Climate Change Adaptation: From Science knowledge to local implementation

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Zusammenfassung

Problem. Der Klimawandel trifft die Landwirtschaft in Entwicklungsländern am härtesten. Obwohl viele Studien über die Folgenabschätzung zum Klimawandel existieren, beurteilen nur wenige eine räumlich differenzierte Auswirkung und stellen konkrete Anpassungsstrategien für Kleinbauern zur Verfügung. Viel hängt auch davon ab, ob die Bauern den Klimawandel wahrnehmen und ob sie davon überzeugt sind dass er sie treffen wird. Es fehlt Wissen über die Wahrnehmung von Klimarisiken durch Landwirte, und darüber, wie ihre Entscheidungsfindung bei gleichzeitiger Einwirkung von mehreren Riskien beinflusst wird. Klimawandelanpassung findet bereits an vielen Orten statt, die Skalierung von erfolgreichen Beispielen scheitert oft. Was fehlt, sind neue tools, die ein kosteneffizientes Monitoring und Evaluierung des Fortschritts in der Anpassung an den Klimawandel ermöglichen.

Forschungsziel. Die hier beschriebene Forschung zielt darauf ab den Klimawandeleinfluss räumlich zu evaluieren, die Wahrnehmung der relevanten Akteure zu verstehen und effiziente tools für Monitoring und Evaluierung zu entwickeln, die eine Anpassung durch Bauern evaluieren können.

Methoden. Die Studie verwendete mehrere Methoden um den Prozess der Anpassung zu studieren und Wissenschaftsergebnisse zur lokalen Umsetzung von Strategien in einer Fallstudie als gekoppeltes Mensch-Umwelt-System (HES) zu zeigen. Als Erstes wurden Geographische Simulationsmodelle zur Ermittlung von räumlich differenzierte Auswirkung eingesetzt. Zweitens wurde ein Ansatz von Mentalen Modellen verwendet, um Unterschiede in der Wahrnehmung von Experten und Bauern zu untersuchen und Klimarisiken im Zusammenhang mit anderen Risiken zu verstehen. Drittens wurde ein Prototyp für Monitoring und Evaluierung der Umsetzung von Anpassungsstrategien entwickelt.

Resultate. Das DSSAT-Modell wurde zur Feststellung der räumlich differenzierten Folgenabschätzung verwendet. Die Ergebnisse zeigen, dass die Ertragsvariabilität für ausgewählte Anpassungsoptionen zwischen den geographischen Standorten variiert. Für die Fallstudie Cauca in Kolumbien zeigen die Ergebnisse der Mentalen Modelle, dass Experten und Bauern die Befürchtungen der Risiken unterschiedlich wahrnehmen. Die Clusteranalyse ergab vier Typologien von Wahrnehmungen bei Bauern. Die Verwendung von GeoFarmer in einem der vier Pilotprojekte zeigte eine zunehmende Anwendung und Skalierung klimagerechter Landwirtschaftspraktiken durch die Bauern nach Demonstrationsveranstaltungen auf.

Fazit. Die Studie hat gezeigt, dass nachhaltige Umsetzung von Anpassungsstrategien durch Bauern nicht mit einem wissenschaftlichen Ansatz oder einem tool erfasst werden können. Vielmehr identifiziert sich eine erfolgreiche Anpassung an den Klimawandel durch eine Mischung aus was wo funktioniert (räumliche Allokation), warum es funktioniert (Akteure) und wie es skaliert werden kann (räumliche Umsetzung). Dies fordert transdisziplinäre Prozesse um die lokale Umsetzung der Anpassungsstrategien zu ermöglichen, und regelmässiges Monitoring und Evaluierung. Das Monitoring und Evaluierungssystem sollte unterschiedliche Ebenen erfassen können, wie zB das Sammeln von Indikatoren auf lokaler Ebene, Wahrnehmungen auf der Communityebene, und den Evidenz- und Wissensaustauschs auf globaler Ebene.

Summary

Problem. Impacts from climate change on agriculture are expected to hit economic livelihoods in developing countries hardest. Although many studies exist on climate change impact assessment, few of them assess spatially differentiated impact gradients and translate them into actionable strategies and possible adaptation pathways for smallholders. The success of implementation of these strategies relies in no small extent on farmers' perceptions of climate change including their knowledge and beliefs how it will affect them. There is not enough knowledge about farmers' perception of climate risks and how it influences decision making under multiple stressors. However, climate change adaptation is already happening in many places, but scaling of good practices often fails. What is missing are new tools that allow cost-effective monitoring and evaluation of climate change adaptation strategies at scale.

Goals. The research described here aimed for spatially assess impact-gradients and derive options for adaptation, understand climate-risk perceptions of relevant actors and develop tools for monitoring and evaluation to measure and track the evidence of farmers' adoption of adaptation strategies.

