Science to support climate-smart agricultural development

Concepts and results from the MICCA pilot projects in East Africa

10

MITIGATION OF CLIMATE CHANGE IN AGRICULTURE SERIES

Food and Agriculture
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MITIGATION OF CLIMATE CHANGE IN AGRICULTURE SERIES 10

Science to support climate-smart agricultural development

Concepts and results from the MICCA pilot projects in East Africa

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Cover photo: Todd Rosenstock

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Acronyms and glossary of key terms

AGB	Aboveground Biomass
AfSIS	African Soil Information Service
C	Carbon
CA	Conservation agriculture
CARE	Care International in the United Republic of Tanzania
CCAFS	CGIAR research program on Climate Change, Agriculture, and Food Security
CDM	Clean Development Mechanism
CGIAR	Consultative Group on International Agricultural Research
CH_4	Methane
cmolc	Centimoles of charge
CO_2	Carbon dioxide
CSA	Climate-smart Agriculture
CSL	Centre for Sustainable Living
DBH	Diameter at breast height
EADD	East African Dairy Development Program
FAO	Food and Agriculture Organization of the United Nations
***f*NRB**	fraction of Non-Renewable Biomass
GHG	Greenhouse gas
GPS	Global Positioning System
GWP	Global warming potential
HICAP	Hillside Conservation Agriculture Project
HSD	Honest Significant Difference
ICRAF	World Agroforestry Centre
IPCC	Intergovernmental Panel on Climate Change
LCA	Life cycle analysis
LDSF	Land Degradation Surveillance Framework
MICCA	Mitigation of Climate Change in Agriculture Programme
N	Nitrogen
N_2O	Nitrous oxide
NAMA	Nationally Appropriate Mitigation Action
PAS	Photoacoustic Spectroscopy
URT	United Republic of Tanzania

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Executive Summary

This document reports on the concepts driving the scientific activities of FAO's Mitigation of Climate Change in Agriculture Programme's (MICCA) pilot projects in East Africa. It provides results from the research, briefly describes the analytical approaches used and concludes with key messages relevant to discussions on climate-smart agriculture (CSA).

CSA links three critical issues that must be addressed to ensure a sustainable future. One, it supports society's potential to sustainably increase agricultural productivity to support the rapidly growing population. Two, it builds the resilience of food systems and the adaptive capacity of farmers to climate change. Three, it aims to reduce the impact of food, fuel and fiber production on the climate system and combats climate change when appropriate. MICCA operates at the nexus between climate regulation and livelihood advancement.

In October 2011, MICCA partners established two pilot projects in East Africa. The MICCA pilot projects aim to help mainstream CSA in the region by identifying, verifying and scaling up farm management practices that can both increase productivity and set smallholder farmers on a pathway toward emitting fewer greenhouse gases (GHGs) per unit of produce, where possible. As there are many unknowns about what farming approaches are best for reaching CSA's multiple objectives, the underlying premise of the MICCA pilot projects is that strong linkages between science and development are essential to the expansion of CSA in developing countries. Acting on this premise, the partners implementing the MICCA pilot projects have worked together to co-locate multidisciplinary and multiscale research to generate sound decision-relevant information for farmers, development organizations, communities and policy makers. With the goal of improving site-specific and socially appropriate interventions, the implementing partners have applied rigorous experimental approaches and advanced analytical tools to test methods and generate data that reduce the uncertainty about the social and environmental impacts of field and farm management practices, such as conservation agriculture (CA) and zero-grazing dairy production. The layers of quantitative and qualitative information serve to evaluate and generate CSA innovations and identify the constraints to their application. This information was created with the specific purpose of supporting the upscaling of prioritized and targeted innovations.

In reviewing the broad research findings, it must be taken into account that because of the resources allocated for the pilot projects this was a study of limited duration (two-years) and scope. The following list presents the main site-specific findings that have been garnered from the research efforts described in this publication and that are pertinent to CSA practices:

- In cereal-based cropping systems of Kolero in the United Republic of Tanzania, leguminous trees and mineral nitrogen (N) fertilizer can sustainably intensify production by increasing productivity under CA without significantly increasing GHG emissions.

- In integrated crop-livestock systems of Kaptumo, Kenya, partial GHG budgets suggest that smallholder dairy production can be relatively climate-friendly when combined with agroforestry and when pasture is managed wisely.

- The probabilistic model applied at both sites indicated that yield improvements anticipated with CA adoption were unlikely to be achieved given the social and ecological contexts of the sites. Using such probabilistic approaches may be a rapid way to target CSA interventions.

The scientific approach that was followed permits a few general messages and suggestions for future efforts on 'research for development' or 'research to inform policy' that are aimed at quantifying the parameters of potential CSA practices and their implications at nested scales.

- The data precision and variability of a wide range of factors, including farming systems, inputs, farming configurations, the timing of farm activities, ecosystem characteristics, weather and socio-economic conditions, characterizing the emissions associated with different practices that are assumed to be climate-smart will continue to present challenges.

- In estimating emissions for integrated farming systems, it may be important to implement whole-farm measurements or estimates, as quantifying the impacts of only one part of the farming system may miss critical emission hotspots or mitigation leverage points, or overlook options that simultaneously address adaptation and food security. For example, to identify mitigation leverage points, a probabilistic analysis of alternative farm systems could help to focus measurements on parts of the system where there are the greatest uncertainties and that have a large impact on total emissions.

- Research and development stand to benefit from greater integration. Development practitioners, working with local communities, can ensure that research is demand driven and grounded in reality. Research carried out with the active participation of farmers can validate the practices being promoted through development initiatives and estimate the potential impacts of different activities. However, integrating research and development presents some challenges. For example, the time period required to guarantee robust research results may exceed the time span allocated for development programmes. Because of these mismatched timeframes, development programmes and policies may be based on limited empirical evidence.

- Because CSA is meant to have impacts far beyond the farm gate, and is influenced by policy and enabling environment, so the continued integration of research, development and policy is essential. National policies and action plans geared toward enhancing climate change adaptation and mitigation from agriculture need to be continually shaped by the evidence associated with practices that are most likely to succeed, and the feasibility of their implementation and scaling up must be based on field experience and lessons learned.

1. Introduction

Population growth and dietary changes will drive global food demand to unprecedented levels in the coming decades. To keep pace, food production will have to increase 60 percent by 2050 (FAO, 2013). Historically, production increases have resulted either from intensifying production on existing agricultural land or expanding the agricultural frontier. Both of these land-use strategies, however, have already contributed significantly to climate change, and their continued application will further stress Earth's climate system (Foley *et al.*, 2011; Tilman *et al.*, 2011). Moreover, anticipated changes in climate will likely create less favorable growing conditions, which will constrain food production capacity throughout the world. The Contribution of Working Group II to the Fifth Assessment report of the Intergovernmental Panel on Climate Change (IPCC) confirms that global warming above 2°C could reduce crop yields significantly and threaten local and global food security (IPCC, 2014a).

The connection between the twin challenges of ensuring global food security and addressing climate change has caused governments, development organizations and scientists to search for opportunities to address these challenges in an integrated way. In the process, the concept of CSA has emerged and attracted attention from policy makers and development practitioners alike. The concept has been highlighted at multiple science conferences and policy fora. The term 'CSA' refers to agriculture that simultaneously increases productivity, strengthens resilience to climate variability, mitigates GHG emissions where possible and contributes to achieving food security and development objectives (FAO, 2010). CSA establishes a framework for understanding and addressing the co-dependent issues of food and climate and makes explicit a possible integrated agenda for sustainable development. However, the introduction of a new unified approach demands that general questions about CSA's scientific basis be addressed, as well as more specific questions about the relationships among food production, climate change adaptation and mitigation and how multiple objectives can be achieved simultaneously (Neufeldt *et al.*, 2013).

Even for the most thoroughly researched agricultural systems and management practices, information on how food production, adaptive capacity and climate change mitigation co-vary under different management regimes is sparse (Ogle *et al.*, 2014). Empirical evidence for CSA is typically derived from aggregated information that combines research across farming activities and regions. Recently, more and more data have been collected on the impact of farm management on food production and GHG emissions and removals (Linquist *et al.*, 2012). For example, MICCA has investigated the synergies between food security and mitigation benefits from the adoption of sustainable land management technologies (Branca *et al.*, 2011). The MICCA report suggests there is substantial potential for global co-benefits. On average, farmers can increase yields by 69 to 121 percent by adopting agroforestry and better agronomic practices, respectively, and at the same time reduce GHG emissions and/or accumulate carbon (C) in soils or biomass to varying degrees, depending on local climate conditions.

The effect of field management on food production in developing countries is relatively well known for many practices and agricultural ecosystems. However, knowledge of GHG sources and sinks in smallholder farming systems is extremely limited (Rosenstock *et al.*, 2013a). For example, there are fewer than 20 studies of nitrous oxide (N_2O) emissions from soils in sub-Saharan Africa. This is significant because agricultural soils and N applied through organic or inorganic fertilizers are responsible for the majority of global anthropogenic N_2O emissions (IPCC, 2014a), and trends indicate that countries and development programmes will make even greater use of fertilizers in the coming decades (FAOSTAT, 2014). The lack of data on N_2O means that there is virtually no reliable estimate for the potential environmental impacts of fertilizer application (Shcherbak *et al.*, 2014). Along with the dearth of data on soil emissions of N_2O, there is insufficient information for virtually every GHG source and sink (e.g. C accumulation in biomass and soils or methane (CH_4) emissions from enteric fermentation from ruminants) when considering smallholder farming systems. Data are particularly scarce for African agricultural systems, but the situation is not significantly better in Central and South America or most parts of Asia. Uncertainty about emission rates in tropical developing countries is one factor that compromises the ability to identify and scale up management solutions with any assurance of mitigation benefits. This uncertainty also limits policy action and the transition toward greener economies. However, it should be noted that uncertainty in emissions rates is only one of several uncertainties that affect the ability to select and scale up appropriate technologies. Others uncertainties relate to social factors (e.g. land tenure and strength of farmer organizations), economic factors (e.g. profitability and market access) and climate change predictions.

The promotion of CSA innovations outside the social and environmental context where they have been evaluated may have a positive effect, no effect, or even unintended negative consequences for the targeted beneficiaries. For example, evidence for CA shows that its ability to achieve CSA's goals are highly site-specific, subject to weather, the broader production goals of the household, fertilizer availability, and social and labour demands (Andersson and D'Souza, 2013; Giller *et al.*, 2009; Rusinamhodzi *et al.*, 2011; Sommer *et al.* , 2014; Thierfelder *et al.*, 2012). The evidence suggests that application of CA outside its socio-ecological envelope can generate negative outcomes for farmers, communities and the environment. CA is just one example; similar lessons have been found when analyzing other CSA practices, such as fertilizer trees (Ajayi *et al.*, 2011).

The limits of current knowledge and the demand for prioritizing and targeting CSA solutions make it important to generate data that support CSA specifically and the emerging science around CSA more generally. Knowledge useful to CSA development can translate existing knowledge, which tends to be restricted to specific geographic areas and particular topics, into usable information that systematically calls attention to uncertainty. It is equally important to develop research methods and data that capture and quantify the complex relationships among the often competing objectives across multiple dimensions in order to provide development organizations, communities and policy makers with actionable and robust information.

These goals have guided reseach activities at the two MICCA pilot project sites in East Africa. The pilot project sites, established in October 2011, near Kaptumo, Kenya and Kolero in the United Republic of Tanzania make interesting case studies because of the contrasting farming systems (e.g. dairy production and tea cultivation as a cash crop vs slash-and-burn agriculture and the production of staple grains), market orientation (e.g. the combination of commercial and subsistence farming vs purely subsistence farming), and potential mitigation opportunities (e.g. livestock management vs avoided deforestation and crop intensification). This document first describes the conceptual approach applied by ICRAF, FAO, EADD and CARE. It then presents results, organized around three different scales of production, from the first two years of the pilot projects. The conclusion articulates key messages about the science of CSA and the links between science and development projects and offers development practitioners working on CSA some lessons that have been learned during the implementation of the pilot projects.

2. Conceptual framework

The scientific research carried out through the MICCA pilot projects sought to identify, verify and scale up CSA by co-locating multidisciplinary and multiscale research to generate high-value information suitable for a range of decision makers (Fig. 1). The implementing partners collected and analysed biophysical and socio-economic data to evaluate the ecological and economic costs and benefits of various production practices and systems, as well as the constraints that hinder their utilization. These data provide the foundation for recommendations on the significance and appropriateness of CSA innovations for agricultural development in the target regions. The data can also be used to develop regional estimates of the interventions on GHG balance and poverty. The research design is optimized to deliver appropriate information to multiple target audiences: development organizations, scientists and policy makers. By developing audience-specific information, the MICCA pilot projects provide timely and cost-effective information to support mainstreaming CSA.

The MICCA pilot projects are integrated with and attached to larger ongoing development programmes and add a specific climate change component to these programmes. This approach bridged boundaries between groups working in science and development. It established two-way channels of communication that calibrated the research agenda to the needs of the eventual users of the information and provided an outlet to push the results of the research into extension programmes, ultimately linking (scientific) knowledge with (development) action (Cash *et al.*, 2003).

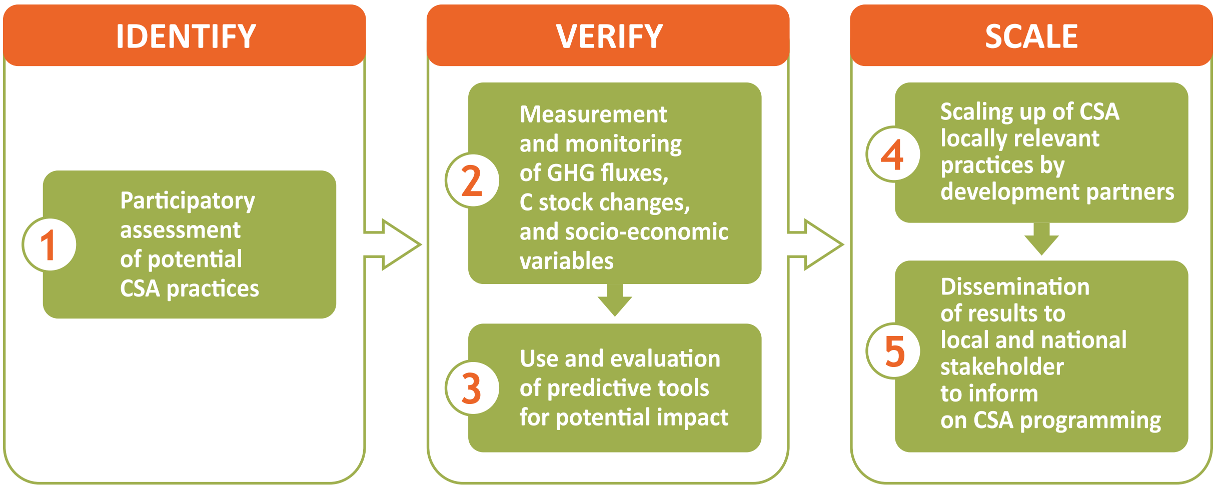

Figure 1. MICCA's five-step approach to identify, verify and scale up CSA in Kaptumo, Kenya and Kolero, the United Republic of Tanzania. The approach produces stakeholder-designed and scientifically-verified CSA innovations for extension programmes, governments and the private sector. This report briefly considers each step but focuses on steps 2, 3 and 4.

Three ideas are fundamental to the pilot project's research activities: the research design should enable the generation and collection of information to support decision making by development partners (e.g. what types of interventions are appropriate and where); analysis and results should be multiscalar so as to fit with the different levels at which decisions are made; and it is important to integrate, not ignore, uncertainty.

Information for decision making

The primary objective of MICCA pilot project research is to evaluate the climate smartness of practices, systems and landscapes to support the scaling up of appropriate technologies. Various groups are currently looking at CSA principles. For example, farmers consider CSA practices when selecting technologies to adopt on their farm, and global policy makers take CSA into account when formulating agricultural investment plans. Because of the range of decisions relating to CSA, the pilot projects' science activities must generate knowledge capable of informing and supporting decisions on a variety of topics, from farm management to broader programmes and policies.

The inherent challenge in conducting decision-relevant research is that end users have different needs. They require information at specific levels of certainty and spatial scale and packaged in different ways. Development organizations, for instance, may only want to know how farming practice 'A' compares to practice 'B' in terms of livelihood-climate synergies, and if practice 'A' is applicable under certain conditions. For example, does the intensification to zero-grazing dairy units from pastured animals increase or decrease GHG emissions per unit of product? In contrast, policy makers may need to identify the best CSA innovation at regional scales to prioritize investments.

The necessity to understand the target audience and account for the various information needs dictates the design of a strategic research campaign. The sampling of biophysical or economic parameters is typically constrained by costs. For this reason, research on CSA always faces tradeoffs among three different criteria: the cost of measurement or modeling, the accuracy of the estimates and the geographic scale. Under resource constraints, monitoring programmes can only hope to maximize two of these criteria (cost, accurancy, scale) at any given time. The third criteria must be somewhat compromised. Coupling resource constraints with the fact that stakeholders require different types of information (e.g. acceptable levels of uncertainty and scales) and meeting the needs of multiple groups within place-based research is a fundamental challenge of the MICCA pilot projects' on-the-ground scientific endeavours.

The MICCA pilot projects' science activities focus on developing research strategies that reduce uncertainty to acceptable levels to aid decision making. The underlying premise is that CSA is operating in a data-poor environment that increases uncertainty and complicates programming and policy activities. This situation is not unique to CSA and development programming in general. However, the degree of uncertainty about GHG fluxes has created an opportunity to improve (and develop new) research for development processes. In response, MICCA pilot project implementing partners have targeted research questions and used analytical approaches that maximize the utility of the data generated. This approach can be seen in a two different examples in MICCA's GHG measurement approach. For instance, it is well known that GHG fluxes are highly variable in time and space (Parkin and Kaspar, 2004; Parkin, 2006). Because the capacity to measure GHG is limited by human and institutional resources (e.g. analytical capacity), experimental decisions must be taken about where and how often to measure. In the approach adopted in the MICCA pilot projects, measurements were taken at the sites one to two times per week. With this intensive sampling, it was not feasible to capture the variability across many farms and landscapes. Instead, MICCA examined representative farms and farming activities rather than capture variations at larger scales. This design was selected because it offered greater confidence that spatial and temporal variability in fluxes would be accounted for and that the needs of the primary immediate users of the information, EADD and CARE, as well as the research community and national policy decision makers, would be respected. The resulting data provides an example of how the sampling frequency can have a significant impact on GHG estimates, which form the foundation of GHG inventories and monitoring, reporting and verification SSA systems.

