feed are also accounted and are depending on the type and quality of grazing management. Based on the survey data and information from the project significant changes occurred within two years of livestock management within the different farm clusters. Table 5 displays these changes as average inputs given in the CFT for adult productive cattle, the most important source for livestock emission (changes).

The CFT only shows carbon stock changes for tree biomass, therefore there are no changes estimated for the baseline year 2009. The emissions from crop management (crop residue management and direct and indirect field N$_2$O) are higher compared to the SALM/IPCC method with an average of 0.6 tCO$_2$e ha$^{-1}$ yr$^{-1}$ because the CFT more comprehensively considers different sources of emissions including fertilizer production as well as different sources of N$_2$O emissions from the fields including soils, inorganic fertilizers, organic fertilizers (manure and compost), and crop residues. The impact of emissions from inorganic fertilizers is highly insignificant given the low application rates of 5–23 kg ha$^{-1}$ yr$^{-1}$.

With regard to livestock emissions, the management of livestock including feeding practices and manure management significantly affects the overall emissions. Enteric fermentation is linked to the feed characteristics. Farm cluster 6 has the highest emissions with 7.8 tCO$_2$e ha$^{-1}$ yr$^{-1}$ which is due to its lower percentage of diet from feed mix instead of open grazing. Animals feeding in open grazing are more active and have higher maintenance energy requirements. Cluster 7 has the lowest enteric emissions due to a high percentage of animals confined in small areas (homesteads and stalls) fed with a mixture of tropical grasses (Napier grass) and crop residues. The differences of emissions from manure management among the farm clusters is similar to the IPCC estimation, however, the CFT calculates higher emissions in the order of magnitude of 120% although the same manure management conditions were used. The CFT also accounts for indirect N$_2$O emissions from manure management. The different emissions from feed are basically a result of the share of feed mix compared to feeding in open grazing conditions.

In 2011, the total emissions are reduced while carbon is stored in the soil and trees as part of the promotion of SALM practices. In particular the livestock emissions decreased significantly which clearly indicates the impact of the management practices such as composting and improved livestock management. Most of the farms now switched to more ‘zero grazing’ management where the livestock is confined in small areas within the homestead and 80–90% of the feed is from a feed mix of fodder legumes (e.g. Calliandra fodder), Napier grass and some crop residues. Since composting manure is among the key activities within the project, the manure emissions were also reduced. The crop management emissions on the other hand remained stable given that although inorganic fertilizers were not used the crop areas under compost and mulching application increased with higher N$_2$O emissions from these fields.

### 3.3. Mitigating greenhouse gases from smallholder farms

After assessing the changes of farm-based GHG emissions and removals over 2 years and the differences between the four farm clusters using two farm quantification methods, this section now takes a closer look at the mitigation benefits which could be achieved as a result of adoption of sustainable land management practices. Figure 4 presents the annual mitigation benefits for each carbon pool and emission source of the farms using the two quantification methods. Positive values indicate benefits (emission reductions or emission removals). The average mitigation benefit and the ranges among the different farm clusters are shown for each method.

The annual benefits from woody biomass of trees planted in the project range among the four farm clusters between 0.8 and 1.1 tCO$_2$ ha$^{-1}$ using the SALM methodology and 0.4–0.6 tCO$_2$ ha$^{-1}$ with the CFT. Both methods follow the IPCC guidance and use allometric biomass equations and default root-to-shoot ratios for calculation. The sequestration rate is low due to the fact that the average diameter (DBH) is around 5 cm after 2 years of project implementation. The difference between the two methods can be explained by...
Figure 4. Annual carbon benefits in smallholder farms (tCO$_2$ e ha$^{-1}$ yr$^{-1}$) SALM/IPCC = SALM methodology and IPCC emission factors; CFT = cool farm tool; EF = enteric fermentation; M = manure management; F = emissions from feed characteristics.

The different equations applied. The CFT applies the general tropical moist equation of Brown (1997, updated) while a more site-specific equation was used from Kuyah et al. (2012) for the other method. This study concludes that in particular smaller trees (dbh < 10 cm) dominate the landscape and that apparently small differences in the equations for small trees could add up to a large amount of carbon when looking at a landscape.

The emission reduction benefits from improved crop residue and fertilizer management are very low. With regard to fertilizer management, all farms in the different farm clusters ceased to apply inorganic fertilizers during the first 2 years, however, already the baseline fertilizer application was too low to result in significant emission reductions. Further, farms reduced the burning of residue biomass. However, the increase of emissions due to the introduction of N-fixing plants and composting of residues offsets the emission reductions.

The annual benefits from soil carbon sequestration due to adoption of management practices such as mulching, composted manure and introduction of soil fertility trees are on average 0.9 tCO$_2$ e ha$^{-1}$ using the RothC modelling approach and 0.8 tCO$_2$ e ha$^{-1}$ applying the empirical model approach of the CFT. The range calculated with the CFT between the different farm clusters is larger compared to the RothC model.