Methods. This research used multiple methods to study the adaptation process and bring science output to local implementation of strategies in a case study as a coupled human-environmental system (HES). First, geospatial simulation modelling was used to analyse impact-gradients and adaptation options. Second, a mental model approach was used to study differences in experts and farmers perceptions and better understand climate risks in the context of other risk. Third, a prototype was developed for cost-effective monitoring and evaluation of the implementation of adaptation strategies.

Results. The Decision Support System for Agrotechnology Transfer (DSSAT) model was used to identify impact gradients for dry beans in Central America and dry beans and maize in East Africa. Findings show that yield variability for selected management options varies between sites. For the case study Cauca in Colombia, findings of analysing mental models of experts and farmers reveal that they perceived concerns and enablers for adaptation similarly, but risks and barriers to adaptation differently. The cluster analysis of farmers' risk rankings revealed four typologies of farmers based on their perceptions. Using the GeoFarmer application in one of the four pilots uncovered the increased adoption and scaling of climate-smart agriculture practices after demonstration sessions.

Conclusions. This research demonstrated that the sustainable implementation of adaptation strategies by smallholders could not be captured with one approach or tool. Instead, successful adaptation to climate change is a mix of identifying what works where (spatial allocation), understanding why (actors for implementation) and how can it be implemented on the scale (spatial adoption). It calls for transdisciplinary processes of transferring scientific knowledge to local implementers and tracking of adoption of practices and technologies by farmers. Tools for monitoring and evaluation should be capable of capturing different system levels of adaptation; collecting indicators at the farm level, perceptions at the community level, and enable processes of knowledge sharing through a network of actors at the global level and in between sites.

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Part I

Part ONE: Synopsis

Chapter 1

Introduction

Global climate change is one of the current issues concerning science and society largely. New ways of collaboration between science and society need to provide knowledge for decision makers to reduce risks from climate change while being able to meet sustainable development goals [121].

Invisible and slowly progressing climate change as a risk makes it elusive; and people's perceptions are constrained by temporal-, social-, geographical-distance and by uncertainty [144]. Science of climate change is driven by globalizing research failing to provide sufficiently reliable predictions on the local scale [59]. While public concern and climate change awareness have gained more weight recently among society [87, 82], implementation of policies to reduce emissions and risks from climate change is still slow [14, 56].

In the climate change discussion, agriculture plays a double role: on the one hand, it is one of the leading contributors to global greenhouse gas emissions (GHG) [125]; on the other hand, risks from weather fluctuations and seasonal anomalies already affect agricultural yields and food security in many regions of the world [92]. Furthermore, impacts from climate change on agriculture are expected to hit economic livelihoods in developing countries hardest [48, 58].

1.1 Climate Change Impacts, Vulnerability, Adaptation and Resilience

In the climate change literature, vulnerability includes various concepts and elements including sensitivity or exposure to harm and the lack of adaptive capacity [67]. Vulnerability and adaptive capacity, however, are not determinants of climate change policy support. Factors determining peoples' policy support are their beliefs concerning the causes and local impacts of climate change [129].

Adaptation is a process of adjustment to actual or expected climate and its effects. In human systems, it seeks to avoid harm or take advantage of opportunities. Actions that aim for maintaining the state of the current system are categorised as *incremental adaptation*, fundamental changes to the system in response to climate and its effects are associated with *transformational adaptation* [67]. Adaptation is a human-environment interaction in a spatial and temporal setting [155]. Also, adaption needs to be framed in a socio-political process, involving authority, knowledges ad subjectivities across scales by multiple actors [40]. Finally, non-climate stressors, i.e. land tenure, environmental degradation, globalization of markets, market failures, state fragility and armed conflicts, among others, affect smallholders on rural livelihoods and can contribute equally or more to vulnerability of farm households [98].

In the current practice, the focus of adaptation is often framed as top-down problem-focused approach. Thus, several authors call for pathway thinking in the decision-making process of adaptation to consider dependencies, interactions and constraints in the human-environment system [162], and, using a multiple exposures framework instead of sectorial approaches and technical fix solutions [44].

The Paris Agreement frames adaptation in a different and broader context of multiple stressors to reduce farmers' socioeconomic vulnerability first, then address risks from disaster events and finally support the development of socio-ecological resilience to cope with climate change [155].