Match scales of data with scales of action

Decision makers not only need varying levels of certainty about the indicators and processes, they also need information tailored for specific units of management. Smallholder farmers are less interested in understanding how shifting land management practices affect CO_2 fluctuations at the regional level. They are more interested in how changing management practices on their field and farm will affect productivity and incomes. Policy makers, on the other hand, might require information at a coarser resolution and be interested in aggregate impact of programmes and policies on household livelihoods, climate change or agricultural resilience in villages, regions or at national levels.

A nested multiscale sampling approach was adopted to develop information that will be appropriate for multiple decision makers. The minimum unit considered is the smallholder field. Individual fields, ranging from less than 0.005 ha to greater than 2 ha, were measured because this corresponds to the scale of the farming and management activity. Livelihood indicators, as well as indicators of vegetation and soil health on the entire farm were also monitored. The decision to aggregate information to the whole-farm level was based on the fact that this total aligns with the decision unit of the individual households. Households make decisions about production practices for all of their plots, not just one field (Seebauer, 2014; Tittonell *et al.*, 2009).

On a practical basis, an inquiry at the landscape scale provides a key piece of information. It gives the researcher a sense of the diversity and prevalence of agricultural systems and management practices; information that is critical for upscaling results and targeting interventions. On a more theoretical basis, landscape-scale information may be the appropriate scale for policy makers and carbon markets to make interventions. There is need for landscape-scale interventions and institutions that can provide appropriate incentives and support services that can permit individual farmers to adopt sustainable practices and benefits from them.

MICCA pilot project research activities have targeted decision-relevant research at multiple scales depending on the site. The inherent differences between the farming systems in the two sites and the different opportunities these systems offer for livelihoods and climate change mitigation demanded a bifurcated approach. Farms in Kaptumo are typically smallholder dairy farms. The type of smallholder farm (e.g. free grazing, semi-zero grazing, and zero grazing) determines activities across the entire farm and has cascading effects on farm structure and management. For example, intensification of the system may require the import of feeds and the collection, storage and application of manure. It may also require making silage out of fresh feedstuffs to improve digestibility and milk production. In this situation, the farm is typically a contiguous unit. Farming in Kolero, in contrast, is characterized by slash-and-burn agriculture, with farmers often cultivating several plots at significant distances from each other. The crop grown is determined by the plot's topographic position and distance from the homestead. Kolero is a landscape in constant transition, as fields shift between cultivation and fallow, forming a complex, always changing, agricultural mosaic. The diversity of the pilot project locations provided an ideal testbed for the research framework across a diversity of management systems and scales.

Integrating, not ignoring, uncertainty

Development programmes rarely consider uncertainty and variability in the outcomes of proposed interventions (Jeuland and Pattanayak, 2012). Yet, uncertainty surrounds all variables typically used to describe agricultural systems, including biophysical factors, such as soil conditions, and socio-economic factors, such as labour demands and input costs. The impacts of interventions are highly varied, subject to many biophysical and social influences and dependent on a range of factors. Neglecting uncertainty as an input parameter and failing to consider uncertaintly when modeling a structure of proposed responses creates a situation where recommendations or predictions based on averages will almost certainly be wrong when applied to an individual farmer. To present decision makers with useful information on likely outcomes of their decisions, it is essential to consider knowledge gaps and the associated uncertainty (Hardaker and Lien, 2010; Hardaker *et al.*, 2009). Generating more detailed information on factors where there is large uncertainty, along with the large effects this uncertainty will have on outcomes, will have a high value for improving decisions on farms and at programmatic or policy levels.

When projecting an intervention's impacts on development and climate change, uncertainties and knowledge gaps take on an especially prominent role. It is paramount to pursue strategies that clearly and transparently address uncertainties, for instance through data collection that allows for establishing distributions of key variables within landscapes. Such distributions open the door for techniques, such as Monte Carlo analysis, that explicitly include uncertainties and knowledge gaps in impact projections, at least wherever plausible distributions for these input parameters can be defined. This helps decision makers envision both the most likely and most extreme outcomes and better understand the potential risks involved in carrying out an individual action. Furthermore, it is important to feed this information back into research programmes as it has been found that for many different types of investment decisions most measurement efforts are being made in areas that have little impact on improving the decisions. The areas where further information could narrow uncertainty and improve decisions are often not intuitive and can only be revealed by formal decision-making and uncertainty analysis. The results of such analyses can be easily explained to decision makers as spectrum of possible scenarios that range from likely and less likely. There are many examples where such analyses have contributed to improved decisions for government and private sector actors (Hubbard, 2014).

3. Sites, farming systems, and partnerships

The MICCA pilots projects were selected by FAO based on a set of criteria chosen to maximize the diversity among the farming systems, target important national systems and contribute to ongoing development programmes that are promoting practices compatible with CSA. The pilot projects added a climate component to existing development programmes and tested 'science for development' partnerships. Partnerships with ongoing development programmes helped to build on existing efforts and knowledge and introduced and promoted CSA results within the wider communities in which MICCA project partners work.

Project sites overlap with these development projects. Moreover they were demarcated as 100 km^2 landscapes (10 x 10 km^2). This demarcation was selected to increase comparability of results with other ongoing research projects, such as the African Soil Information Service (AfSIS)[1] and the Consultative Group on International Agricultural Research (CGIAR)'s Climate Change, Agriculture, and Food Security (CCAFS) Program's Benchmark Sites[2]. This unit was considered large enough to encompass variability in key landscape features, yet small enough to be logistically practical for field operations.

Two MICCA pilot project sites were selected in East Africa: Kaptumo, Kenya and Kolero in the United Republic of Tanzania (Fig. 2). The Kaptumo site is principally characterized by smallholder dairy farming, which is widespread throughout Western Kenya. By contrast, farmers in the Kolero site manage the landscape using slash-and-burn methods to grow a mix of crops along with maize as a staple crop. Hence, the primary focus of CSA opportunities in Kaptumo center on livestock and farm-level management, whereas in Kolero, the focus is on reducing slash-and-burn farming and related agricultural expansion.

Figure 2. Location of MICCA pilot project sites.

Kaptumo, Kenya

Kaptumo, Kenya is situated in South Nandi County in the Western Highlands of Kenya (35°029' E, 00°007' N). Temperature ranges between 16 and 31°C, with annual precipitation between 1 500 and 2 200 mm. Precipitation is generally distributed across two seasons, the 'short rains' (October and November) and the 'long rains' (March through June). Despite showing a dominant bimodal pattern, precipitation can occur throughout the year. Soils of South Nandi County are well-drained and deep with friable clay and a thick humic top layer. Natural vegetation of the region was originally tropical rainforest.

Land cover in South Nandi County has been undergoing a long process of conversion from its natural forest state. Since before the turn of the 20th century, forest has been cleared for agriculture. Today, the Kaptumo area consists of crop-livestock systems producing mainly dairy and tea (Fig. 3). Cows are primarily fed on unimproved pasture, but many farmers provide supplemental feeds, such as Napier grass or concentrates. Except for tea and passion fruit, crops are grown for subsistence, with maize being the predominant staple food. Recently, there has been a shift in cultivation to sorghum and beans because of the presence of Maize Leaf Necrosis Disease in the area. Each farmer has an average of two acres and three cows, which are typically cross-bred and grazed in paddock systems. Like much of the highlands of Western Kenya, Kaptumo has experienced significant population growth, which has put increasing pressure on the land. However, some farmers within the Kaptumo landscape still have relatively large plots of land compared to other farming communities in the region.

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[1] www.afsissoils.net

[2] www.amkn.org/about/benchmark-sites/

Figure 3. Common farm in the Kaptumo area with grazing animals in a paddock, tea bushes in the background and trees planted along the borders of fields and farms. Photo: Todd Rosenstock

MICCA pilot project activities in the Kaptumo area are implemented within the framework of the EADD whose goal is to raise one million farm families out of poverty by improving market access and profitability of dairy enterprises. ICRAF is an implementing partner. Kaptumo is one of more than forty sites involved in the EADD. When the Kaptumo site was established, EADD was already operating in Kenya, Rwanda and Uganda. In 2014, EADD began Phase II of its operations in the United Republic of Tanzania and new areas of Uganda and continued to support most of its Phase I sites. The MICCA pilot projects add value to EADD by providing a rigorous assessment of the mitigation potential of various production interventions (principally the transition from low-intenstity grazing systems to higher-intensity confined animal systems) being promoted by EADD. MICCA pilot project early research and ICRAF's close partnership with EADD contributed to the programme's move to integrate CSA into their Phase II activities.

Kolero, the United Republic of Tanzania

Kolero and the surrounding region sit within the Mvuha, Bungu, Kasanga and Kolero Wards in the rugged and remote Uluguru Mountain Range in the eastern part of the United Republic of Tanzania (37°48' E, 07°015' S). Temperature ranges between 22 and 33°C, with annual precipitation between 1 500 and 1 800 mm throughout most of the study area. Precipitation falls in a bimodal pattern. The long rains start in early to mid-March and extend until the beginning of June. The short rains start at the end of October and last until the beginning of December.

Kolero is a landscape in constant transition. Slash-and-burn agriculture is the common land management strategy. Patches of forest are burned and then cropped for a few years before being left fallow. Kolero was originally covered with tropical forest. Today, the only remaining original forest is situated in a reserve beyond the borders of the 100 km^2 research area. The rest of the forest patches are small and scattered. They are mostly reserved as sacred forests and managed by traditional rules and norms. Land parcels within the 100 km^2 study site are managed and are in some state of cultivation or fallow

(Fig. 4). Each farmer cultivates approximately 2.5 acres. Half of the farmers having secure land tenure (Zagst, 2011b). Cultivation of field crops (maize, upland and paddy rice, beans, and cassava) dominate agricultural fields, with maize being the most socially desirable. A range of horticultural crops including cabbages, tomatoes and bell peppers, can be found during certain periods of the year but only in limited quantities. Other than chickens, livestock production is rare. A few farmers keep pigs or goats, but livestock keeping is not widespread. The mountainous terrain requires agriculture to be practiced on slopes, sometimes approaching a near vertical incline.

MICCA pilot project science activities in the Kolero area are implemented through a collaboration among FAO, ICRAF and CARE and were originally attached to the CARE Hillside Conservation Agriculture Project (HICAP). The goal of HICAP was to address the critical food insecurity problems perpetuated by poor farming techniques, lack of financial resources for agricultural investment, inadequate input supply and poor access to markets. MICCA pilot project activities provided support for demonstration plots and experiments on CA and helped to widen the scope of interventions to include agroforestry, improved cookstoves, soil and water conservation techniques and raising awareness about climate change. The CARE-HICAP project concluded in February 2013 after four years of operation, and the phase two transition period continued in 2013-2014.

Figure 4. Sown and fallow land on hillslopes, land use characteristic of Kolero in the Southern Uluguru mountains. Photo: Todd Rosenstock

4. Identifying CSA 'options'

Countless plausible CSA management measures are available for most farming systems and activities, and many lists of these measures are widely available (Monteny *et al.*, 2006; Smith *et al.*, 2008; FAO, 2013; IPCC, 2014b). For example, enteric fermentation and the associated methane emissions from cattle account for over 80 percent or more of the GHGs of the dairy value chain around Kaptumo (Weiler, 2013). To increase productivity and decrease the emissions intensity of production (kg of emissions per kg of product), farmers can implement a range of options. They might improve animal diets by feeding more energy and protein dense forages and supplements (Bryan *et al.*, 2012), or they could contribute to CSA goals by improving animal health with better disease control. Farmers and development practitioners have a wide array of potential practices to select from. However, not all practices are relevant for a particular farming context. Biophysical conditions and socio-economic constraints render some practices unsuitable or make it highly improbable that they will be adopted by smallholder farmers. MICCA pilot projects therefore set out to create a 'menu' of CSA relevant practices that farmers may select from based on local farming conditions and individual preferences[3].

To set the research agenda, ideally the menu of socially acceptable options that would serve as the foci of CSA experiments would be identified in a participatory manner before the scientific activities began. However, this was not possible for the MICCA pilot projects. Due to time limitations, the participatory development and refinement of practices had to take place concurrently with research. The foci of the CSA experiments were selected through a mixed approach in which the available list of possible practices was filtered based on the judgement of experts and development partners to establish a short-list of practices. The initial selection was derived from scientific literature and expert opinion. These surveys produced an inventory of potential practices that might be useful to farmers in the region (Table 1). The limitation of this process is that the initial list is not exhaustive and some key practices may have been unintentionally overlooked.

Table 1. Qualitative evaluation by experts of selected CSA options and co-benefits for smallholder dairy in Kaptumo. '+' equals a positive effect, '-' equals a negative effect and '+/-' equals an uncertain effect based on scientific opinion.

Practice	Food security & livelihoods	Mitigation potential			Select adaptation benefits
		CO_2	CH_4	N_2O	
Animal breeding	+	na	+	+/-	More resilient genetics to temp.
Changing grazing intensity	+/-	+/-	+/-	+/-	Maintain/improve soil health
Pasture species introduction	+	+	+/-	+/-	Improved nutrient cycling
Improved fodder and feeding	+	+/-	+	+	Diversify feed supply
Improved/efficient manure handling	+	+	+	+/-	Buffers for soil health
Biogas	+	+	+	+/-	Reduce pressure on fuelwood
Agroforestry	+	+	+/-	+/-	Diversify products and diets

The lists of practices were discussed with technicians and field staff at EADD and CARE. Through this process the partners agreed on the set of practices that the experiments would focus on. In Kolero, four options were identified: CA, improved cookstoves, soil and water conservation, and agroforestry. In Kaptumo, the MICCA pilot project focused on improved dairy feeding (with Napier grass, Rhodes grass, *Desmodium*, sorghum, fodder shrubs, silage and hay making), manure management through composting and biogas, and agroforestry.

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[3] Detailed descriptions of the approach to developing and implementing the 'menus' of CSA practices can be found in the associated MICCA Series #11 (Rioux *et al.* in preparation).

5. Verifying climate smartness at multiple scales

As discussed in Section 3, MICCA pilot project science activities aim to provide decision-relevant information for a range of target audiences. The sites differed from one another in terms of the biophysical conditions of the two farming systems and particular potential development pathways that were available. Consequently, activities at the two pilot sites could not mirror each other. Instead, complimentary, but distinct, approaches had to be adopted to generate information that was appropriate to the site and local stakeholders. This section presents the research results and their implications for development. The results are organized around three spatial scales:

- field-level tradeoffs between productivity and GHGs with changes in soil and fertility management,
- farm-level GHG impacts of intensifying smallholder dairy production, and
- land-use and land-cover change at the landscape level and CSA options.

Field level: Tradeoffs between productivity and GHGs from changing soil and fertility management in Kolero maize production

Maize is among the most widely grown staple crops in the United Republic of Tanzania. In Kolero, maize is grown on hillslopes and in valleys throughout the study area. Due to unpredictable rainfall patterns, soil erosion, lack of inputs, unimproved seed stock and poor agronomic practices, maize yields are low in the area, typically less than 1 metric ton per ha per season and often much less. However, farmers prefer maize over other staple crops and continue to plant it despite its poor performance.

Under certain conditions, CA has been found to increase crop yields, enhance carbon content in soils and maintain soil moisture (Thierfelder *et al.* , 2012; Verhulst *et al.* , 2011). When CA is used in highland areas such as Kolero, it may further enhance crop production and resilience, even in highly degraded soils, due to the interactive effects of improved plant nutrition and soil moisture. In this way, CA may be considered consistent with CSA goals and is often promoted as a CSA practice (FAO, 2013). However, there are conflicting data on yield benefits and the GHG mitigation potential of CA in farming systems globally. There is also very limited information on the food-climate tradeoffs specific to CA in Sub-Saharan Africa (Baker *et al.* , 2007; Giller *et al.* , 2009; Palm *et al.* , 2013; Rusinamhodzi *et al.* , 2011). Despite the variability in results, CA is among the most widely prescribed agricultural interventions in sub-Saharan Africa (Andersson and Giller, 2012). Because of the limited information on the impacts of CA in the United Republic of Tanzania and the fact CA was the principal agricultural practice being promoted by CARE under the HICAP programme, MICCA implementing partners established experiments to better understand the relationships among CA, maize productivity and GHG emissions for farming conditions in the Kolero region and fed this information back into local and regional development discussions.

Under HICAP, CARE established a demonstration site at the centralized public space, the ‘Centre for Sustainable Living’ (CSL), in Kolero, the most populous village in the area, and the village hosting the closest market. The primary use of this site was to showcase farming practices and train farmers. Its central place in the community made it a good location for the CA experiment. At the site, ICRAF and CARE tested five ways maize could be cultivated, with each ‘treatment’ replicated three times each in a completely randomized design (Fig. 5). The experiment included five treatments: a conventional practice and four CA-based treatments. The five treatments can be described as follows: 1) conventional tillage; 2) no tillage with mulch placed between maize rows only; 3) no tillage, complete mulching soil coverage plus cover crop (*Lablab*); 4) no tillage, complete mulching plus N-fixing trees (*Gliricidia sepium*); and 5) no tillage, complete mulching plus N fertilizer at the rate of 75 kg of N per ha. Treatments 1 and 2 were selected to reflect farmers’ practices. Treatment 2 also reflects how CA is typically being implemented by farmers in the area based on Zagst *et al.* 2011b. Treatments 3 and 4 are CA practices being promoted under HICAP. Treatment 5 was chosen because it was the general recommendation based on research across sub-Saharan Africa. The CA plus *Gliricia* treatment is sometimes referred to as ‘CA with Trees’, a form of CSA practice that is promoted to combine the advantages of CA and leguminous agroforesry to sustain agricultural productivity in sub-Saharan Africa.