GHG emission reductions in livestock account for the largest share of all mitigation benefits. The results based on the CFT in particular reflect also the changes in management and feeding practices in the project. The first method (SALM/IPCC) merely reflects the change of livestock units which also explains the larger range between the different farm clusters. On average, the highest annual benefits calculated with the CFT are emission changes from enteric fermentation (3.2 tCO$_2$ e ha$^{-1}$ yr$^{-1}$), followed by manure management and emission changes from improved feeding practices.

The overall average mitigation benefits of the two quantification methods result in 4–6.5 tCO$_2$ e ha$^{-1}$ yr$^{-1}$ for the SALM/IPCC method and the cool farm tool respectively. With regards to the different farm clusters it can be observed that there are significantly different mitigation benefits depending on typologies of the crop–livestock systems, their different agricultural practices, as well as adoption rates of improved practices during the project.

3.4. Uncertainty

In agriculture uncertainties can be very high and due to this high level of uncertainty it is essential to include respective information to understand, interpret ad compare different agricultural systems. Following the classification provided by Gibbons et al. (2006) this section takes a closer look at the uncertainty in activity data (inventory or survey data) and uncertainty in the emission factors applied for the farm quantification.

A comparison study of carbon accounting tools for arable crops (Whittaker et al. 2013) which identified the cool farm tool as the highest ranking calculator that is currently available, concluded that uncertainty was clearly lacking in the...
majority of the tools and that none of the tools provide an account of which sources of GHG the final results are most sensitive to Whittaker et al (2013). An absence of uncertainty suggests a lack of comprehensiveness as this can provide some information on the robustness of the data sources and detail any temporal or spatial uncertainty (Guo and Murphy 2012). The CFT provides results in various formats and with a breakdown of all emission levels. It allows reviewing all excel-based calculations including the referenced sources for emission factors and default values. With regard to the IPCC tier level of emission factors, the CFT has adopted a higher tier level. For instance, N\textsubscript{2}O emissions from soils are estimated on a tier 3 level based on emission factors on specific soil parameters and on fertilizer types (Hillier et al 2011, 2012). A higher tier level was also adopted for the estimation of livestock emissions and emissions from land-use change. However, the overall uncertainty or source-specific uncertainties are not presented. In applying calculators like the CFT uncertainty is mainly related to the emission factors used rather than the uncertainty in activity data (survey data) which are provided by the user as input data. This is where quantification protocols such as the SALM methodology provide valuable information since such methodologies inherit rigorous sampling and uncertainty requirements from the IPCC guidance in particular for addressing uncertainty of activity data.

Figure 5 presents the uncertainties of activity data surveyed for the year 2011 including input data for the soil modelling as a relative precision of the mean values. The target precision level according to the SALM methodology is 15% at the 95% confidence interval. Following IPCC guidance, the precision is defined by the t-value x standard error of the mean. The relative precision is defined by the precision divided by the mean.

In addition, the uncertainty of the RothC modelling is also shown for the two agricultural seasons which reflects the uncertainty of the emission factors for soil organic carbon sequestration. This soil model response is calculated by using the model input parameters with the upper and lower confidence levels. First, the upper and lower limits of the 95% confidence interval is defined for all model input parameters by sample mean ±t-value x standard error of the mean. The model is run with the minimum and maximum values of the input parameters. The uncertainty in the model output is given by:

\[
\text{Uncertainty} = \frac{|MO_{max} - MO_{min}|}{2 \times MO}
\]

where: \(MO_{min}\): the minimum value of modelled SOC changes at the 95% confidence interval. \(MO_{max}\): the maximum value of modelled SOC changes at the 95% confidence interval. \(MO\): the mean value of modelled SOC changes at the 95% confidence interval.

The uncertainties for the different parameters range as much 10%–87%. Low uncertainties are associated with crop
yields and residues information from the farm surveys in the magnitude of 10–20% followed by uncertainties on manure and compost quantities (26–31%). The differences between the four farm clusters are surprisingly small for these parameters given the differences in the sample sizes. Tree biomass seems to be highly variable within the surveyed farms resulting in very high uncertainties (51%–87%) which underpins the heterogeneity and variability of tree biomass in agricultural landscapes. Small trees with diameters below <10 cm dominate the landscape though they accounted for only a minor share of the biomass compared to very few scattered larger tree (Kuyah et al 2012).

The modelled SOC emission factors for the two seasons in 2011 are higher during the first season (46%–75%) compared to the second season (37%–47%). One explanation for this is that farms grow more divers’ crops during the first season while in the second season mostly maize and beans are planted. This calculated uncertainty of the model response takes into account the uncertainties of the model input parameters including climate and soil data used to parameterize the model. To reduce the potential year to year variability of climate data five-year averaged data were used to parameterize the soil model.