In the literature, adaptation in agriculture is associated with three main strategies [78, 117]:

- Coping strategies for current variability and existing systems on a low signal of climate change (e.g., heat-tolerant varieties, adaption of management practices)
- Systemic changes in moderate climate change signal (e.g., farm diversification, new crops)
- Transformation of systems without adaptation to a strong climate change signal (e.g., abandon crops and change to livestock system, leave agriculture)

Resilience is a useful lens to link ecological and social contexts to tackle the climate change problem [32]. The International Panel on Climate Change (IPCC) defines Resilience as:

> "The capacity of social, economic, and environmental systems to cope with a hazardous event or trend or disturbance, responding or reorganising in ways that maintain their essential function, identity, and structure, while also maintaining the capacity for adaptation, learning, and transformation." [67, p.5]

1.2 Climate Change in Colombia

For Colombia, it is estimated that by 2050 climate change will impact 3.5 million people and 80 percent of currently grown crops will require adaptation measures [118]. Scholars have shown that major cash crops grown by smallholders in the central Andean region of Colombia will face substantially reduced climatic suitability by 2050, which has serious implications for the food security of the metropolitan area of the capital Bogota [39].

For this reason, urgent actions are required from all Colombian actors to increase resilience to climate change, including the government, institutions and civil society. As for most Latin American countries, understanding how institutions shape decisions is crucial for Colombia [37]. Historically, institutional integration between local and national levels in Colombia has been difficult. Smallholders in Colombia are at risk from multiple stressors, including climate change, trade liberalization, and violent conflicts, and policies have been addressed separately in the past [44].

The violent conflict internally displaced a cumulative population of 6.9 million persons from 1985 to 2015 [107], the majority of displaced people moved from rural to urban areas. The persistent armed conflict and related social vulnerability in rural areas have led to profound mistrust in the state [90].

1.3 Climate Change Communication and Policy

In the Paris Agreement, the United Nations Framework Convention on Climate Change (UNFCCC) has established a goal of limiting the average temperature to well below 2 degree celsius above pre-industrial levels by the end of the twenty-first century [158]. Achieving this goal would significantly reduce the long-term risks and impacts of climate change. While national greenhouse gas inventories are monitored through National Determined Contributions (NDCs), an analogue method to monitor adaptation processes does not exist. While there is a consensus that adaptation is needed, there is no clear process established to track and monitor adaptation that would provide evidence where adaptation is already occurring and what are the enablers that drives adaptation [155]. Also, policy implementation is often delayed on the national level because of variability-driven uncertainty of local impact [123]. The role of science in adaptation policy and practice is to provide science for adaptation and provide research results that are solution-oriented and at the service for society [18]. Further, science should provide the methodological frameworks to effectively document adaptation in a global stocktake approach, as it was mandated in the Paris Agreement [155].

1.4 A premise: sustainable adaptation of farmers livelihood systems

The agriculture sector in developing countries is especially vulnerable to climate change [9] and needs to become more resilient in the future through actions initiated by governments, supported by the international research and development community [2, 122]. Smallholders' food production in less developed countries faces many challenges and risks, often with substantial adverse effects on food security and livelihoods [103].

Non-specialists mostly seem to underestimate and misinterpret these causes and risks [35]. Misinterpretation occurs because they are unable to distinguish climate variability from climate change [47]. Farmers perceive the likelihood that climate change might affect them directly as low [11]. The success of agricultural climate policies relies in no small extent on farmers' perceptions of climate change including their knowledge and beliefs how it will affect them [28, 108].

The sustainable livelihood framework (SLF) has been widely used as a standard approach to studying farmers' livelihood systems [141, 120]. The livelihood approach helps to understand the diversification of rural livelihoods as part of a coping strategy regarding hazards from climate shocks [15]. Using approaches from systems dynamics (SD) [147], the dynamics between livelihood capitals in agricultural systems could be analysed and better understood [20, 154].

Finally, agriculture needs to become smarter to tackle climate changes. Promoting both adaptation and mitigation at the same time, is a promising way forward in agriculture to foster agricultural practices and technology that sustainably increase productivity, make farmers resilient to climate shocks while reducing greenhouse gas emissions from agriculture where possible [89], often referred to as Climate Smart Agriculture (CSA).

1.5 Digital Agriculture

Digital agriculture is considered to be promising for overcoming some of the impediments that farmers have always been facing in agriculture; efficient access to relevant knowledge and sharing of information [5]. In the age of digitisation, information and communication technology (ICT) or digital farming can help to overcome some of the impediments and help farmers to better adapt to new threats like climate change [38]. In this context, smart farming [53] using ICT components is a promising solution to tackle some of this challenges and has been pushed recently by many national and international initiatives, with some progress in developing countries [6].

However, the use of ICT in agriculture does not always lead automatically to higher yields and profits for farmers. To be successful, the implementation of ICT initiatives needs to recognise the local context of capabilities and user needs, and it must recognise the problem of the gender digital divide which can drive marginal groups of smallholders into new digital poverty [94, 5].

Finally, ICT-based approaches are more cost-effective for monitoring and evaluation in agricultural development projects as compared to traditional approaches. Such ICT-based approaches often incorporate feedback mechanisms using short surveys, i.e. in mobile-phone applications, text-messages and interactive-voice-response (IVR) surveys, to collect information by asking structured and simple questions to farmers [69]. Farmers responses can then be linked to performance-based indicators in ICT systems for a digitised evaluation of development projects [55].