The site was prepared according to the treatments before establishing the experiment in the long rain season of 2012. Double digging was conducted along the maize planting row before the 2012 long rain seasons and repeated one and a half years later, before the 2013 short rain season and after the heavy floods during the 2013 long rains. Plots were 3 m by 5 m separated by a 2 m unplanted buffer to minimize treatment drift among the small plots. Maize plants were spaced at 30 cm within rows and 75 cm between rows. *Lablab* was intercropped between rows of maize 2 to 3 weeks after planting when maize reached 'knee height' at the intra-row spacing of 50 cm in accordance with extension recommendations. Seedlings of *Gliricidia sepium* were planted before the long rain seasons of 2012 at a spacing of 1 m by 1 m (3 rows per plot and 5 trees per row). The shrubs were cut down at the beginning of the 2012 short rains, and the coppices were pruned approximately every two weeks to minimize aboveground competition with maize crops. The foliage biomass was evenly spread in the plot as mulch. Similarly, crop residues after harvesting from each plot were retained on the farms and evenly spread as mulch according to the prescribed treatments. The only exception was in the conventional cultivation plot, where no mulch was applied and treatment 2 where mulching was only applied in rows. Maize plants were sampled at physiological maturity to determine grain and stover yields. These results were then extrapolated to determine yields per ha. GHGs were measured using static chamber techniques and gas chromatography following the protocol described in Annex III. Gas samples were taken approximately twice a week to capture temporal variability in fluxes.

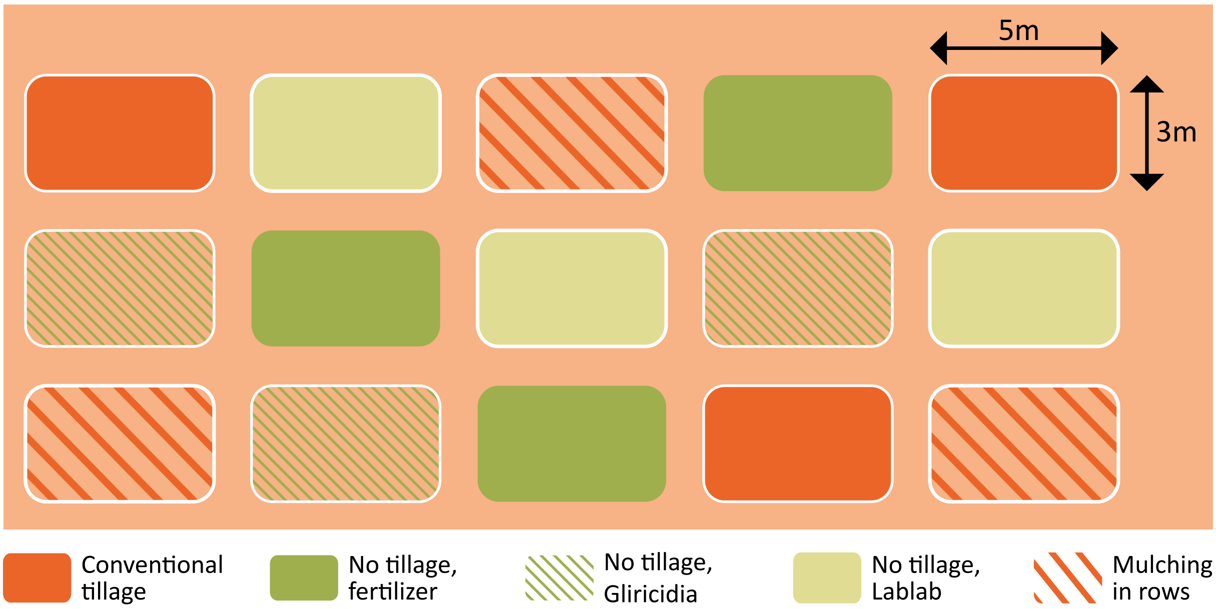

Figure 5. Experimental layout of CA trial at the CSL in Kolero, United Republic of Tanzania. Five treatments reflecting a gradient of farming practices, from current non-CA practices to CA with fertilizers, were evaluated for their effect on productivity and GHG fluxes (CO_2, N_2O, and CH_4). The experiment's two-year timeframe was too short to assess the effect of the treatments on soil C stocks.

For the first three experimental seasons, maize grain yields varied by season and by treatment (Fig. 6). Except for the short rain season in 2012, CA generally improved maize grain yield when compared to conventional cultivation using a hand hoe. Yields at this time were nearly twice as high as those produced in other periods. Consequently, the effects of soil management may have been undetectable due to the overall favorable conditions. Relative to the control, increases in maize grain yield across the three seasons averaged 26 percent for *Gliricidia* and 44 percent for fertilizer treatments compared to only 3 percent and 6 percent for mulching and *Lablab* treatments, respectively. Significant differences were noted in treatments where CA was complemented with either mineral N fertilizer or *Gliricidia* in the long rains of the 2012 and 2013 seasons. These results are in line with other evidence that has indicated that increasing the N available to plants may be particularly important for CA systems in sub-Saharan Africa, where the amount of soil cover is suboptimal due to low biomass production and availability (Vanlauwe *et al.*, 2014), which is often the case in Kolero. These findings suggest that maize grain productivity was driven more by nutrient inputs than by benefits brought about by soil management.

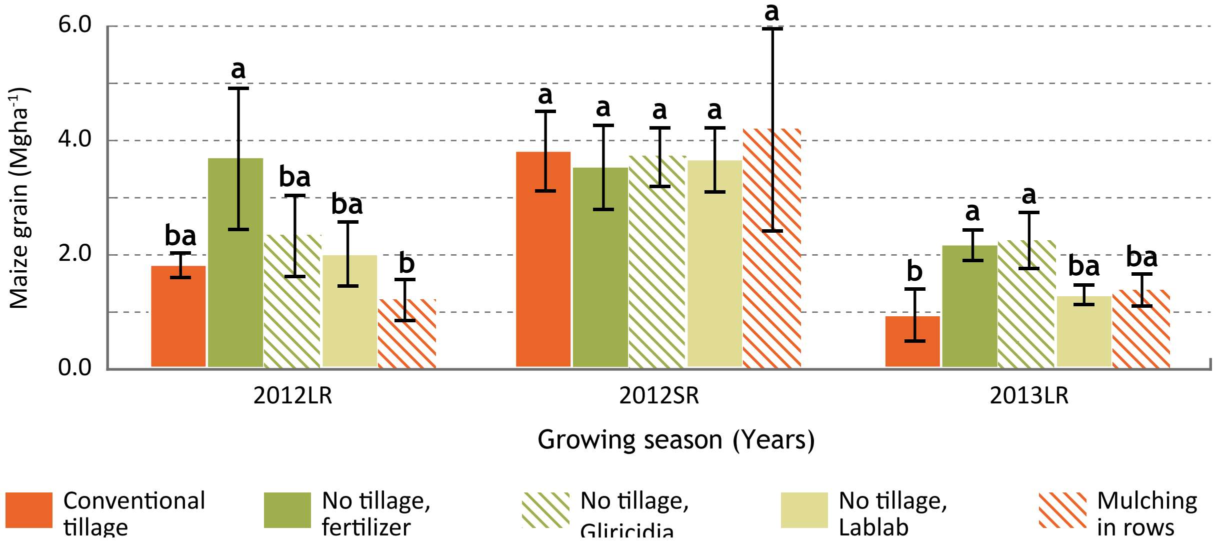

Figure 6. Maize grain yield under various conservation agriculture based practices at Kolero, United Republic of Tanzania for the long (LR) and short rain (SR) seasons in 2012 and 2013 growing seasons. Means within a season followed by the same letter are not significantly different at α = 0.05 according to Tukey's honest significant difference (HSD) Test. Vertical bars indicate standard deviation (N = 3)

Based on these findings, it appears that improved soil management has the potential to increase maize yields. But the question arises: do these management activities also lead to greater GHG emissions and necessitate tradeoffs between food production and climate regulation services? Data collected during the long rain season of 2013 suggest that this may not be the case. Although the *Gliricidia* treatment was among the highest yielding and had the highest GHG emissions in absolute terms, emissions were not significantly greater than most other treatments (Table 2). In addition, the fertilizer treatment, which also consistently yielded relatively high amounts of grain, had the fewest GHG emissions of any treatment. Recognition of the potential food-GHG tradeoffs has led to the adoption of compound indicators that integrate both outcomes, like the 'yield-scaled global warming potential (GWP)' which is defined as Mg GWP per Mg product (Linquist *et al.*, 2012; van Groenigen *et al.*, 2010). By this measure, the fertilizer and *Gliricidia* treatments outperformed other options (Table 2). If the results can be confirmed in subsequent locations and seasons, they would indicate that these management strategies would be win-win solutions, producing more food without emitting significantly more GHGs.

These findings align with the conclusions of a recently published meta-analysis that examined the impact of N fertilizer use on N_2O emissions in agriculture. The analysis demonstrates that emissions remain low, near the natural background levels expected without fertilizer use, until available N exceeds plant uptake, at which time the emissions increase non-linearly (Shcherbak *et al.* , 2014). What this conclusion suggests, and the Kolero results support, is that there may be potential to increase the application of N in sub-Saharan cropping systems from the current levels, around 8 kg N per ha (Morris *et al.* , 2007), to levels that can significantly stimulate and sustain production (Sanchez, 2002; Townsend and Palm, 2009; Vitousek *et al.*, 2009) without increasing GHG emissions. Despite the proimising data, management recommendations need be tempered against constraints in Kolero. Mineral fertilizers can only be purchased in Morogoro, more than 130 km and 5 hours away by dirt road. Poor access and associated costs of the inputs make it unlikely that mineral fertilizer can be a true option for farmers in the area under current conditions. Given these constraints and the data that suggests that the maize systems are limited in N, extension programmes would do well to facilitate greater nitrogen availability by promoting the planting of N_2-fixing trees such as *Gliricidia* or to improve the use and establishment of *Lablab* in the farming system. Those practices, however, also face contraints related to tenure arrangements and dietary preferences.

Table 2. Maize productivity and GHG tradeoffs based on data collected 1 January to 30 June 2013. Variability indicates standard error (N = 3) for the treatment. Treatments with different letters are significantly different ($p < 0.05$) calculated by Tukey's HSD.

Treatment	Grain yield ($Mg\ ha^{-1}$)	GHG emission ($Mg\ CO_2e$ six $months^{-1}$)	Mean yield-scaled GWP ($Mg\ CO_2e\ Mg\ grain^{-1}$)
Cultivation	0.9 ± 0.3 a	9.0 ± 0.12 a	10.0
Mulching	1.4 ± 0.2 a	8.8 ± 0.09 a	6.3
Lablab	1.3 ± 0.1 a	9.4 ± 0.09 a	7.2
Gliricidia	2.2 ± 0.3 a	10.0 ± 0.14 a	4.5
Fertilizer	2.1 ± 0.2 a	7.4 ± 0.15 a	3.5

The interpretation and extrapolation of these results should be done with caution. By adding biomass and conserving soil organic matter, reduced tillage systems significantly modify soil C cycles. Short-term experiments on these farming systems describe processes that occur between soil equilibrium states and do not necessarily reflect long-term dynamics of the system. It has been shown that productivity and climate change mitigation benefits from adoption of changes in tillage practice, only take effect when practiced over periods as long as 10 to 20 years; there is a significant time-dependency for the outcomes to become manifest (Rusinamhodzi *et al.*, 2011; Six *et al.*, 2004). The findings of this effort, however, compliment this conventional wisdom and suggest that GWP may be reduced even in the short term under some conditions. Regardless, the need for long-term maintenance of reduced tillage systems to deliver benefits represents a central challenge. Many CSA techniques (e.g. CA, agroforestry, terraces) require long-term investments, which may be impractical for many smallholder farmers.

Measurements conducted during this experiment indicate the potential impact of research design on emissions estimates, which are fundamental input data for GHG accounting and formulating development programmes and policies. GHG emissions showed considerable temporal and spatial variability, with flux patterns differing among treatments. For example, peak N_2O fluxes of the conventional and *Gliricidia* treatments were asynchronous in terms of when they occured and their magnitude (Fig. 7). Variations measured from six static chambers (vertical bars in graph) provide an indication of the range of flux rates over space. Large variability was observed during many sampling events, despite the small scale of the experimental field (around 0.05 ha). The impact of spatial and temporal heterogeneity on emissions estimates is well established in scientific literature (Davidson *et al.*, 2002; Parkin, 2006; Rochette and Eriksen-Hamel, 2008), but this impact is perhaps less well known in development discourse. In short, the methods used in the monitoring programme have the potential to radically alter estimates of GHG emissions, be it soil fluxes, soil C, biomass C or enteric fermentation (Johnson and Johnson, 1995; Lee *et al.*, 2009; Rosenstock a *et al.*, 2013). In this study, fluxes were measured twice per week to be able to represent daily and weekly fluctuations and quantify flux rates as accurately as possible given resource constraints and experimental conditions. Previous field research that quantified soil fluxes in sub-Saharan Africa has mainly been limited to short-term field investigations (often less than three months) or relatively infrequent measurements (once per month). The serious issues these research strategies could pose when trying to gain general conclusions about GHG impacts of various management options are apparent (Fig. 7). Given the variability over days (see July) and weeks (see April) and throughout the year (compare the long rains of April to June to the October to November dry season), it is clear that estimates are sensitive to the timing of measurements. Annual estimates extrapolated based on bimonthly, monthly or seasonal measurements may be significantly off the true value because the measurements may have either completely missed peak fluxes or misrepresented peak fluxes as average (e.g. Gomez-Casanovas *et al.*, 2012). It is for such reasons that understanding the methods underlying GHG emissions (and sequestration) data and the consequential uncertainty it creates is paramount when interpreting the information and utilizing it in development and policy making.

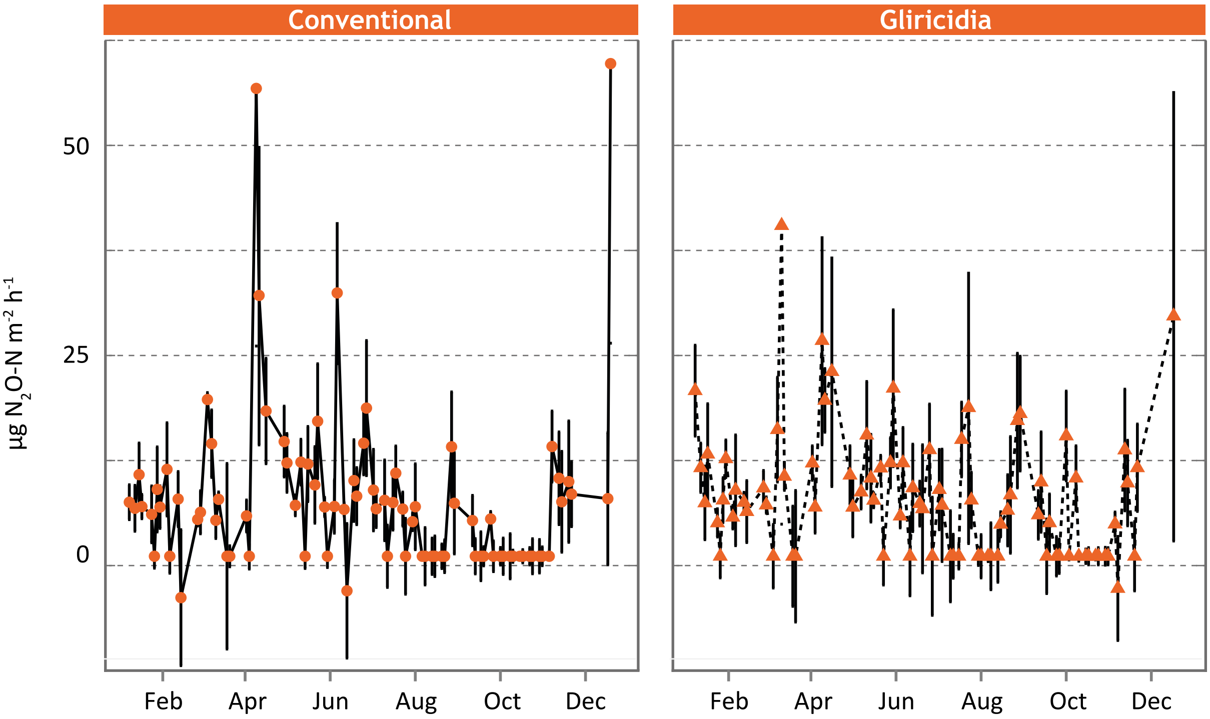

Figure 7. N_2O fluxes from the conventional and Gliricidia treatments measured over 84 sampling points in 2013. Vertical bars are standard error across six chambers. Fluxes below detection limit were set to zero in accordance with good practice (Parkin *et al.*, 2012) but graphed, with standard error, to show variability. The variation within and between treatments can complicate the production of robust GHG estimates. Sampling methodology should be considered when evaluating the robustness of GHG emissions and C sequestration data.

Farm level: GHG impacts of agricultural intensification in Kaptumo, Kenya

Dairy production is a predominant livelihood for as many as 1.8 million smallholder farmers in Kenya (TechnoServe Kenya, 2008), many of whom farm in the highly productive agricultural zones of Rift Valley counties. Milk is consumed by the household and sold in local, county and national markets. Smallholder dairy farms in the Rift Valley are diverse enterprises that include crops and livestock. Dairy farmers produce milk but also grow food for subsistence and cash crops (Henry *et al.*, 2009). The farms in the Kaptumo area reflect this variety. Farmers plant maize, beans, bananas and tea. Frequently trees are planted for shade, fodder and windbreaks along field and farm boundaries. Cattle, chickens and other livestock are also raised.