This assessment of uncertainty shows the high variability within different farm types as well as between different parameters surveyed to comprehensively quantify GHG emissions within smallholder farms.

4. Discussion and conclusion

The results of the whole farm quantification in this letter demonstrates the variation in both the magnitude of the estimated GHG emissions per ha between different smallholder farm typologies and the emissions estimated by applying two different accounting tools. The farm scale quantification further shows that the individual management practices have a significant impact on emission reduction and removals independent from the actual farm sizes (figure 6).

Overall, the total GHG emissions and removals including the baseline carbon stocks of trees ranged between 5.2 and 8.9 tCO₂e ha⁻¹ in 2009 and 1.3–4.2 tCO₂e ha⁻¹ in 2011 using the SALM methodology and IPCC emission factors. In comparison to this, the CFT calculates ranges between 5.9 and 10.1 tCO₂e ha⁻¹ in 2009 and 0.5–2.6 tCO₂e ha⁻¹ in 2011. Both tools reflect the differences of management practices and adoption of sustainable land management activities within the crop–livestock systems of the four farm clusters.

The range between the two quantification tools is 0.7–2.0 tCO₂e ha⁻¹ in 2009 and 0.1–1.6 tCO₂e ha⁻¹ in 2011. This variation can be explained by the different system boundaries of the tools, as this considers which sources of emissions were included in the calculations. For instance, the CFT more comprehensively includes emissions from soils and livestock which is reflected in higher GHG emissions estimates in 2009. In 2011, the comparatively lower GHG emission profiles estimated with the CFT demonstrates that the adoption of various management practices affects the whole farm emission intensity and that more comprehensive whole farm quantification potentially could estimate more mitigation benefits from such practices. However, the inherent uncertainty related to the emission factors applied by calculators such as the CFT has substantial implications for reported agricultural emissions. Further, since the user is responsible for the input of precise and accurate activity data, the goal and scope need to be defined for its intended use. Nevertheless, the CFT is a user-friendly and comprehensive ‘tier 2’ calculator to inform users on the sources and mitigation options on a farm level.

On the other hand, for the quantification of project- or landscape-based mitigation benefits a monitoring system must be in place to collect the data and to estimate the uncertainties inherent in the activity data. Methods combining activity monitoring and soil modelling as proposed in the SALM methodology are well applicable to smallholder conditions, since they require mere activity monitoring by the farmer where easily measurable parameters are monitored that allow to quantify soil carbon stock changes and woody biomass with known uncertainties.

The whole farm quantification in 2011 compared to the baseline conditions in 2009 demonstrates the significant mitigation opportunities in smallholder crop–livestock systems if emission sources are comprehensively considered. In particular the reduction of GHG emitted by livestock systems has enormous scope because significant reduction in the amount of methane produced by improving the quality of diets (Herrero et al 2009) and improved management practices including grazing and manure management is possible.
Soil carbon is important for soil structure and related nutrient and water holding properties. Hence increasing soil carbon stocks results in improved crop growth and contributes to enhance climate resilience. In addition the increase in soil organic carbon through sustainable agricultural land management (SALM) practices such as the use of cover crops, residue management and agroforestry will also reduce the need for synthetic nitrogen fertilizer at a given level of crop production.

From a methodological point of view, the IPCC GGP represent a huge set of guidelines and protocols which are applied to monitoring and reporting of national GHG inventories under the UNFCCC and are further adapted by most of the carbon accounting tools. The national oriented approach and the ‘silos’ quantification of different sectors, categories and carbon pools contradict the complex smallholder farming systems with interacting production system components and management practices. As a result, existing project-based offset schemes and emission calculators often recognize only discrete activities and emission sources. In smallholder conditions, where probably a package of different agricultural activities with multiple climate benefits is more appropriate to meet smallholder’ multi-stranded management approaches, assessing the combined effect through a simple additive approach might over- or underestimate the whole farm GHG mitigation impact since the complex systems interactions between different mitigation actions is not considered. Thus, there is also lack of evidence of how combinations of mitigation methods targeting specific GHG may have synergies with other GHG (Smith et al. 2001).

To develop effective quantification systems to estimate the emissions of prevailing agricultural practices including their interactions in smallholder crop–livestock systems and their impact on smallholder landscapes, a more holistic quantification and accounting approach is needed. Such a system needs to assess the GHG emissions in integrated landscape systems and at the same time is suited to determine which mitigation actions and in particular which combination of different mitigation actions are most efficient in terms of GHG emission reduction. Identifying the optimal GHG mitigation pathways for these systems that can be aggregated on a landscape level requires to fully understand the trade-offs and synergies between mitigation actions and climate change adaptation, food security and farm profitability and sustainability.

Acknowledgments

The author appreciate the insights from Vi Agroforestry with their exceptional expertise in strengthening smallholder farmer organizations and providing demand driven agricultural advisory services. The author would like to thank Vi in Kenya for providing the smallholder farm data used in this study.

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