Chapter 2

Research Problem and Gaps

2.1 Climate change impact assessment on crop performance

In recent years, a substantial number of research papers have been published revealing the impact of climate change on agriculture [66]. Most of these research studies assess the threat of climate change for agriculture and food production on a global and regional scale [127, 164, 124, 151]. Although outputs of these studies are essential instruments for awareness building of policy and decision makers [25, 73], they are not suitable to communicate climate change risks to farmers [46]. Farmers perception is primarily shaped by variability-driven local change [123, 47]. Even more, results from global and regional climate change assessments are often not applicable to derive adaptation strategies for the most important spatial scale in agriculture, the community and farm level.

Also, future climate scenarios, mainly provided by the International Panel on Climate Change (IPCC), have limitations because of the coarse geographical and temporal scale of climate models [113] and because of uncertainties from variability between multi-model predictions [83]. Another relevant issue in agricultural impact assessment is incomplete historical weather data records, especially in developing countries [91, 114]. To tackle the limitations on available data, scientists use statistical downscaling methods [115], combined approaches of remote sensing data and historical climate records [140] and weather simulators [77], to provide consistent climate data for modelling.

A reasonable number of studies apply crop models (CMs) together with climate scenarios, i.e., a current climate baseline compared with future climate scenarios, to assess the climate change impact on crop performance [75, 52, 143, 41]. Universities and research centres mostly develop CMs, but they are focusing on food crops, i.e., cereals, legumes and root crops among others. For cash crops like coffee, cocoa or other crops that have not been in the focus of public funded research, advanced CMs models are not publicly available to climate change scientists.

As a consequence of missing CMs, studies often use empirical modelling approaches to evaluate the impact of climate change on crops [116]. Empirical approaches use ecological niche modelling [128, 21], apply a fuzzy logic approach on edaphoclimatic requirements [164], or use climate envelope models [62] to create a spatial distribution of a suitability index for each crop. A limitation of empirical approaches, however, is that these models can not provide information about the impact on productivity. Also, they can usually not disaggregate the impact based on abiotic factors and management practices, i.e., crop varieties, soil types and agronomic management. Thus, estimations of crop responses to climate change using climate information and empirical approaches are not enough to derive accurate adaptation strategies at the local level.

Despite the lack of accuracy of climate change impact assessments, impact gradients, and, consequently, required adaptation measures vary significantly between sites [24]. Therefore, practical adaptation actions require assessments of the spatial distribution of impact gradients that would need different pathways of adaptation [78, 117].

Gap 1: While many studies focus on the impact of climate change on agriculture and crops, few studies assess spatially differentiated impact gradients and translate them into actionable strategies for smallholders and possible adaptation pathways; there is a need to assess spatial accurate impact gradients and simulate options for adaptation strategies.

2.2 Perceptions of climate change

The next problem is that we do not understand well farmers' perception of climate change and how it is related to adoption rates of adaptation strategies [104]. Thus, the communication of impacts from climate change that requires adaptation of existing systems has been difficult for experts [101], because long-term predictions are not relevant for farmers [144]. The perception of facts that are far in distance and time is explained in the literature as the perceived psychological distance between impacts and individuals [142]. Farmers, especially in developing countries, are more affected by inter-annual climate variability and short-term risks like impacts from shocks, rather than long-term changes.

The success of climate change policies, however, relies on farmers' perception about risks from climate [108, 28] and how they see climate risks in the context of other risks in their livelihood system. There is a growing literature on how perceptions influence farmers' decision-making for up taking adaptation strategies [102]. Many of these studies focus on comparing meteorological data with peoples' memories of historical climate events [19]. They hypothesise that farmers' perceptions about climate risks are related to adaptive behaviour [68]. Thought agreeable, climate change research should integrate risk perceptions in the context of the farmers' livelihood system without focusing on climate risks only. Because in the context of smallholder farming in developing countries farmers are often exposed to multiple stressors, including climate risks, but not only. If multiple stressors act simultaneously on farmers' decision making, vulnerability is enhanced, and adaptive capacity to climate risks constraint [120].

Also, farmers might have different risk perceptions than experts, leading to significant consequences for the communication of adaptation policies. In other research areas than climate change, studies have shown that understanding the differences in risk perceptions between experts and farmers can be essential for risk communication and more critical to avoid policy failure [16]. Experts as climate change actors often promote the implementation of agricultural adaptation strategies as a top-down approach based on impact assessments [51], rather than employing a participatory bottom-up approach to understand perceptions and local dynamics. As a result, experts recommend *one fit all solutions* [43], and they do not take into account the local dynamics between livelihood capitals at the farm level.