Milk yields are relatively low in the Kaptumo area, averaging approximately 4.5 litres per cow per day (Zagst, 2011a). Much of EADD's efforts in the region are intended to intensify production and increase the quantity and quality of milk produced by enhancing animal diets with protein, supplements and silage; improving animal genetic resources through artificial insemination; and improving manure management (recycling faeces to cropland). Intensifying dairy production can deliver multiple benefits, including increased income for the houeshold and reduced global warming intensity (Bryan *et al.*, 2011; Thornton and Herrero, 2010). The intensification of smallholder dairy systems in Western Kenya typically follows a transition from animals grazing on unimproved (often degraded) pastures of native species or tethered by roadsides to semi-confined systems where animals spend part of their day on pasture or paddock and part under confined conditions ('semi-zero') to fully confined systems (zero grazing), where animals are continuously confined and fed controlled diets of feeds produced both on and off the farm (Tittonell *et al.*, 2009). Although there is significant variation within each of these three farm types, in practice, Kaptumo farms closely match this simple typology. On average, most Kaptumo farmers tend toward the extensive end of the spectrum. Animals primarily feed on pasture but are provided some supplemental feeds, molasses and/or concentrates (Weiler, 2013). In 2011, fewer than 30 of the more than 7 000 households in the Kaptumo division used zero-grazing systems

(Zagst, 2011a), but that number is set to increase with the expected expansion of breeding services as population growth puts greater pressure on the land, the drive for greater productivity increases and markets become more accessible. The question that needs to be asked is: What are the implications of the intensification of smallholder dairies?

The diversity of farming activities on smallholder dairy systems complicates GHG quantification. There are many different sources and sinks of GHGs, such as animals, soils and biomass (Fig. 8). This diversity confounds efforts to understand the climate implications of various development trajectories. Through management practices, farmers control the quantity and distribution of nutrients linking the C and N cycles among different farm components; both those components that are directly involved in dairy production (e.g. leguminous feeds for livestock) and those that support household livelihoods more broadly (e.g. manure applications on vegetables). Because of the interactions among these different components, quantifying impacts of only one part of, not the entire, farming sytem may miss emission hotspots or mitigation leverage points (Rosenstock *et al.* 2013a).

Despite the prospective need for taking a systems approach when quantifying smallholder mitigation opportunities, whole-farm GHG analyses represent a departure from conventional practice in agricultural GHG research, which has generally focused on individual farming activities, such as N_2O emissions from mineral fertilizer applications (e.g. Shcherbak *et al.*, 2014), life-cycle analysis (LCA) of commodity production systems (e.g. Gerber *et al.*, 2013) or project-level assessments with *ex-ante* modeling (Jönsson, 2011). There are few examples where GHGs have been quantified on the scale of individual farms, particularly in smallholder farming systems in tropical developing countries (Seebauer, 2014). When not conducted using process-based models (e.g., Crosson *et al.*, 2011), whole-farm GHG quantification can be considered analogous to that of GHG inventories at other spatial scales. Inventories stratify land cover and land management activities and apply emissions factors based on each source category.

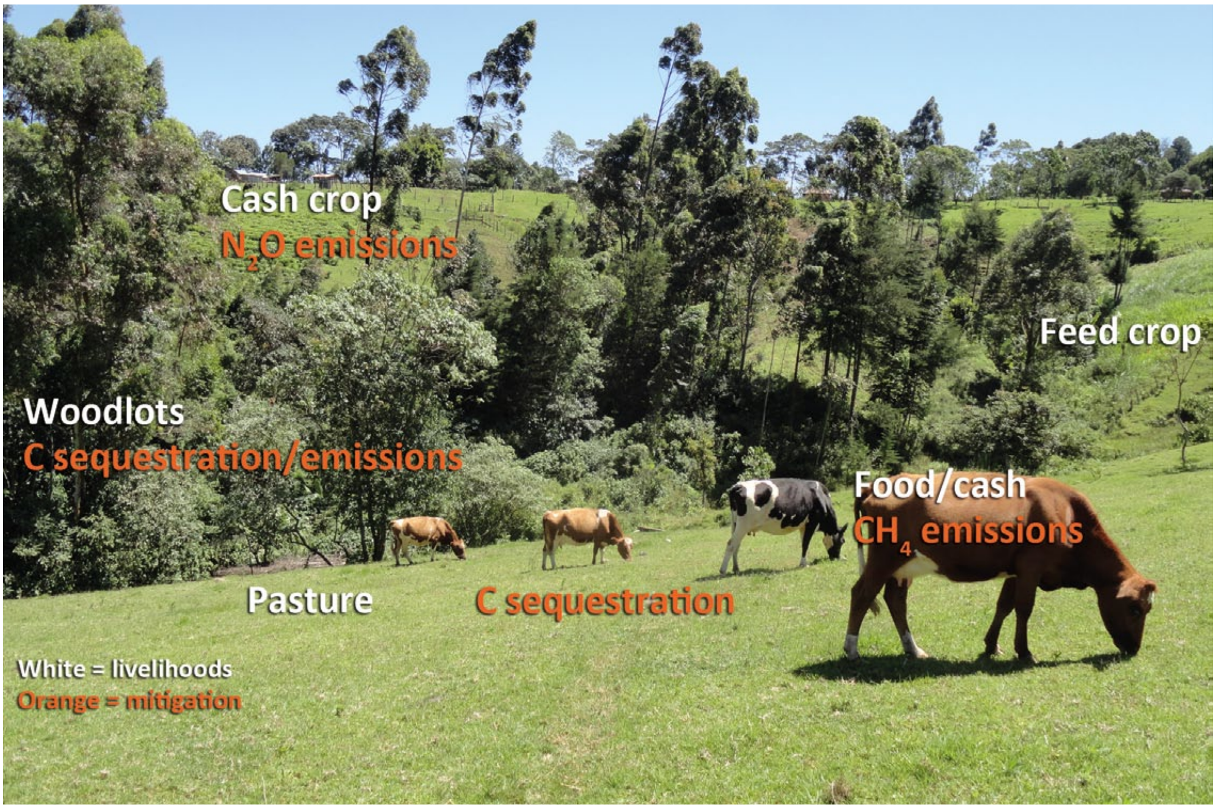

Figure 8. Farming activities and select GHG impacts of smallholder dairy landscapes in Kenya. Understanding the potential livelihood and GHG implications of changing practices in these complex systems requires quantification and estimation of each of the various components. Photo taken approximately 1.5 km southeast of Kaptumo town. Photo: Todd Rosenstock.

Because there has been very little effort to quantify the GHG balance at the farm level in developing countries, there is little foundation on which an approach to empirical work at this scale can be built. To explore the question of the GHG implications of intensification, partial farm GHG balances were calculated for three farms representing the dominant farm types. The IPCC Tier 1 guidelines and default stock, stock change and emissions factors for the relevant farm components were applied. This approach is similar to commonly available GHG calculators and relies on similar data (see Colomb *et al.*, 2012; Milne *et al.*, 2013). Although efforts have been made to include all relevant GHG sources and sinks, some have been omitted. For example, data were unavailable to estimate fluxes on land used for off-farm feed production and emissions from manure applications to croplands, as it is difficult to estimate nutrient additions from manure of variable nutrient concentrations. These omissions are due to the difficulties in collecting robust data on such activities in farmer-managed experiments in rural Kenya. Consequently, this analysis represents only partial GHG budgets, not full balances nor a complete LCA of all farm products. Following the calculation of partial farm balances, the IPCC default values were compared to C stocks derived from measurements of Kaptumo soils and biomass obtained via dry combustion (soil) and inventory approaches (biomass). Descriptions of experimental methods can be found in the Appendices.

Three farms that are characteristic of the dominant farm types in the region (Weiler, 2013; Zagst, 2011a) were selected for this analysis. They can be considered as intensification scenarios for the region. The grazing farm supports a significant number of animals on existing land with minimal additional feed (Table 3). The zero-grazing farm occupies the least land and supports less than half the animals. It uses both feed grown on the farm and some imported feed. The zero-grazing farm practices a significant amount of agroforestry, with the number of trees per ha more than seven times greater than on the semi-zero grazing farm and almost six times greater than on the full grazing farm.

Table 3: Characteristics of experimental farms representative of the three farm types near Kaptumo, Kenya.

	Grazing	Semi-zero grazing	Zero grazing
Area (ha)	16.2	9.6	1.9
No. of cows	24	11	10
Cattle feed	Pasture, molasses, maize residues	Pasture, molasses, maize residue, Napier grass	Napier grass, maize silage, concentrates
No. of trees ha^{-1}	74	54	424
Trees on farm	Woodlots, border planting	Border planting	Border planting, windbreaks
Crops grown	Pasture, maize	Kale, Napier grass, pasture, tea, maize	Kale, Napier grass, vegetables

The partial GHG balances suggest that extensive and intensive dairy production may be relatively climate neutral in the Kaptumo area. Cumulative GWP, based on calculations consistent with IPCC guidelines, suggest that emissions and removals for both the full grazing system and the intensive zero-grazing systems were nearly on balance (Table 4). This can in large part be attributed to agroforestry and the significant amount of C accumulating in aboveground biomass in croplands and forest plantations. Annual changes in biomass C stocks offsets CH_4 emissions from enteric fermentation. It should be noted that biomass and soil C are GHG sinks of finite time periods, while other emissions such as N_2O are longer lived and hence have a more cumulative impact. Therefore, promoting agroforestry is a medium term (10-15 year) mitigation strategy. These results must be confirmed through more complete GHG analyses, including field and laboratory measurements, and should be interpreted narrowly. Furthermore, when emission sources not considered in these balances are taken into account, the balances would differ, perhaps significantly, from the values reported here.

Methane emissions from enteric fermentation accounted for 16 to 43 percent of the GHG balances in this analysis. These findings are substantially lower than those presented in a recent LCA of smallholder dairy production in Kaptumo, which indicated that 83 percent of emissions in the value chain resulted from enteric fermentation (Weiler, 2013). Differences in the values highlight the sensitivity of GHG accounting (field, farm, LCA or otherwise) to the boundaries set by the examiner. The analysis conducted here provides an initial indication that broadening the spectrum of inquiry to capture the range of activities that smallholder farmers are engaged in may help fully represent the cumulative system-level impacts and even highlight new mitigation leverage opportunities. To provide a comprehensive picture of these complex systems, future work needs to expand the characterization and quantification of various GHG sources and sinks to include, for example, biomass C accumulation in tea, N_2O emissions from manure applications and other livestock. Only then will it be possible to know the full impact of smallholder farmers on GHG emissions.

To highlight specific impacts on GHG sources and sinks and identify mitigation opportunities, many development organizations use GHG calculators based on similar approaches to those applied here in order to obtain *ex-ante* emissions estimates for changes in practices. However, the relevance of existing approaches, specifically the IPCC Guidelines for National GHG Inventories (IPCC 2006) and associated Tier 1 emissions factors for whole-farm GHG analysis in tropical countries, especially those in sub-Saharan Africa, is an outstanding question given the current state of knowledge and data gaps. In this analysis, 'best-fit' IPCC default factors for C stocks and stock changes were applied. In many cases, however, the default factors applied were signifantly different than measured values for the systems. For example, carbon stock in woody biomass on cropland ranged between 0.8 and 18.2 Mg C per ha when measured using standard forestry techniques and regional specific allometric equations for agricultural lands (Kuyah *et al.*, 2012). This value is less than half the 41 Mg per ha for biomass on croplands in African agrosilvopastoral systems mentioned in IPCC guidelines. This affects the cumulative balance calculation because C stock changes are relative to initial C stock values and overestimates aboveground biomass C sequestration potential of trees on these farms by more than 50 percent. It is worth noting that the measured biomass values are consistent with those recently compiled for Africa (Nair and Nair, 2014). Similar discrepancies between default and measured values were also apparent for soil C stocks, but in this case there was significant underestimation. Default factors underestimated soil C stock by approximately 25 percent compared to measured values. Although IPCC guidelines using Tier 1 are sometimes used for farm-scale analysis, they were not designed for this purpose. Tier 1 approaches were intended to be used when the source activity was relatively inconsequential to total GHG budgets, perhaps contributing less than 5 percent of the total. Significant variation in GHG flux rates occur between points (locations or animals) due to edaphic mechanisms that control biological emission processes, for example pH, soil type, soil moisture and soil C for denitrification and N_2O emissions (Davidson *et al.*, 2000). For this reason, emission factors tend to only produce reasonable estimates at larger scales when local variations average out. In addition, IPCC Tier 1 emissions factors were generated based on research results from global datasets, but tropical smallholder farming systems are typically underrepresented in these datasets (e.g., Stehfest and Bouwman, 2006). As a result, Tier 1 default factors may misrepresent flux rates considerably. A comprehensive analysis of the extent of this situation is currently lacking. CSA programme developers, even when undertaking a first approximation to set programmatic priorities, need a better definition of the utility and uncertainty of these empirical models for systems and locations where the evidence base is limited.

Table 4: Partial farm balance and relative contribution of sources and sinks for three typical Kaptumo-area farms (described in Table 3). Calculated according to IPCC guidelines (IPCC 2006).

GHG stock or flux	Units	IPCC default (head^{-1} or ha^{-1})	Farm type		
			Grazing	Semi-zero	Zero grazing
Livestock and manure management					
Enteric fermentation					
Dairy	kg CH_4 yr^{-1}	46	276	215	230
Other cattle	kg CH_4 yr^{-1}	31	568	207	155
Manure management					
Dairy	kg CH_4 yr^{-1}	1	6	5	5
Other cattle	kg CH_4 yr^{-1}	1	18	7	5
Subtotal	kg CH_4 yr^{-1}		869	433	395
Subtotal, GWP	Mg CO_2e yr^{-1}		30	15	13
Cropland remaining cropland					
Biomass					
Aboveground, stock	Mg C ha^{-1}	41	335	105	79
Aboveground, stock change	Mg C yr^{-1}	0.01	-42	-13	-10
Soil C					
Soil C stock	Mg C ha^{-1} 30 cm^{-1}	63	515	161	121
Soil C stock change	Mg C yr^{-1}	0.02 - 0.05	15	13	5
Non-CO_2					
Manure spreading	N_2O-N kg N^{-1}	0.02	------------------nq------------------		
Subtotal	Mg C yr^{-1}		-27	0	-4
Subtotal, GWP	Mg CO_2e yr^{-1}		-98	0	-16
Grassland remaining grassland					
Biomass					
Aboveground, stock	Mg C	16.5	112	71	Na
Aboveground, stock change	Mg C yr^{-1}	0.01	-1	-1	Na
Soil C					
Soil C stock	Mg C ha^{-1} 30 cm^{-1}	47	320	202	Na
Soil C stock change	Mg C yr^{-1}	0.05	16	10	Na
Subtotal	Mg C yr^{-1}		15	10	Na
Subtotal, GWP	Mg CO_2e yr^{-1}		48	34	Na
Forest remaining forest					
Biomass					
Aboveground, stock	Mg C	21	25	-------------na-------------	
Aboveground, stock change	Mg C yr^{-1}	0.01	-0.3	-------------na-------------	
Soil C					
Soil C stock	Mg C ha^{-1} 30 cm^{-1}	63	75	-------------na-------------	
Soil C stock change	Mg C yr^{-1}	0.05	4	-------------na-------------	
Subtotal			3	-------------na-------------	
Subtotal, GWP	Mg CO_2e yr^{-1}		13	-------------na-------------	
Total, GWP	**CO_2e yr^{-1}**		**-7**	**48**	**-2**

Notes

1. IPCC default factors selected based on good practice for Tier 1 default values for relevant site specific characteristics (IPCC, 2006).
2. Global warming potential (GWP) calculated for a 100-year time horizon based on 34:1 CH_4 to CO_2 and 298:1 N_2O:CO_2 according to IPCC AR5 (IPCC, 2014c).
3. Negative numbers represent C accumulation; positive numbers represent emissions.
4. Other livestock (chickens, sheep, rabbits, etc) are not considered because of highly fluctuating populations in this area.
5. Manure management of zero-grazing estimated as managed on pasture (same as grazing) system because of a lack of data on manure excretion rates.
6. No farmers in the study use mineral fertilizers.
7. Non-CO_2 emissions from manure spreading on fields are not estimated because data on quantity spread and manure N content are unavailable.
8. Aboveground biomass flux calculated as ratio of default biomass accumulation rate (2.6Mg C ha-1 yr-1) to default total stock (21 Mg C). This represents a 12 percent change in C stock per year, which is a conservative estimate given existing data on C sequestration potential in agroforestry systems in Africa (Nair and Nair, 2014).
9. Cropland, grassland, forest belowground biomass, litter, deadwood and aboveground herbaceous biomass in grasslands assumed to be in steady state.
10. Soil C stock change in croplands calculated for relevant land use, tillage and input default factors over a 20-year time-frame.
11. Soil C stock change in grasslands calculated for relevant land use, management and input default factors over a 20-year timeframe.
13. na = not applicable
14. nq = not quantified

Landscape level: Options to improve livelihoods and climate resilience in Kolero, the United Republic of Tanzania

In the Uluguru Mountains, deforestation and forest degradation is affecting biodiversity, ecosystem services and landscape structure (Hall *et al.*, 2009). These changes are a result of increasing population and expanding infrastructure development, including roads (Burgess *et al.*, 2007). The expansion of agriculture and uncontrolled fire in the region are also contributing factors (FBD, 2009).

These drivers of land use change are evident at the MICCA pilot project site in Kolero, and the consequences can be seen throughout the landscape. Deforestation and land degradation have proceeded rapidly in recent history. An analysis of changes in land cover and land use, using post-classification change detection techniques (e.g., Mpanda *et al.*, 2011) of Landsat satellite images over an area that included (but was larger) than the 100 km^2 site, indicate that between 1975 and 2005 the area of closed forest in the three wards in the Uluguru Mountains has decreased from 10 086 ha (47 percent of the land base) to approximately 6 119 ha (28 percent of the land base). This is nearly a 40 percent reduction, representing approximately 4 000 ha. This annual rate of decline (1.3 percent) is consistent with previous estimates of forest cover decline in the United Republic of Tanzania (Hall *et al.*, 2009; URT, 2013). Forest loss is largely due to the expansion of agricultural lands. Over the same 30 year time period, the extent of cultivated land increased 78 percent, from 4 913 ha to 8 735 ha; again a near 4 000 ha change (Fig. 9). The trends in forest cover and agricultural land would suggest that there is increasing pressure on the land base to produce food and fuel.

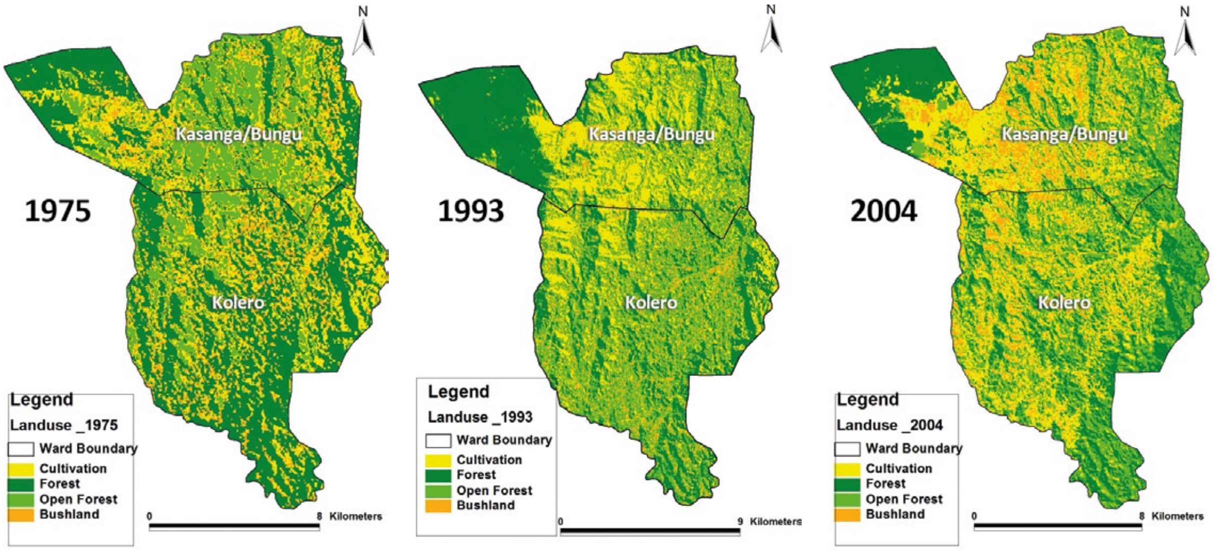

Figure 9. Land-use change in three wards in the Uluguru Mountains of the United Republic of Tanzania.

Changes in land use and land cover can have significant consequences for C dynamics (Chen *et al.*, 2002). The most significant fraction of the C in tropical forests is contained in the aboveground biomass (more than 6 times the soil C stock). The ratio of C stocks in aboveground biomass and soils (0 – 20 cm) for slash-and-burn agriculture and agroforestry systems is much lower 2:1 and 1.5:1, respectively, and the C in agricultural lands (pastures, crops, grasslands) is almost entirely contained in soils (Palm *et al.*, 2005). This suggests that the historical decline in forest cover in the Kolero area would likely have had a significant impact on GHG emissions from the region. To better understand the impacts the shifts in land cover and land use had on C dynamics, field biomass inventories were conducted following standard forestry techniques. The inventories quantified aboveground biomass across range of types of land cover and land use, including forest patches, fallows and agricultural lands. Results appear to indicate that fallows contain only 38 percent less C than forests, which is relatively more C than expected from previous assessments (Mpanda *et al.* in preparation). This would suggest that fallow areas may store a more significant amount of C in the landscapes than previously thought, which would reduce the cumulative impact of slash and burn on the climate. However, to understand the impact of land cover changes on C, future work needs to be done to scale up C inventories measured at the plot level to the landscape level (Mpanda *et al.* in preparation).

Measured soil GHG fluxes in the Kolero area are relatively low (see field-level section above). Typical C in biomass of tropical forests and fallows often exceed 50 Mg C per ha. The relative amount of land currently being used in the region for agriculture is 41 percent and for fallow 26 percent. These three findings suggest that decreasing the pressure on the fallow areas may present an opportunity to reduce C emissions and improve livelihoods. A number of strategies could serve this purpose including: improving agronomic practices to maintain and improve soil fertility and reduce the need to expand agriculture into new sites; and reducing fuelwood collection and consumption to curb land degradation. MICCA implementation partners identified four primary practices to achieve these two goals: improved cookstoves, agroforestry, soil and water conservation and CA (see Section 3). The rest of this section describes recent efforts to integrate improved cooking stoves and agroforestry into the Kolera area.

Improved cooking stoves

Woodfuel (fuelwood and charcoal) accounts for 95.4 percent of the household energy budget in the United Republic of Tanzania (URT 2013). It is estimated that the annual woodfuel consumption has increased from 21 552 000 m^3 in 1990 to 24 970 000 m^3 in 2005 (FAO, 2010b). This increase in demand is reflected in the fact that 70 percent of deforestation in the country is attributable to direct and indirect woodfuel harvesting. The remaining 30 percent of the deforestation is due to the clearance of land for agricultural activities (GVEP International 2012). Due to the pressure on woodfuel resources, prices for both woodfuel and charcoal have been increasing dramatically over the past decade (GVEP International 2012). In rural areas like Kolero, which is 130 km from the nearest major town (Morogoro), fuelwood is the main energy source for households. There are no reports of charcoal extraction for household or commercial purposes. The ability of households to switch to non-fuelwood sources (electricity, liquefied petroleum gas, solar and kerosene) is constrained by their availability and price. Estimates suggest that households in the Kolera area require approximately 54 kg of fuelwood per week (Zagst, 2011b).

The introduction and adoption of improved cooking stoves in Kolero may reduce fuelwood demand. Improved cooking stoves categorically reduce the amount of wood consumed compared to the traditional three-stoned stoves typically found in kitchens in the area. The woodfuel efficiency of cooking on the three-stone stove is less than 10 percent; improved models can have efficiencies of more than 15 percent (TaTEDO 2009; URT 2013). It should be noted that these efficiencies are on the lower end of the range of estimates (e.g. see Jetter *et al.* 2012 and Smith *et al.* 2000), but they still reveal the approximate ratio of efficiency increases that can be achieved. Table 5 demonstrates the range of potential annual emissions reductions per stove. Estimates were based on the Clean Development Mechanism's (CDM) small-scale methodology, *AMS-II.G Energy efficiency measures in thermal applications of non-renewable biomass* (CDM 2014). A key variable in this calculation is the the fraction of non-renewable biomass (*f*NRB), the percentage of fuel that was collected at a non-renewable rate (i.e. harvested at a more rapid rate then it could be replaced through regeneration). Because *f*NRB can often be context specific, the range of estimates is based upon a senstivitity analysis of the *f*NRB variable (between 25 to 100 percent). Because woodfuel demand is a strong driver of forest degradation and deforestation, the CDM national *f*NRB default rate for Tanzania is 96 percent (CDM 2012). Therefore, actual emission reductions will likely be on the higher end of the range presented in Table 5. It should be noted that the emission reduction potential from improved cookstoves is equal to, or often greater than, mean soil C sequestration rates for improved pasture management (0.54 Mg C per ha per year) (see farm-level section above). For the other variables included in the CDM equation, it was assumed the improved stoves would be used throughout the whole year and not experience any reduction in efficiency due to wear. Efficiencies for the baseline, three-stone stove and improved stove were based upon lab tests taken from Jetter *et al.* (2012). Due to a lack of efficiency measurements for the improved stoves promoted in the MICCA pilot project, the efficiency value for the improved stove was based upon the similar wood-burning Upesi stove studied in Jetter *et al.* (2012) The amount of woodfuel saved per year was based upon the estimate of current annual household consumption of approximately 54 kg per household (Zagst, 2011b). The emission reductions reported in Table 5 are rough estimates with a certain level of uncertainty[4]. Still the figures provide a reasonable approximation of the emission reduction potential of this project activity.

Table 5. Potential emission reductions from adoption of improved cookstoves with sensitivity analysis of the fNRB variable.

Fraction of non-renewable biomass (*f*NRB) (%)	**Emission reductions ($Mg\ stove^{-1}\ yr^{-1}$)**
25	0.33
50	0.66
75	0.99
90	1.19
100	1.32

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[4] The CDM methodology for calculating emission reductions from switching cooking technologies contains a large amount of inherent uncertainties. It allows the use of a default emission factor for CO_2 (leading up to 18 percent underestimation) and fails to propogate error for other input estimates (Johnson *et al.* 2010). In Johnson *et al.* (2009) when calculating carbon savings for a cookstove project, 28 percent of the uncertainty was attributed to fuel consumption, 25 percent to emission factors and 47 percent to the fNRB variable. As the fNRB value is one of the most highly changing and uncertain variables (Johnson *et al.* 2009; Johnson *et al.* 2010) a sensitivity analysis applying different values of the fNRB in the equation is included (Table 5).

In September 2013, a total of 237 improved stoves had been constructed and were being used within households, and more stoves were being adopted for use. At current levels of use, this translates into a reduction of more than 300 Mg CO_2e[5] per year. Initial discussions with household members suggest this technology to be among the most viable for the communities, as switching from a traditional stove to a more efficient stove reduced the amount of labour needed for fuelwood collection (traditionally part of women's daily work) and lessened the discomfort caused by smoke inhalation. Although the current estimate of reduced emissions is fairly modest, it can be expected that much greater reductions will be achieved in the future given the nearly 4 000 households in the study area.

Agroforestry

Due to population growth, the agricultural frontier has been expanding at the expense of forest throughout the United Republic of Tanzania. Traditionally, crop farming in Kolero was carried out using slash-and-burn techniques. Before the start of HICAP, almost 90 percent of farmers reported using this technique as a primary land preparation method (Mvena and Kilima 2009). Conditions appear to have changed since then, presumably as a result of awareness raising under HICAP. Zagst (2012b) reports that only 55 percent of the respondents in their survey used slash and burn for land preparation. This decline (from 90 percent to 55 percent) is encouraging. However, the findings cannot be taken as definitive as the two surveys used different interview questions.

CSA has been promoted in Kolero to improve the traditional farming systems. It is important to recognize that HICAP and MICCA do not represent the first attempts to improve agriculture output in the region. Previous efforts to address the sustainability of agriculture in the 1940s to 1950s included the use of terracing (a form of soil and water conservation and CSA). These efforts were largely unsuccessful, perhaps due to poor technical support, labour shortages, or socioeconomic and institutional factors.

Unlike previous efforts, the MICCA pilot project implementing partners promote agroforestry for multifunctional land management. Agroforestry is often among the first practices described in international discussions about CSA. This may be justified given agroforestry's significant impact on dietary quality (Ickowitz *et al.*, 2013) and its potential to provide a buffer against extreme weather by moderating temperatures, conserving soil moisture and mitigating climate change by accumulating carbon in biomass (Verchot *et al.*, 2007). Yet, some of agroforestry's impacts on GHG emissions and removals are complex and poorly understood. For example, the use of leguminous trees can stimulate soil N_2O emissions and reduce CH_4 uptake in upland soils (Rosenstock *et al.*, 2014). Despite uncertainty about the effect of agroforestry on all the components of CSA, various tree species and arrangements of tree planting, including boundary planting, scattered planting on farm, enrichment planting in the fallows and establishing woodlots, have been advocated in the Kolero landscape (Table 6). These have been promoted based on evidence that the benefits, such as timber and dietary diversification, are important to local communities.

Table 6: Trees and shrubs raised locally in the nurseries and planted in Kolero, United Republic of Tanzania

Potential uses	Species
Timber and fuelwood	*Acacia crassicarpa, Azadirachta indica, Grevillea robusta, Khaya anthotheca, Melea azadirachta, Tectona grandis, Terminalia catapa*
Soil fertility	*Faidherbia albida, Gliricidia sepium, Moringa oleifera, Tephrosia vogelii*
Fruit trees	*Mangifera indica, Tamarindus indica, Citrus sinensis, Citrus lemona, Carica papaya*
Spices	*Syzigium aromaticum, Piper nigrum, Cinnamomum* sp.

Land scarcity is prominent in Kolero. Half of the residents own land as individuals, family or clans (Zagst, 2011b). The other half lease or cultivate land under special arrangements from the land owners. Activities related to tree planting and retention are mainly of interest to the land owners and have limited uptake. However, this situation is changing. Through participatory processes, tree species have

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[5] This accounts for estimates of CO_2 emission reductions only. If accounting for other non-CO_2 climate forcing emissions such as CH_4 and black carbon (e.g., Grieshop *et al.* 2011), the actual emission reductions are likely to greatly exceed this reported amount.

been selected for propagation in nurseries (*see* Mpanda and Besa, 2012). Field observations indicate that the planted trees have performed well as a result of the successful adoption of horticultural and silvicultural techniques taught as part of the MICCA pilot projects. Through these empowering activities, continuous backstopping was provided to farmers.

It is too soon to estimate the benefits of increased tree planting, as the trees are still young. Follow-up efforts will be needed to better understand the impacts of these activities on reducing pressure on fallows and intensifying farm production and the consequent effects on livelihoods in terms of food security, climate chage adaptation and on climate change mitigation. Experiences in Kolero support the hypothesis that the potential for expanding agroforestry is limited by land ownership and land tenure systems. To make agroforestry a viable and effective CSA option, these issues will need to be addressed.

6. Decision analysis for targeting climate-smart practices

A key challenge in deploying CSA relevant strategies and applying them at a landscape, district or regional scale is defining the socio-environmental domain in which particular strategies will perform well. Where and for which farmers will benefits accrue from adopting certain techniques? Where and for which farmers will the same innovations fail to produce positive outcomes? Responding to these questions is fundamental, as development outcomes often depend on system or farm characteristics that vary at small scales, sometimes less than 1 m. Furthermore, these critical attributes cover not only biophysical factors, but extend into the socio-economic, cultural and political areas. Data about many aspects of these factors, such as land tenure, the acceptability of a new product or the intra-household distribution of decision-making power, are typically scarce or unavailable. The design and use of methods that integrate the broad range of factors that constrain the adoption of CSA has been an objective of the science activities within the MICCA pilot projects.

Many studies that aim to assist in targeting interventions or projecting the impacts of innovations do not adequately consider uncertainties and the inevitable variation in outcomes among farms, villages and communities. Impact projections should not only consider soil types, harvest dates and climate, but should also take account of the socio-economic conditions on small farms, where farmers may be struggling with insecure land tenure, poor market access and limited access to information. The likelihood of important variables being ignored in targeting policy and management decisions is greatest for those factors that are difficult to measure. Such factors are often critical in determining the benefits that farmers are likely to receive from adopting new land management practices.

Recommendations for targeting interventions are often developed with the help of deterministic models that translate a number of input variables into projections of system performance. Substantial investments of time and money are often made to generate robust information for all required inputs, but many decision-makers in development contexts have neither sufficient funds nor the time to conduct extensive studies. There are also normally a few variables that cannot easily be measured, such as the future adoption rate of a particular technology or the risk of project failure. Such variables are frequently estimated by 'best-bet' fixed point estimates that mask the uncertainty that surrounds these variables. These projections can be misleading, because they provide precise numbers, even though most, if not all, input variables are uncertain to some extent.

A probabilistic modeling approach does not require precise numbers for all input variables. Instead, it can accept probability distributions as inputs that allow for the consideration of the state of uncertainty about each variable. Besides reflecting uncertainties for variables that have actually been measured (e.g. by considering standard deviations around the mean of a variable), probabilistic modeling opens up opportunities for including 'intangible' variables. It is much easier to accept, for example, that the adoption rate for a new technology may be between 10 and 70 percent than it is to define a precise value. Uncertainty around such factors is often large, but a probabilistic modeling approach makes this uncertainty explicit, rather than hiding it behind best-bet assumptions. Because the ability to include uncertain factors permits the inclusion of determinants of success, for which little to no data is available, a probabilistic approach facilitates comprehensive targeting that is difficult to realize in fully deterministic targeting approaches.

Within the MICCA pilot projects, a simple exercise to illustrate the potential of a probabilistic approach to targeting interventions at the project level has been undertaken (Rosenstock *et al.*, 2013b). The objective of this study was the projection of likely yield benefits for farmers at the MICCA pilot project study sites upon adoption of CA. The first step in the assessment was a comprehensive collation of the main factors associated with the success of CA. These effects were extracted from a recent review on CA (Giller *et al.*, 2009) and a meta-analysis on no-till and yield (Rusinamhodzi *et al.* , 2011). The search for drivers of CA success yielded the following 10 factors: slope, soil, biomass production, precipitation, N input, farm size, tenure security, livestock density, access to markets and access to information (Giller *et al.*, 2009; Rusinamhodzi *et al.*, 2011). Since all of these factors were mentioned as critical influences on yield increases under CA, they were combined into an additive model that totalled up the individual yield effects of all factors. As will often be the case in such exercises, ranges for effects of some factors could directly be extracted from the literature, in particular from the work of Rusinamhodzi *et al.* (2011). However, in that work, no information was included for the effects of livestock density, tenure security, access to markets or access to information. Since important factors must not be omitted from models designed to provide comprehensive impact projections, estimates were derived from calibrated expert opinion (Hubbard 2014). Calibration involves a learning process that improves a researcher's ability to estimate confidence intervals for uncertain variables through a series of exercises that help gauge the level of certainty about a range of topics (Morgan, 2014). Especially for factors for which little information was available, the estimated effect size varied widely. However, since the basic mechanisms of all effects were reasonably well understood, it was nevertheless possible to make distinct estimates for specific conditions for major factors at the sites. For instance, estimated yield effects due to livestock density were positive for sites with low livestock numbers (due to reduced competition between fields and animals for biomass). Negative effects were more likely for farms with high stocking densities, which is in keeping with the major constraint to CA in mixed crop-livestock systems (FAO, 2013).