Top-down policies are often impact-based, bottom-up approaches, in turn, focus on social domains like vulnerability, adaptive capacity or community needs [119, 51]. Experts should acknowledge that adaptation is a social process [1]. Thus, the social dimensions and enablers together with the relevant actors for implementation must be understood to make adaptation successful.

Gap 2: There is not enough knowledge about farmers' perception of climate risks and how it influences decision making under multiple stressors and composed dynamics between livelihood capitals in their livelihood system. Research is needed to understand farmers' perception of climate risks within the context of their livelihood system and how different farmers and experts perceptions are.

2.3 Monitoring and Evaluation of implementation

When it comes to the implementation of adaptation strategies, experts as implementers are facing several challenges, like, difficulties in defining what adaptation strategy should be in practice (spatial prioritisation), identifying what works where (spatial allocation), and tracking the implementation to show evidence of successful adaptation (spatial scaling). What experts need for efficient tracking of climate change adaptation are robust approaches for monitoring and evaluation (M&E). M&E in climate change adaptation should evaluate the efficacy of agricultural technologies, practices, services, and programs at multiple levels, from the local to the global level [88, 49]. To make that possible, M&E tools should offer continuous feedback, guidance for action, and more responsiveness to changes and emerging opportunities while testing and implementing adaptation strategies [54].

Traditional M&E approaches for agricultural development projects are costly [50] and can only cover a small sample of the target population. They are often not well fitted to measure adoption of adaptation strategies on a larger scale, including many farmers in the evaluation process. ICT provides low-cost possibilities for more appropriate M&E [69], including vast numbers of farmers in the M&E process. It is a promising concept to improve stakeholder participation for testing of new technologies and practices [146]. ICT can help to design the M&E framework for adaptation using performance-based indicators and tracking farmers' adoption of adaptation strategies. However, the success of ICT in climate change adaptation is not well studied. Moreover, the use of ICT in agricultural development projects is no guarantee to overcome the shortcomings that still exist for rural agricultural communities, like low ICT literacy and danger of provoking a new digital divide [94]. There needs to be more focus on studying the use of ICT for enabling the access to critical information for decision-making, coordinating actors, building and strengthening the social capital, improve communication between experts, implementers and farmers and disseminate experience for collective learning in the adaptation process [38].

Gap 3: Climate change adaptation is already happening in many places, but scaling of good practices often fails. Traditional approaches for monitoring and evaluation of implementing adaptation strategies are costly and not suitable for scaling. What is missing are new tools that allow cost-effective monitoring and evaluation of climate change adaptation strategies at scale.

Chapter 3

Objectives and Research Questions

To fill the research gaps described in the previous chapter the following objectives and research questions are relevant to this study:

3.1 First objective and research goal

Goal 1: Spatially assess impact-gradients and simulate crop yield of different options for adaptation.

The first objective was articulated to provide modelling approaches that can be used to identify the expected impact of climate change on agricultural crop systems, spatially differentiate impact gradients and simulate responses of adaptation options.

The following first two research questions for this objective were derived:

1. Where (location) are high-impact hot-spots of climate change?

2. How can crop yields for adaptation strategies be simulated in a model and outputs translated into actionable strategies for smallholders?

For the first objective, methods and procedures were developed and applied not only for the case study area in Colombia. They were used in several projects within the geographical scope of developing countries in the tropical south.

3.2 Second objective and research goal

Goal 2: Understand climate-risk perceptions of relevant actors and create a systemic view of multiple-risks in the farmers' livelihood system that may hinder the implementation of adaptation strategies.

The second objective examines mental models for understanding perceptions and the factors that enable adaptation and successful implementation of adaptation strategies.

The following research questions were shaped:

3. What are the differences in perception between experts and farmers on climate change risks in the farmers' livelihood system?

4. What factors on the farm level of the agricultural production system can influence decision making and may hinder the implementation of adaptation strategies?

These research questions were answered through a structured approach of applying different methods for risk perceptions in the context of climate change in the case study area in Colombia.

3.3 Third objective and research goal

Goal 3: Develop and test new tools for monitoring and evaluation to measure and track the evidence of farmers' adoption of adaptation strategies.

5. How can the implementation of adaptation strategies be monitored and evaluated using an ICT based approach?

6. Can ICT tools be a cost-effective and scalable alternative for monitoring and evaluation of the implementation of adaptation strategies compared to traditional approaches?

The third objective focused on research questions around the implementation of adaptation strategies and the urgent question how can evidence be built based on performance indicators and the employment of ICT tools for data collection.

Chapter 4

Study Area and Conceptual Framework

This section describes the geographical scope of the research and introduces to the case study region. It justifies the selection of the case study region and gives an overview of the conceptual framework used for this research.