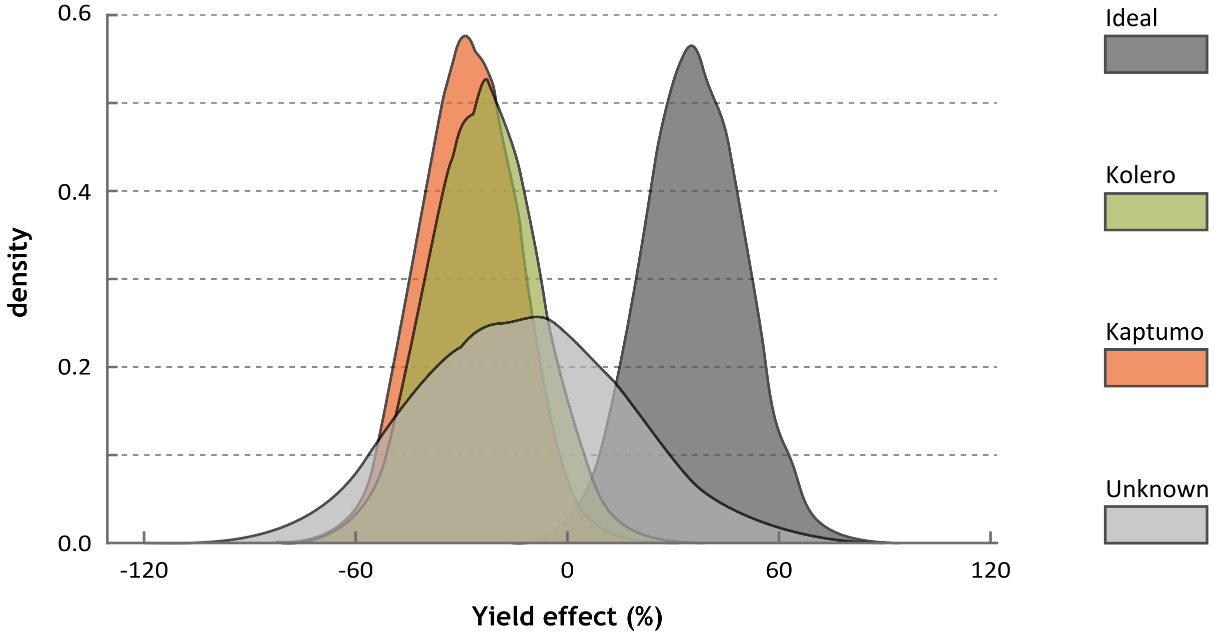

Figure 10. Probability density functions of the effects of adopting CA at a baseline location in sub-Saharan Africa, for which no information is available (Unknown), for the two sites (Kolero and Kaptumo), as well as for an ideal smallholder location, in which many enabling factors align to improve projected yield effects (Rosenstock b *et al.*, 2013). Results are based on a Monte Carlo analysis with 10 000 runs (see Annex V for description of Monte Carlo methods).

While not providing definitive forecasts of yield effects of CA adoption, this simple analysis distinguished between high-potential and low-potential sites. It also provided a baseline scenario illustrating the full spectrum of likely effects that CA adoption might have (Fig. 8). Interestingly, both MICCA sites were found to have limited potential of achieving yield gains from adopting CA, with a higher likelihood of yield losses compared to gains.

A possible disadvantage of the probabilistic modeling strategy is that validation of the model may not strictly be feasible without extensive observational studies. Many outcomes are possible according to the probability distributions, and only a few data points are available for 'ground-truthing'. When evaluating projections at the site level, each site only produces a single data point that can be compared to model output. With this caveat in mind, it is noteworthy that many Kolero villages have experienced varied success with CA and even those that adopted CA typically adopted only part of the full CA package. The failure of some CA practices to take a firm hold in the villages has happened in spite of multiyear CA promotion activities dating back to before the start of the MICCA pilot projects. Given the predominantly negative yield effect projections indicated by our model, the slow uptake of CA can be explained.

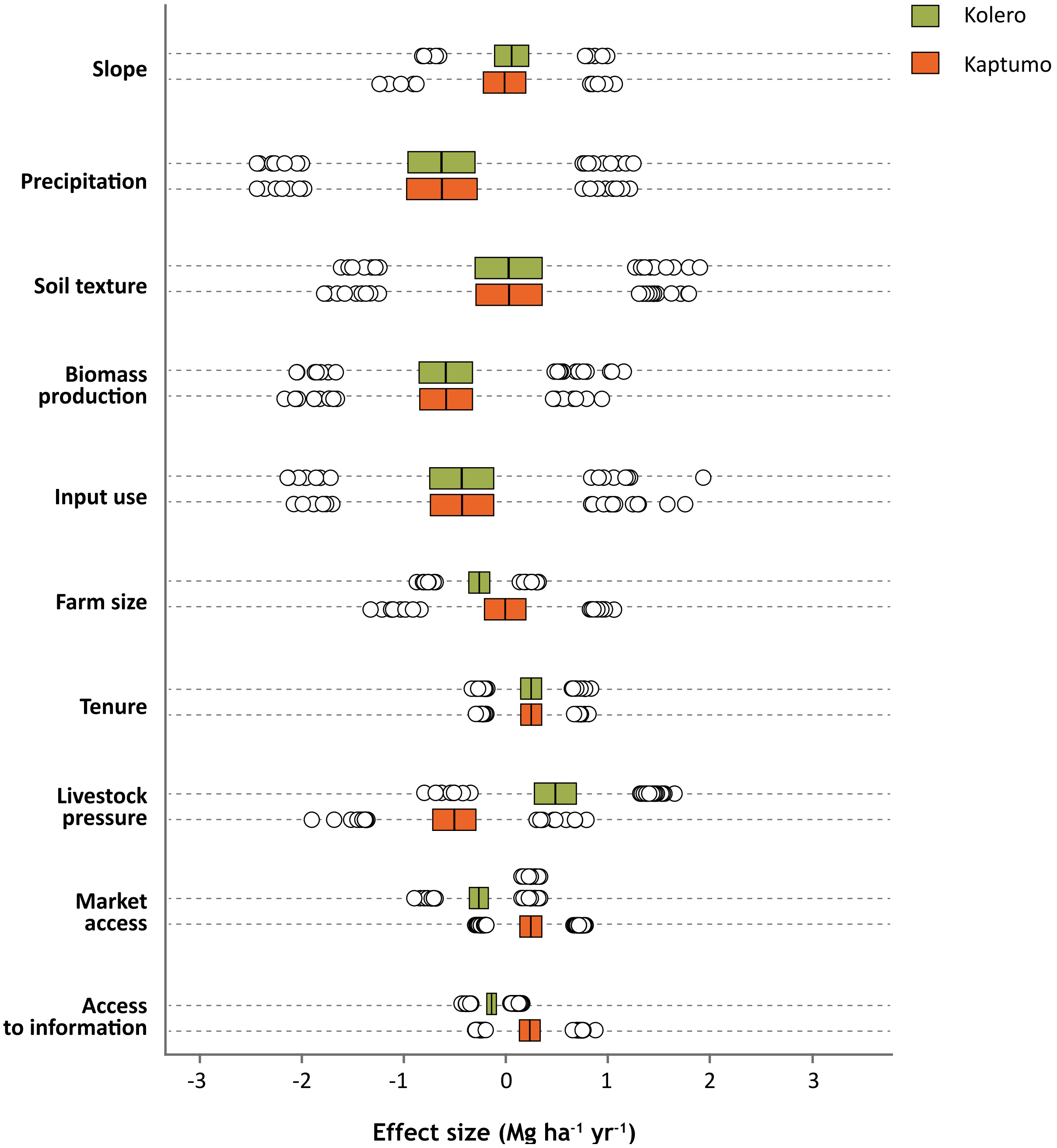

Figure 11. Effect sizes of important factors associated with yield effects of CA at the MICCA sites in Kaptumo and Kolero. 1 Mg = 1000 kg (Rosenstock b *et al.*, 2013).

The modeling exercise was also instructive in determining site factors that should be in place wherever CA is promoted to smallholder farmers. It also pointed toward system or household characteristics that should be considered when targeting this practice. An analysis of the simulation results identified the major constraints to adoption of CA at the MICCA sites (Fig. 9). This shows that even though projected yield effects were similar for both sites (Fig. 8), the underlying reasons for low yield improvement potentials differed considerably. At Kolero, yield potentials were low mainly due to small farm sizes, as well as limited access to markets and information. Kaptumo, on the other hand, suffered from competition for scarce biomass resources between livestock and agricultural crops. Such insights can benefit intervention targeting in two ways: they can identify locations in which CA simply does not have much potential; and they can, in some instances, point to limiting factors at the site or for some farmer typologies that could be addressed by accompanying interventions, such as land tenure reform or improvements in marketing or information infrastructure.

In summary, this analysis showed that considerable guidance for targeting interventions can be obtained from a relatively rapid analysis. This finding contrasts starkly with commonly taken approaches that either aim to estimate impacts based on less than comprehensive datasets or collect large amounts of detailed information in an attempt to build comprehensive models that are then of limited use for targeting interventions in locations with lower data availability. In spite of some advantages of probabilistic modeling approaches, there is no doubt that farmer-managed test plots on farmers' fields can generate additional certainty about the likely impacts of an intervention. The purpose of this approach is not to dispute the value of farmer-managed test plots on farmers' fields, but rather to provide a first-cut selection mechanism to judge the suitability of particular sites for certain practices *ex-ante*. Where conditions appear generally favorable for the practice, the expenses of further testing of the proposed practices will likely be justified. Where basic site factors do not seem to favor a practice, however, field tests of the respective technologies may not be the most effective use of resources. The probabilistic analysis can also point to measurements that would have high value for reducing uncertainty and improving targeting.

This approach appears well suited for selecting and prioritizing interventions and accounts for uncertainty and variability in outcomes at the programmatic level. However, the approach is flexible and can equally be applied at other levels of decision making. For example, similar models could be run with spatially explicit data on biophysical and socio-economic constraints to better inform extension programmes. The primary constraint here is the availability of georeferenced data that captures and maps the variations found at a site or across regions. Currently, many national governments across East Africa and other regions are developing agricultural plans that focus on or integrate climate change, including Nationally Appropriate Mitigation Actions (NAMAs), National Adaptation Plans and National Agricultural Investment Plans. In many cases, these plans are not systematically evaluated as business cases where major uncertainties are adequately considered regarding the socio-ecological constraints to adoption, success of interventions, relative benefits, risks, monitoring, reporting, and verification requirements when making the decision. By building on and extending the frameworks described here, a transparent and rigorous assessment that provides strategic targets for CSA investment portfolios can be established.

7. Development implications and way forward

Decision makers, whether they be farmers, development practitioners or policy makers, are contending with challenging questions as to how to adapt to climate change while advancing other development goals related to livelihoods, food and nutrition security and the sustainable use of natural resources. Climate change mitigation is an important dimension of CSA and a goal of low-emission development. While mitigation is being given due importance in the development of NAMAs, it continues to be a contentious topic globally as there are ongoing arguments related to unequal emission contributions among countries and corresponding national responsibilities to curb these emissions. Also, as has been seen when promoting ecological approaches to agriculture, farmers in developing countries tend to prioritize practices that safeguard or improve their livelihoods. Consequently, integrating development objectives with environmental and climate goals is a fundamental concept for CSA.

The MICCA pilot projects were designed to address the livelihoods of smallholder farmers and at the same time enable them to contribute to global efforts to mitigate climate change. The MICCA programme chose to capitalize on two very different development projects in Kenya and Tanzania and carry out robust scientific research that could bring about a better understanding of the emissions associated with local agricultural practices. This involved developing an approach to adequately measure GHGs and assess and articulate the uncertainty of measurements of different practices in different geographies. In some cases, modeling was done to assess the yield impacts associated with adoption of specific practices.

In reviewing the broad research findings, it must be taken into account that this was only a two-year study, and as explained earlier, the sample sizes were small due to the resources allocated for the quantification methods. The following represent the main site-specific findings relative to CSA appropriate practices garnered from the research efforts described in this publication:

- In the integrated cropping systems of Kolero in the United Republic of Tanzania, where N limits production, leguminous trees and mineral N fertilizer can increase productivity under CA without significantly increasing emissions.

- In the integrated agro-sylvopastoral systems of Kaptumo, Kenya, contrary to expectations, partial GHG budgets suggest that smallholder dairy production can be relatively climate-friendly when combined with agroforestry and when pasture is managed wisely.

- The probabilistic model applied at both sites indicated that potential yield improvements associated with CA adoption were unlikely to be achieved given the social and ecological contexts of the sites.

The scientific approach that was followed permits a few general messages and suggestions for future activities in the areas of ‘research for development’ or ‘research to inform policy’ that were designed to quantify the parameters of potential CSA practices and their implications at nested scales.

- The data precision and variability of a wide range of factors, including farming systems, inputs, farming configurations, the timing of farm activities, ecosystem characteristics, weather and socio-economic conditions, characterizing the emissions associated with different practices that are assumed to be climate-smart will continue to present challenges.

- In estimating emissions for integrated farming systems, it may be important to implement whole-farm measurements or estimates, as quantifying the impacts of only one part of the farming system may miss critical emission hotspots or mitigation leverage points, or overlook options that simultaneously address adaptation and food security. For example, to identify leverage points, a probabilistic analysis of alternative farm systems could help to focus measurements on parts of the system where there are the greatest uncertainties and that have a large impact on total emissions.

- Research and development stand to benefit from greater integration. Development practitioners, working with local communities, can ensure that research is demand driven and grounded in reality. Research carried out with the active participation of farmers can validate the practices being promoted through development initiatives and estimate the potential impacts of different activities. However, integrating research and development presents some challenges. For example, the time period required to guarantee robust research results may exceed the time span allocated for development programmes. Because of these, mismatched timeframe development programmes and policies may be based on limited empirical evidence.

- Because CSA is meant to have impacts far beyond the farm gate, and is influenced by policy and enabling environment, the continued integration of research, development and policy is essential. National policies and action plans geared toward enhancing climate change adaptation and mitigation in agriculture need to be continually shaped by the evidence associated with practices that are most likely to succeed and the feasibility of their implementation and scaling up must be based on field experience and lessons learned.

To achieve development outcomes, farmers, development workers and organizations, researchers and policy makers will always be making tradeoffs connected to a wide range of economic, social, cultural and environmental issues. There is still much to be understood in terms of identifying CSA best options in different scenarios and how to scale up successful initiatives so that they have a meaningful impact at multiple levels. Proactively linking scientific research with development projects has enormous potential to simultaneously determine research needs and frame development actions so that they meet the demands of smallholder farmers and the requirements of national governments.

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Annexes

Annex I: Biophysical data collected

The following data were collected from October 2012 to June 2014 as part of MICCA science activities. Datasets will be available upon request to FAO following the completion of the MICCA pilot project field activities by 31 October 2014.

Data	Description	Time period
Greenhouse gas fluxes from soils	Flux data for CO_2, N_2O, and CH_4 measured from soils with photoacoustic spectroscopy at both sites	2012/4 – 2012/9
Greenhouse gas fluxes from soils	Flux data for CO_2, N_2O, and CH_4 measured from soils with gas chromatography at both sites	2012/11 – 2014/6
Ancillary data for GHG analysis	Soils data including volumetric water content, temperature and bulk density for sites where GHG measurements are being conducted	2013
Maize biomass	Biomass and yield data for maize from the CA study site in Kolero	4 seasons inclusing short and long rains 2012 - 2014
Tree biomass	Biomass data from tree inventories for C dynamics at landscape scale in Kolero	2013
Weather	Rainfall data gathered from manual rain gauges in both sites and the weather station in Kolero	2012 – 2014
Land health surveillance framework	Soils and vegetation assessment for 10 by 10 km sites including site characterization analysis, carbon and nitrogen data, and soil spectroscopy output for physical and chemical properties	December 2011 (Kenya) June 2012 (United Republic of Tanzania)
Land cover and land use change analysis	Maps and image classification of land use change over 30 years created from Landsat (United Republic of Tanzania)	1973 -2013

Annex II: Land health surveillance methods and illustrative results

The health of humans, crops, livestock and the environment are closely related in most developing countries. Soils and vegetation in particular support many ecosystem functions on which livelihoods depend. Soils are fundamental reservoirs and processing units for cycling water and nutrients that sustain crop and grazing land production and eventually produce food. Vegetation stores carbon and is often a primary source for construction materials and fuel.

Population growth throughout the developing world has put significant pressure on the ability of the natural resource base to provide essential livelihood and ecosystem functions. The consequence in most regions has been rapid degradation of soil quality (e.g. decreasing C and N stocks, hydraulic conductivity) with land conversion to agricultural uses. Environmental degradation compromises productivity for the inhabitants today and jeopardizes any chance of providing for those living on the land tomorrow.

MICCA pilot project science activities used the Land Degradation Surveillance Framework (LDSF) methodology developed by ICRAF to characterize the physical environment (soils and vegetation) in the Kaptumo and Kolero regions. The LDSF applies a spatially stratified, randomized, hierarchical sampling strategy to quantify the condition affecting land health and the drivers of change at field and landscapes levels. At 160 sampling sites across 100 km^2, which were organized in 16 clusters of 10 points, field survey teams sample topsoil and subsoil down to 1 m, measure vegetation structure and type, and visually assess erosion and other impacts of human modification of the landscape, such as fire or soil and water conservation techniques (see field guide at Vågen *et al.*, 2010). A fundamental component of the LDSF is that the sampling points are randomly selected (by computer program prior to sampling) and thus may fall anywhere within the 100 km^2 study area. This is important because it overcomes the tendency for 'convenience sampling' in areas that are more easily acceptable (e.g. near roads) and generates data more representative of the landscape as a whole. The LDSF has been applied in more than 100 sites (two of which are the MICCA pilot project sites) across sub-Saharan Africa to map and understand soil properties in Africa.

Figure A1. Kolero field team navigates down the slope to randomly selected waypoints using a Global Positioning System (GPS). Photo: Todd Rosenstock.

Each site generates more than 750 soil samples. Resource demands to process and analyse this large quantity of samples would be cost- and time-prohibitive using traditional wet chemistry. Instead, the soil and plant diagnostic laboratory at ICRAF employs laboratory spectroscopy techniques to analyse soil properties and increase lab capacity. Spectroscopy is based on premise that various elements in the sample will absorb or diffract light at different rates and angles (Shepherd and Walsh, 2007). Shining light of various frequency and kind (e.g. mid-infrared, X-ray) through samples provide 'signatures' of the elemental composition and physical properties, called 'spectra'. The spectra can then be correlated with reference samples analysed by more traditional methods (see Fig. A2). Spectroscopy methods cost roughly 1 USD per sample by comparison to more than 30 USD for wet chemistry.

The LDSF field surveys were conducted in December 2012 (Kaptumo) and June 2013 (Kolero). The Kaptumo team was composed of nine full crewmembers plus intermittent laborers. The 160 sampling plots were completed in 22 days. The Kolero team consisted of sixteen crew members split into two teams, each with three or four porters to help carry equipment and soil samples, and navigate through the rugged terrain based on local knowledge (see Figure A1 above). The Kolero team sampled 151 plots in eighteen days. Nine plots in one cluster were not sampled due to their inaccessible location and farmer resistance two-thirds of the way up the highest mountain in the Uluguru Mountain range.

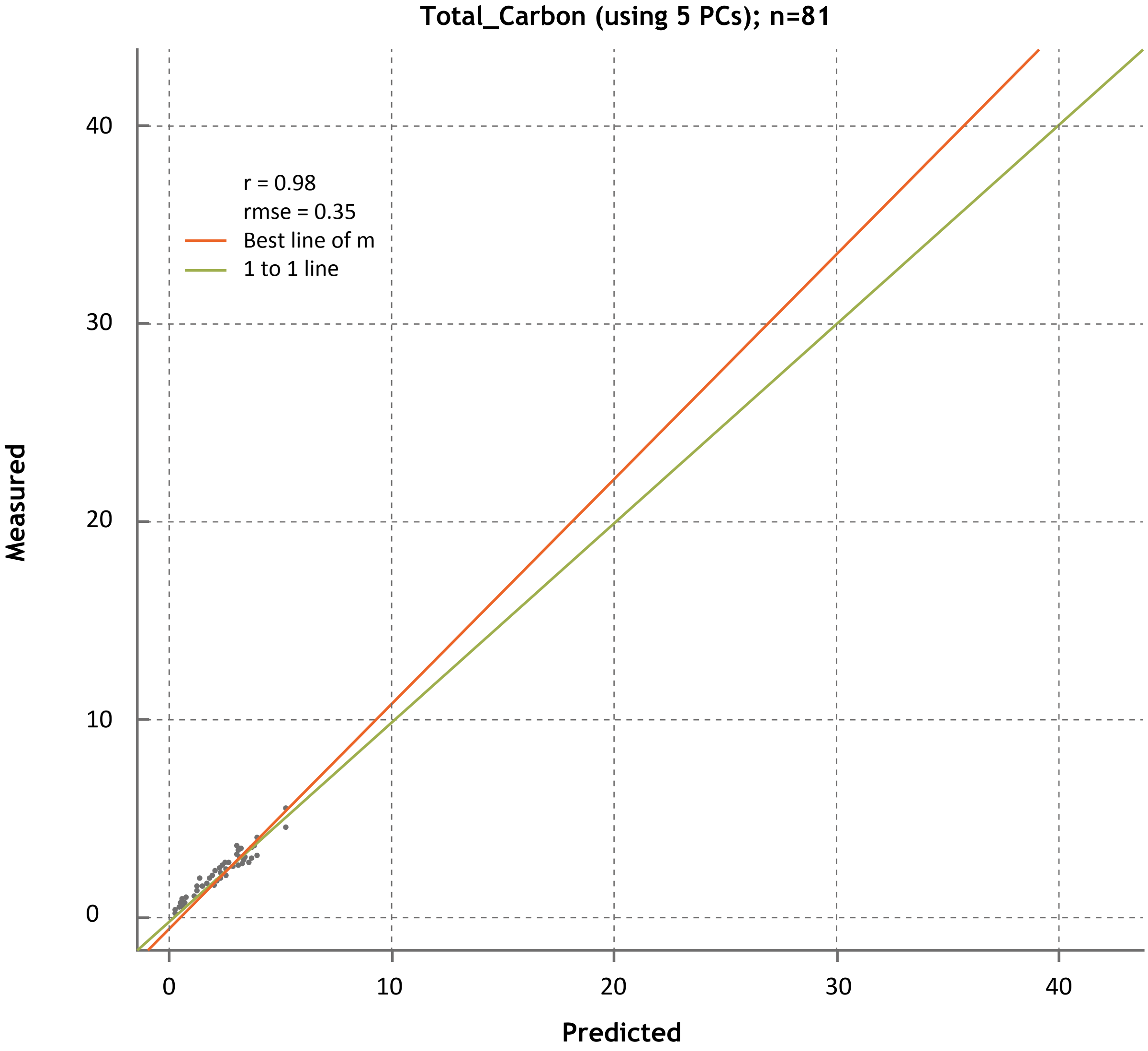


Figure A2. Calibration set for organic carbon using mid-infrared spectroscopy and partial least squares regression on principal components by comparison to traditional methods of soil organic carbon (%) determination by dry combustion ($r^2 = 0.97$). ICRAF uses 30 samples in the reference set and models the properties for the other approximately 720 samples collected as part of the LDSF.

Information on the state of the physical environment is part of the fundamental basis to CSA science. It underlies the understanding of the constraints to agricultural productivity, potential vulnerabilities to climate stresses and the mitigation potential of changing management practices. For example, the pH of soil is strongly correlated with nutrient availability and toxicity. By mapping the soils, it is possible to better understand the type of potential interventions that might be necessary and the range among the locations (see Figure A3). What the LDSF analysis shows is that Kolero soils are typically lower in pH but the levels vary. In both sites, pH is generally lower than desired for crop production (less than 6). Since these data are mapped in a spatially explicit way, it can be possible to pinpoint recommendation for specific intervention; in this case, the likely responsiveness of soils by adding lime to increase pH.

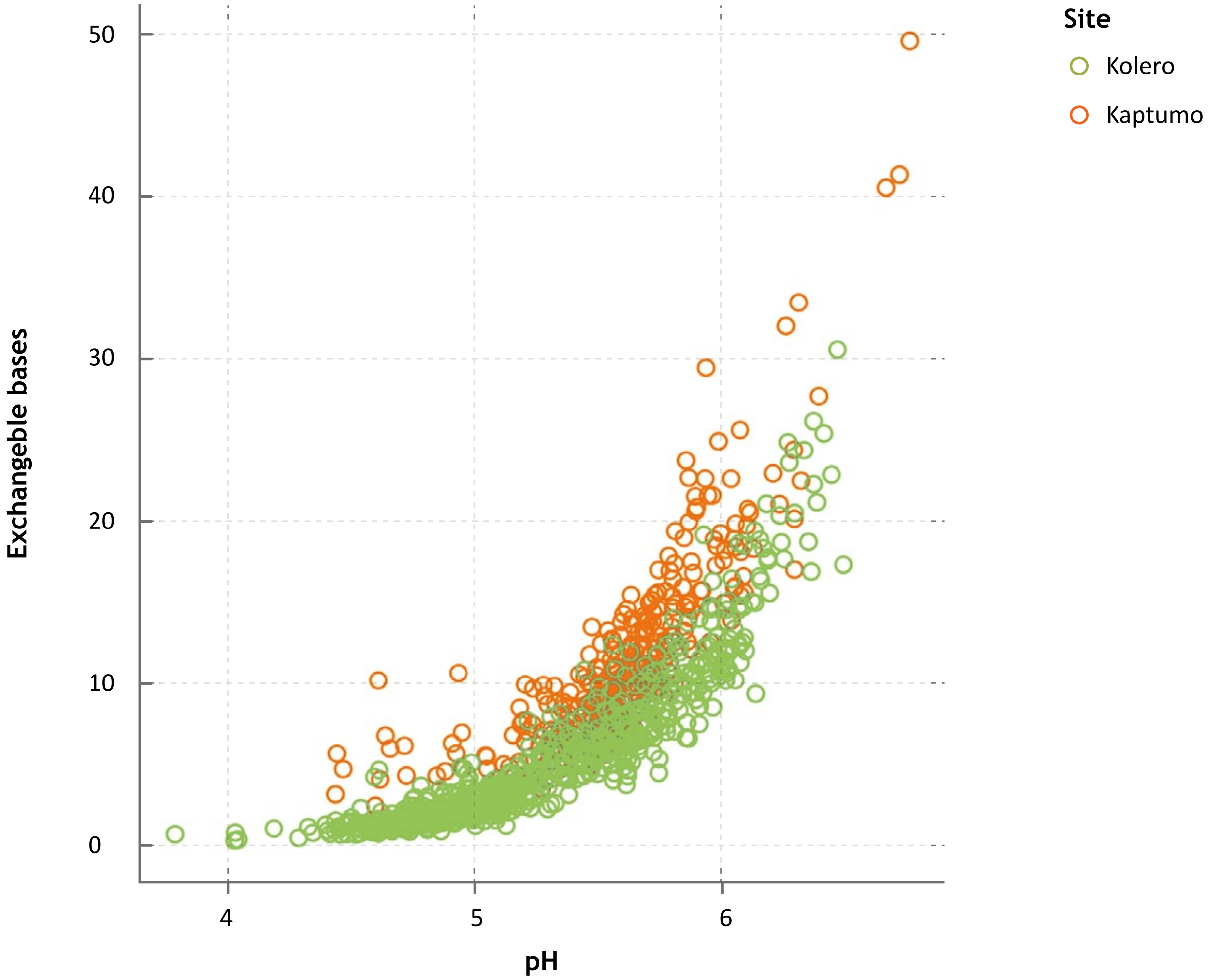


Figure A3. Measures of soil fertility and quality (0 - 50 cm) based on LDSF spectral analysis. The graph shows the clear relationship between pH and exchangeable bases ($cmol_c\ kg^{-1}$).

But the LDSF does not only characterize the soils of a region. It also assesses vegetation and land degradation through empirical measurements and visual inspection. The examiner looks for a number of signs (e.g. erosion, fire and land use) and makes measurements of biomass within the plots. These types of data, first and foremost, provide a baseline of the health of the plot and, when combined with other plots, the entire landscape. Thus, they also can be used for targeting interventions. For example, collection of data from Kaptumo on tree density (see Figure A4) shows that there is significant variation both within and between measurement clusters. Recall that a cluster contains 10 sampling points. This suggests that some areas are more heavily covered with woody biomass than others. Where there is not significant coverage and there is large variation with a cluster, it may suggest this is an area where tree planting might be an appropriate intervention. See Vågen *et al.*, (2010) for the full field data sheet to understand the extent of information collected.

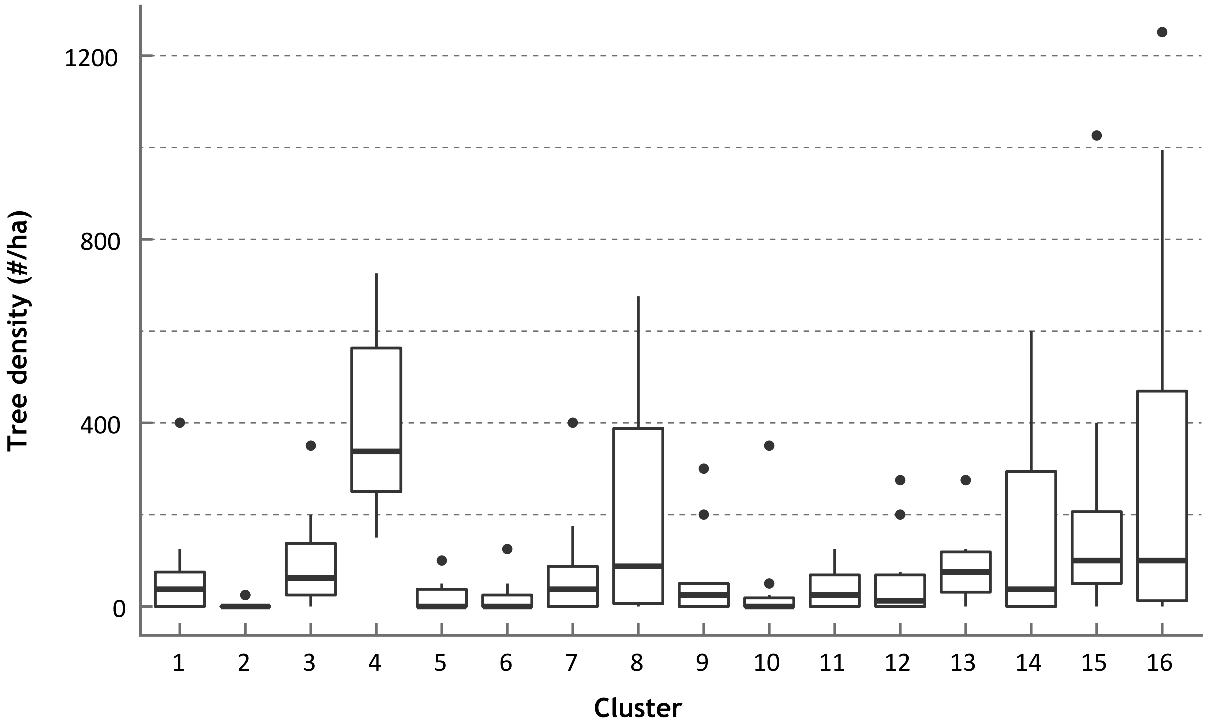


Figure A4. Tree density in the Kaptumo region based on measurements at the 1 000 m^2 plots within each cluster

Perhaps most significantly, the LDSF is spatially explicit. Each sampling point is georeferenced. This facilitates mapping land health properties and the resampling of the points for surveillance purposes to document future changes. It is also a prerequisite for developing spatially explicit targeting of CSA practices. Based on the results of the assessment at the 160 sampling plots, estimates of properties can be made about unsampled locations based on predictions based on co-variates (e.g. mixed models) or interpolation (e.g. kriging or inverse distance weighting). The figure below maps soil organic carbon in the top 20 cm of the Kaptumo area. Soil carbon content is strongly correlated with the physical and chemical properties and the fertility of the soil. With these data, it would be possible to understand potential constraints to production and make recommendations for specific interventions in a spatially explicit way.

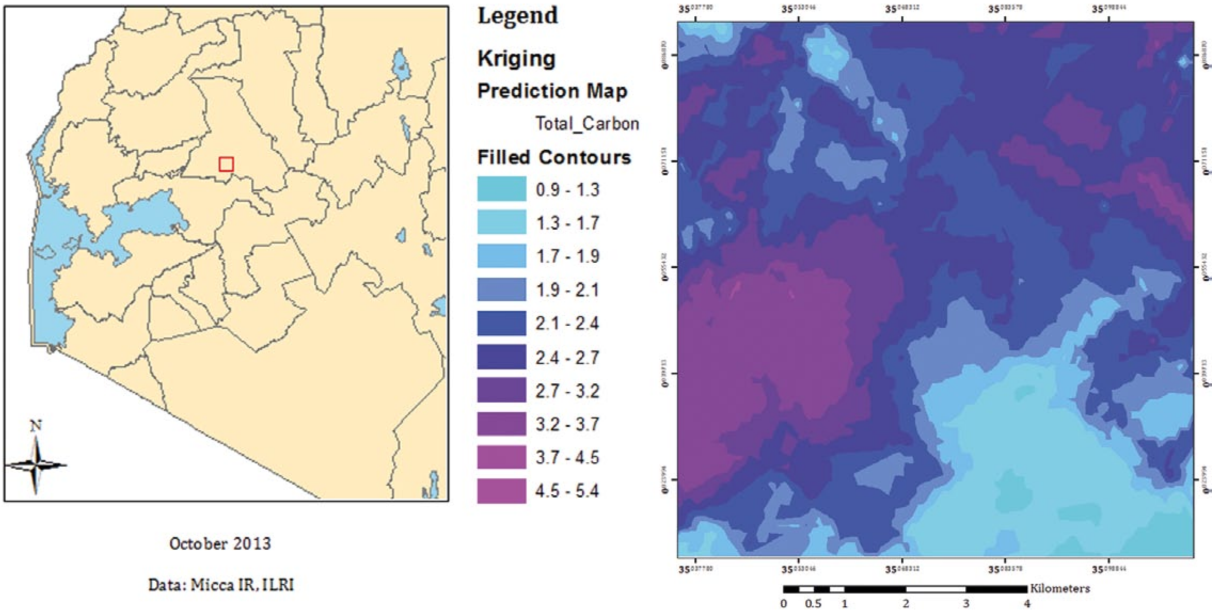


Figure A5. Soil organic carbon (%) in the Kaptumo, Kenya area interpolated from 160 point measurements by ordinary kriging.

Annex III: GHG emission monitoring

GHG emissions due to smallholder agriculture in developing countries, in particular those in Africa, is not well documented. There are relatively few data quantifying emissions from any farming systems. Inference or conclusions based on such limited data that ignores the variation in soils, systems, and management can be imprecise or wrong. As part of the MICCA pilot projects, the aim was to better constrain the uncertainty in the range of emissions from various sources in smallholder systems.

In 2012, ICRAF first monitored soil emissions of GHGs for four months that included the long rains season (Feb – June) in the field with photoacoustic spectroscopy (PAS), the Innova® multi-element gas analyser. PAS circulates air through a soil chamber into the body of the machine where it passes pulsating light through the sample. Light excites molecules in the gas sample creating an audio frequency that can be amplified, measured and converted into gas concentrations. The PAS measured fluxes once every 2 minutes for six minutes. Fluxes were calculated as the rate of change between the first two data points. Only the first two data points were used to minimize chamber artifacts such as pressure gradients or increased relative humidity on the estimated flux.