4.1 Geographic Scope of research

Within the geographical scope of this research are regions in the tropical south, where the Research Program on Climate Change, Agriculture and Food Security (CCAFS) is addressing the increasing challenge of climate change and declining food security. CCAFS has developed the Climate-Smart Village (CSV) approach [79] as a means to agricultural research for development in the context of climate change. Action research on CSV sites seeks to fill knowledge gaps and stimulates scaling of Climate-Smart Agriculture (CSA) as a complementary approach to sustainable intensification of agricultural production [26]. This research study is relevant to several CCAFS regions (Latin America, East-Africa, and West-Africa: see Figure 4.1). Though some of the objectives were applied to different CSVs in all three regions; a more comprehensive case study was carried out in the Colombian CSV Cauca.

4.2 The case study region

For the case study in the Cauca department in Colombia, all three objectives were applied. Being geographically close to the Pacific Ocean, the region is subject to inter-annual climate variability mainly driven by the El Niño Southern Oscillation (ENSO) [112]. The CSV Cauca ranges from 1600 to 1800 masl, and major crops grown by smallholders in the study region are coffee (*Coffea arabica*), sugarcane (*Saccharum officinarum*), cassava (*Manihot esculenta*), maize (*Zea mays*), plantain (*Musa acuminata*) and common beans (*Phaseolus vulgaris*). For several decades, farmers in Cauca among other regions in Colombia suffered

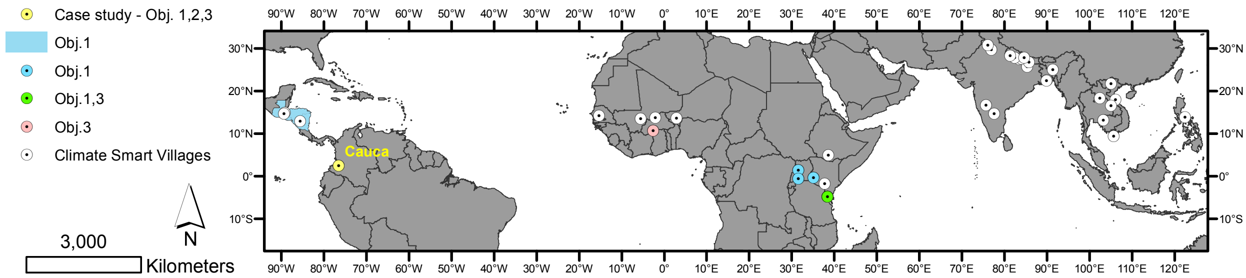

Figure 4.1: The geographic scope of research.

under armed conflicts; hence, the region is lacking behind in infrastructure development. Five villages from a rural community of the municipality of Popayan were selected for this study (see Figure 4.2).

4.3 Motivation for selecting the case study region

According to the last agricultural census [31], farmers in Cauca have a low education level, and 52 % live in poverty according to Colombia's multidimensional poverty index [130]. Based on data collected for this study, about 87% of farmers do not receive technical assistance, and only 11% have applied to formal credits in the past.

Cauca faces many risks for agriculture. The primary stressors alongside climate change acting simultaneously on smallholders are trade liberalisation and violent conflicts [44].

Another important reason for selecting Colombia and Cauca for the case study was a time coincidence of this study with the CCAFS program, starting its research and interventions in Latin Amerika in the same year. CCAFS started its first research activities in West-Africa, East-Africa and South-Asia back in 2011, activities in Latin America and South-East Asia started in the year 2014. The time coincidence was especially relevant for the second objective of understanding farmers' perceptions. An essential requirement for our study was that interventions from climate change researchers should not bias farmers. In fact, interviews with experts and farmers were carried out timely in summer 2014, a few month before CCAFS carried out its baseline surveys, introductory workshops and learning activities with farmer communities in the last quarter of the same year.

4.4 The General Framework for Human Environmental Systems

The conceptual framework of Human-Environmental Systems (HES) is the general framework for this research. The HES framework is a heuristic tool for structuring the complexity of human-environment relationships [133]. It uncovers structure (entities), processes

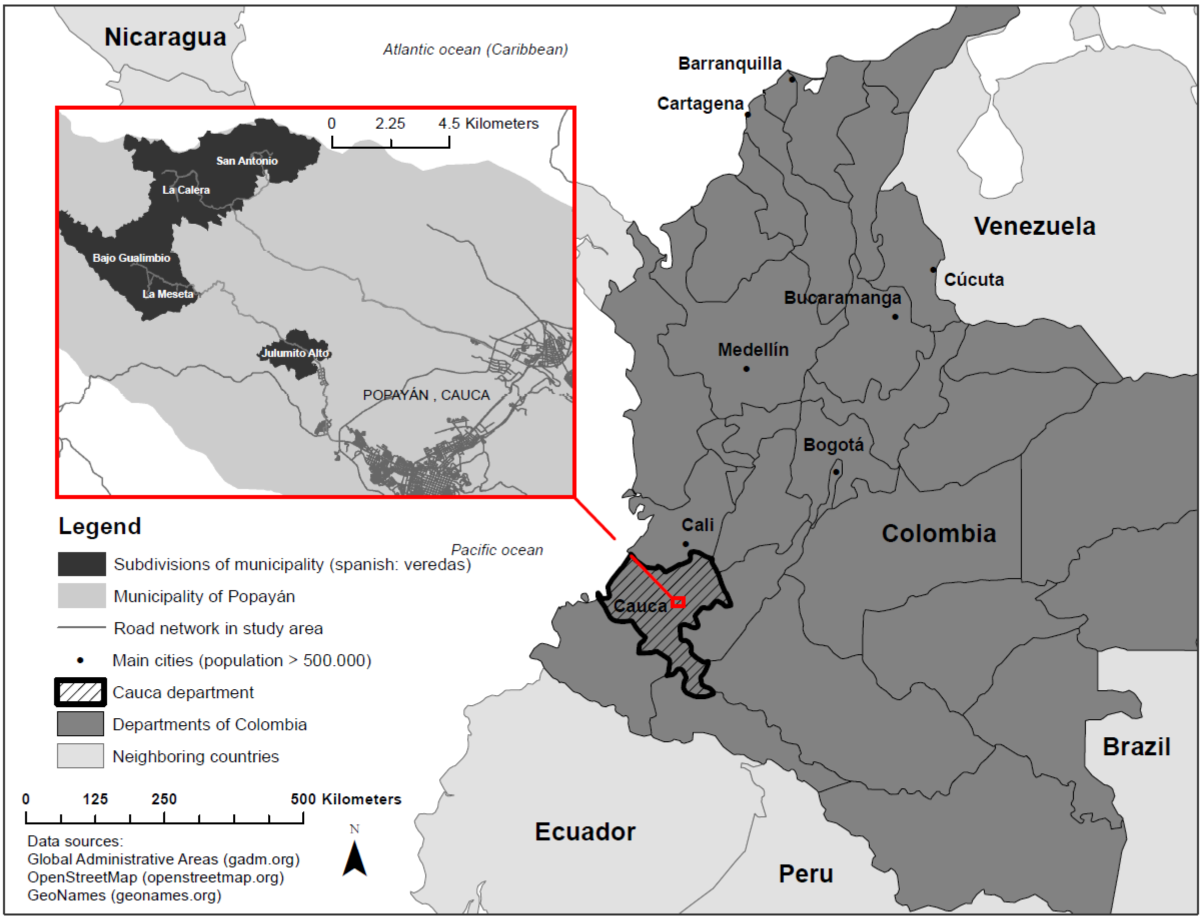

Figure 4.2: The case study area in Cauca Colombia.

leading to action (decision-making) and interactions, feedbacks, adaption, and learning of systems. The seven postulates in the HES framework act as guidelines for research projects and foster a comprehensive analysis of HES (Figure 4.3).

In the following, the seven postulates are described in the context of climate change adaptation.

Postulate 1 - Complementarity (P1): Human and environmental systems are two different, but complementary and interrelated systems. The HES systems development follows stages of pressure from human action that alter the state of the environmental system and affects both systems [134]. As a consequence, it requires adaptive behaviour by humans. HES is useful for vulnerability analysis and impact studies [157] where human decision-making is the critical factor to model systemic feedbacks between the two separate but coupled systems [57].

Postulate 2 - Hierarchy (P2): Hierarchical levels considered by [134] refer to hierarchies in which different systems exist at different levels. The HES framework differentiates between the level of the individual, group, organisation, institutions, society, and the