PAS presented two advantages over other common measurement methods, such as gas chromatography for measuring GHG in rural sub-Saharan Africa. One, it measures multiple molecules (e.g. CO_2 and N_2O) simultaneously. The ability to measure many gas concentrations from the same sample reduces the field sampling time and equipment necessary to monitor multiple GHG fluxes. Two, it calculates gas concentrations immediately. Instantaneous quantification reduces the analytical time between measurement and data, the resources needed to support additional laboratory time, and the error in later stages of sample processing (such as gas leakage in vial storage). The benefits, however, must be counterbalanced against some concerns over interference in the light absorption among gases and between gases and water vapour. The severity of these concerns, however, is very much in debate. Many published studies use PAS without issue (e.g. Iqbal *et al.*, 2012) while some inquiries into the methods have shown potential concerns with performance (Rosenstock *et al.*, 2013c). After this experimentation, ICRAF discontinued use of this instrument, switching to the more standard method of static chamber methods and gas chromatography (Parkin and Venterea, 2010; Parkin *et al.*, 2012). Wikipedia provides a good description of gas chromatography[6] and the protocol used in the field for sampling static chambers is below.

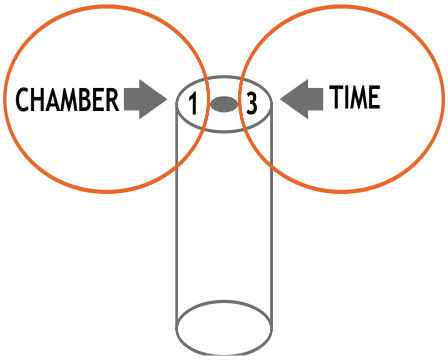
Soil flux monitoring protocol:

Evacuating the gas sampling vials

1. Connect the silicone tubing to the vacuum pump and cap the end of the tube.
2. Switch on the vacuum pump and then connect/pierce the tube with one end of the double ended needle. Connect the other end of the needle to the vial by piercing the rubber septa and evacuate for about 10 minutes depending on the power of the pump. Connect all the gas vials and the silicone tubing in the same manner. Many vials can be evacuated simultaneously depending on the length of the tubing and the power of the pump.
3. Check on the value of the vacuum using the manometer (should read below -550 mm Hg negative pressure). Change the septa if the vial top is not gas tight or if the pressure value reads > -500 mm Hg.

Sample labeling: Label (with the marker) the top of the vials.

- Left side: chamber number
- Right side: time



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[6] http://en.wikipedia.org/wiki/Gas_chromatography

Gas sampling procedure

Fitting the gas flux chamber bases onto the soil surface:

1. Identify the sampling site; choose the points to insert chamber bases to account for potential sources of heterogeneity plus practicial considerations such as the length of cable to the battery to run the fan.
2. Push the chambers 5-10 cm into the ground at least 24 hours prior to the first measurement. Do not remove chamber bases unless necessary to account for field management activities.

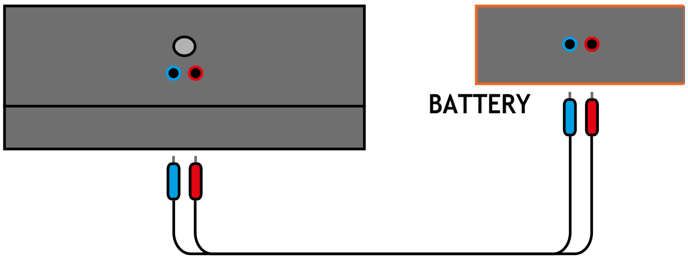
Sampling:

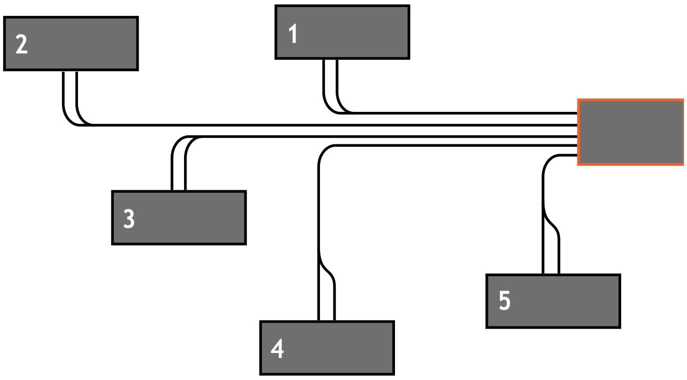
3. Using a ruler record the heights of four points inside the chamber from the ground to the top of the rim of the chamber base.

Connect the cables to power fan.

- Connect one end of each cable to each chamber and the other end to the battery. Remember to connect positive to positive and negative to negative.

- Check to see all fans are working inside chamber lids.

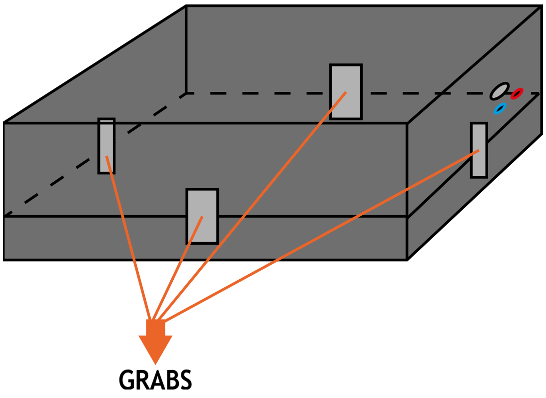




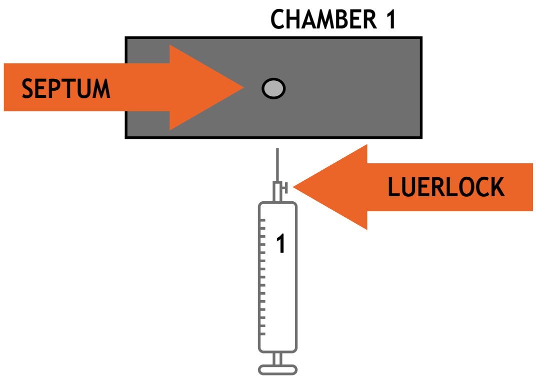
Gas sampling:

Closing the chamber

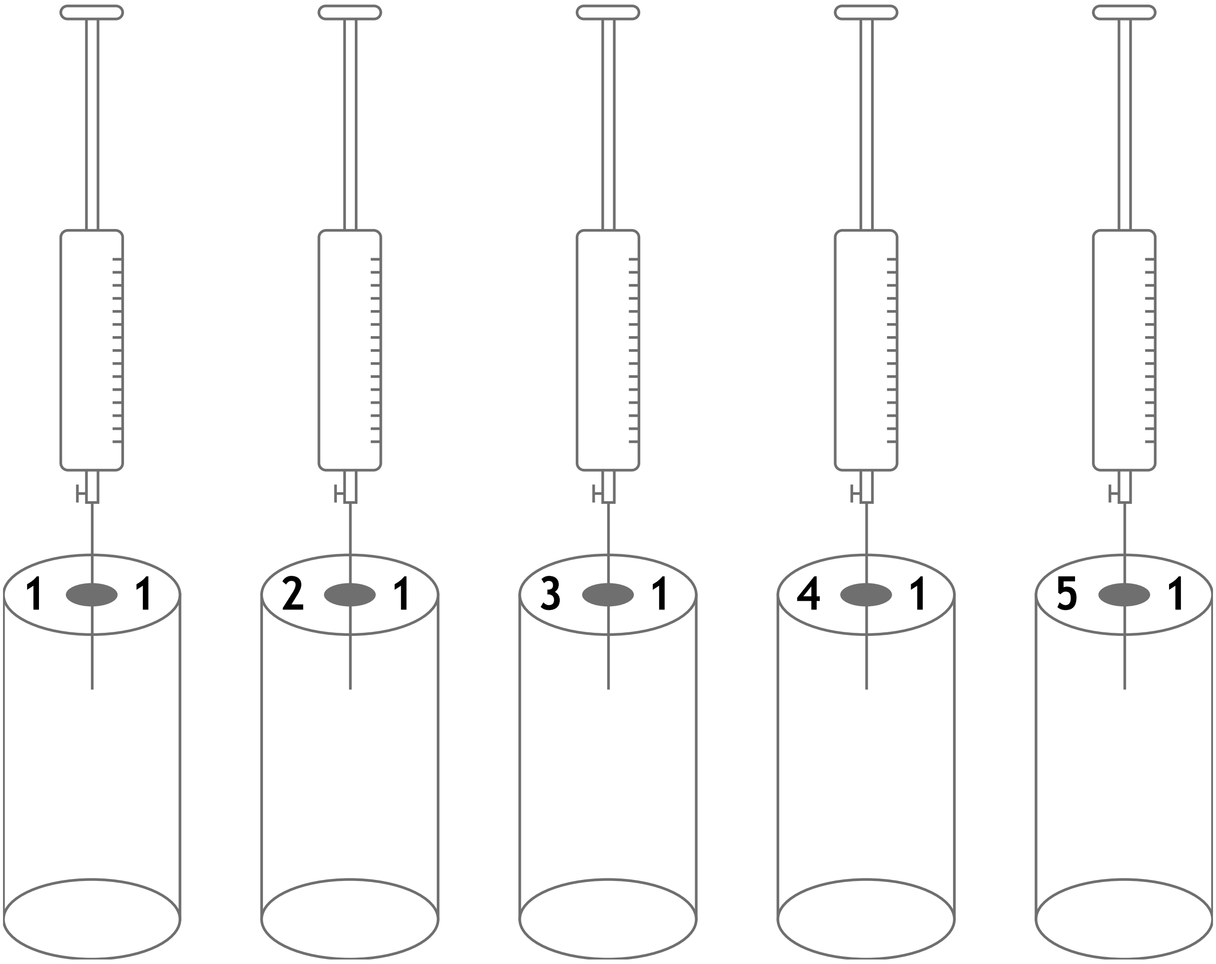
- Put the lid on the base.
- Place the 4 grabs.
- Make sure that the system is tight.
- Start timer
- Begin sampling



Gases are sampled using 50ml gas tight syringes fitted with a luer-lock stopcock. A gas sample from the chamber is injected into an evacuated 20 ml vials, resulting in an over-pressurized vial.



1. Initial temperature measurement: deposit a sensor inside each base. Record the temperature in the template before closing the chamber.
2. Set the timer to zero. When ready to begin sampling, start the timer then close the first chamber tightly with the 4 or more clips (‘grabs’ in figure above).
3. Insert the needle into the chamber through the septum.
4. If not using the fan, pump syringe while inserted to mix gases in chamber headspace.
5. Extract 60 mL gas from chamber headspace with the syringe slowly.
6. Close the luer-lock.
7. Repeat for all the chambers.
8. Record the time you finish sampling all chambers.
9. Insert the needles into the septum of the 5 preevacuated vials respectively (1-1) to (5-1) and inject the gas samples into the vials.



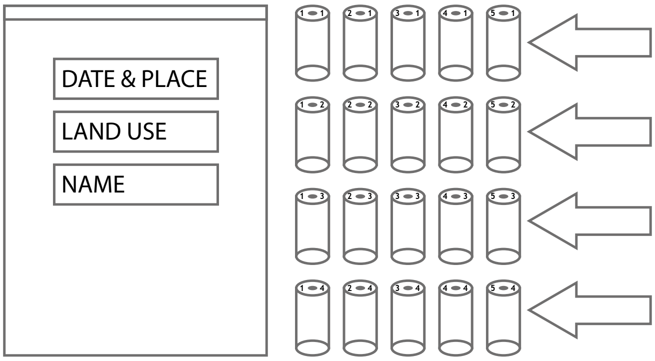
Ten minutes from the time you started the timer, start the second round of sampling for T_2 vials in the same sequence you sampled for T_1 vials and record the finishing time of the last chamber.

Twenty minutes after the start of the timer, sample for T_3 vials in the same sequence as above for all chambers then record the finish time, do this again after exactly 30 minutes on your timer for vial T_4 and ensure you record the finish time.

Finishing:

1. Final temperature measurement: once the gas sampling is finished, open the chambers and record the temperature of the sensors.
2. Pick up cables and sensors.
3. Pack away all vials (20 in total) and the template in a zip lock plastic bag.

Label the plastic bag:



Field Sampling Form

Site: ________________ Treatment: ________________ Ambient Pressure: _____________

Date: ________________ Start time: ___________ End Time: ___________ Elevation:_____________

Chamber No.	4 point Chamber heights				Vial labels			
					T_1	T_2	T_3	T_4
1					1-1	1-2	1-3	1-4
2					2-1	2-2	2-3	2-4
3					3-1	3-2	3-3	3-4
4					4-1	4-2	4-3	4-4
5					5-1	5-2	5-3	5-4
6								

Sampling Time				
	T_1	T_2	T_3	T_4
Start	0m	10m	20m	30m
End				

CH Temp.			
Chamber NO.	Initial	End	
1			
2			
3			
4			
5			
6			

	Start	Mid	Stop
Air temp			
Soil temp			

Observations/Notes

Weather: ________________________________ ________________________________ _______________

State of vegetation: ____ ____

Incidents: ____

Annex IV: Carbon sequestion in biomass

Woody plants remove carbon from the atmosphere and store it in their roots, trunks, and branches. That sequestration of carbon in biomass can represent a significant sink, in particular in areas where plot-level emissions are small. Trees and shrubs are prevalent landscape elements in both MICCA pilot project sites.

Case study farms were selected from Kaptumo area in Nandi South County, Rift valley. Trees in three farming systems (grazing, semi-zero and zero-grazing) were sampled to estimate carbon stocks. Farming systems were classed into four land use types (trees dispersed in cropland, pasture, homestead and woodlot), according to the dominant land use units observed in the field.

The administrative farm location and owner's details (name and contact) were determined and recorded on the datasheet to facilitate follow-up measurements. GPS coordinates of each land use unit boundary were recorded to allow for area calculation of farm features. The GPS coordinates of trees in the plot were also marked standing at the tree base with a GPS devise. The diameter at breast height (DBH) in cm of all trees larger than 2.5 cm within the farm boundaries was measured using a diameter tape. DBH was measured at 1.3 m above the soil level, having the diameter tape held horizontal and tight to the tree. Trunks with protruding dead wood and climbing plants that would distort measurement were cleared prior to measurement. The species name was recorded.

Estimation of biomass and conversion to biomass to carbon

Allometric equations based upon power function were used to estimate aboveground biomass (AGB) of measured trees. The power function equations were chosen because of their greater accuracy for assigning biomass to smaller trees, which dominate agricultural landscapes (Kuyah *et al.* 2012). Aboveground biomass of live trees was determined using the equation $AGB = 0.091 \times (DBH)^{2.472}$ empirically derived for the local conditions (Kuyah *et al.* 2012). The bias associated with biomass estimates was accounted for as $Aboveground\ biomass = AGB_{estimated} + (2.69/100 \times AGB_{estimated})$ (Chave *et al.* 2005), where 2.69 is the relative error associated with the equation by Kuyah *et al.* (2012).

It is generally assumed that 50 percent of the dry mass of wood corresponds to C (West 2009), while the IPCC (2006) documents between 46-49 percent for most tree species in the tropics. Because C projects are interested in the actual C present in biomass, the C content of trees was estimated at 48 percent of the tree's total dry weight, with C fraction for trees in agricultural landscapes determined by Kuyah *et al.* (2012). Carbon estimates for all trees in each farm were divided by the size of land to determine C per ha. The content of the tree's CO_2 was multiplied by 3.67, the ratio of the molecular weight of CO_2 (44) to the atomic weight of C (12), to determine the weight of the C stored by the tree (i.e. the equivalent of CO_2 contained in C sequestered in woody biomass, referred to as CO_2e).

Annex V: Monte Carlo simulations

Most information we have about our environment is subject to some uncertainty. Essentially, the exact amount of carbon stored in a hectare of land, the exact number of small farmers in a given district, or the exact onset date of the rainy season is never known. These uncertainties are a potential problem in projecting the impacts of an intervention or in computing any property of a system with a model. Ignoring uncertainties, working with best-bet estimates only or making assumptions that unknown variables take on certain exact values are common but suboptimal strategies that can lead to wrong results.

Monte Carlo simulation provides an approach to address uncertainties around input variables to models and translate them into probabilistic projections of system outcomes. This is achieved by constructing probability distributions for each uncertain variable, for example a normal distribution based on estimated 90 percent confidence intervals for the value of a particular variable. From each of the distributions for all uncertain variables, one value is then drawn at random, and these values are input into the model, which then computes a single output value. This process is repeated many times (e.g. 10 000 times) with new sets of random values drawn and single outputs calculated in each iteration. All output results are collected and combined to produce a probability distribution of model outputs. This distribution then describes the likelihood of achieving certain outcomes in a way that reflects the uncertainty about all system inputs. Outcome distributions are of interest when identifying the most likely outcomes but also for determining the more improbable, but plausible, ones, which are important when quantifying the risk of interventions.

This document reports on the concepts driving the scientific activities of FAO's Mitigation of Climate Change in Agriculture Programme's (MICCA) pilot projects in East Africa. It provides results from the research, briefly describes the analytical approaches used and concludes with key messages relevant to discussions on climate-smart agriculture (CSA). The MICCA pilot projects aim to help mainstream CSA in the region by identifying, verifying and scaling up farm management practices that can both increase productivity and set smallholder farmers on a pathway toward emitting fewer greenhouse gases (GHGs) per unit of produce, where possible. As there are many unknowns about what farming approaches are best for reaching CSA's multiple objectives, the underlying premise of the MICCA pilot projects is that strong linkages between science and development are essential to the expansion of CSA in developing countries. The scientific approach that was followed permits a few general messages and suggestions for future efforts on 'research to inform policy' that are aimed at quantifying the parameters of potential CSA practices and their implications at nested scales.

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