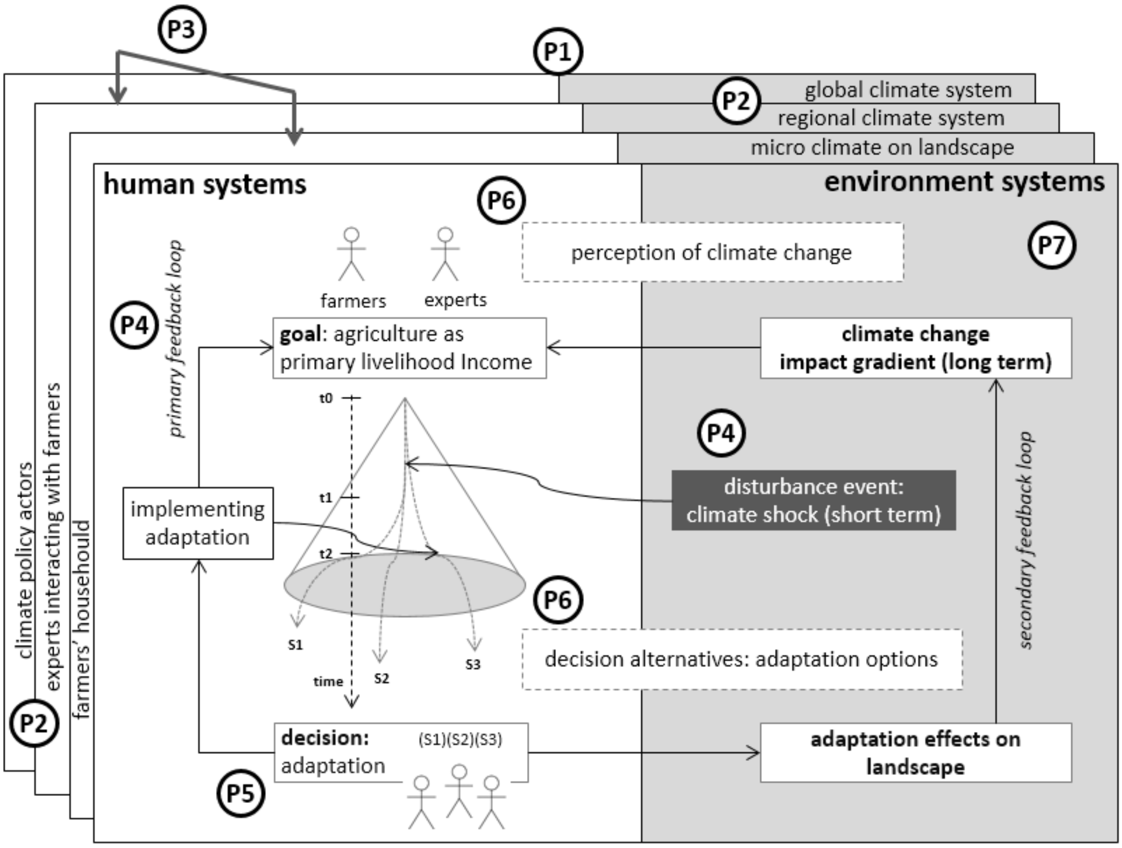

Figure 4.3: The Human-Environment System (HES) as a conceptual framework for this research. Adapted from[133].

supranational level. The level hierarchies are characterised both by downward and upward causation. For understanding the causal interactions between levels, the components and relationships among and between levels must be defined. In this research, the following three hierarchical levels are relevant for human systems in climate change adaptation. First, the individual farmer at the local level, secondly, experts from the regional level that interact with farmers, and third, actors at the policy level making decisions about relevant policies. For the environment system, the local climate variability was used for the first level, the regional climate represents the second level, and the earth climate system and its dynamics stands for the highest level.

Postulate 3 - Interference (P3): Climate change is a typical example of interferences between interests or regulatory mechanisms between levels. Interferences occur during decision-making and not through feedbacks from the systems. The research seeks to understand what differences in perceptions between levels (experts and farmers) can lead to differences in decision making and HES interferences.

Postulate 4 - Feedback (P4): In our HES system model of climate change adaptation (Figure 4.3), feedback loops are elements of thoughts to illustrate how the systems respond to decision-making. Although, primary feedback loops from decision making are goal-driven, based on cost-benefit decisions and easy to perceive by farmers, secondary feedback loops are more difficult to understand, even more, when farmers are focused on short-term goals. Farmers cannot often anticipate secondary feedback loops. However, they are coupled to primary feedback loops and manifest themselves as delayed environmental responses to changes in the human systems. As a consequence, adaptation is needed as a reaction to secondary feedback loops caused by human action in the past.

The promotion of CSA options as adaptation strategies leads to a win-win situation for the HES because of tackling both adaptation and mitigation in one strategy. CSA can sustainably increase productivity, make farmers resilient to climate shocks while reducing greenhouse gas emissions from agriculture where possible [89].

Postulate 5 - Decision (P5): Human systems consist of decision makers with goals and strategies. Goals and strategies can be selected according to preferences and different types of rationalities' in human systems. Humans make decisions based on their individual livelihood goals and beliefs concerning the likelihood of uncertain events and motives (internal factors). The individuals' psychological distance to climate change and perceptions about risks shape their decision making [144, 142]. Also, perceptions of actors at various levels in the HES system can be different and lead to influence on goals and strategies. Thus, it is essential to explore the social dimension of climate change in the HES [54] and to understand differences in risk perceptions [132] to promote the adoption of adaptation strategies and the implementation of climate-smart agriculture at the local level.

Postulate 6 - Awareness (P6): Awareness building is crucial to enable action against the climate change problem, mainly because of its long response time of secondary feedback loops. Humans are aware of causes and consequences of climate change in different ways: non-awareness, awareness as distant cause and impact, awareness of secondary feedback from the environment and need for adaptation, and, awareness of cause and impact including the need for adaptation and mitigation actions. Identifying types of farmers is needed to understand farmers' current choices and attitudes for supporting the implementation of adaptation strategies [65, 102].

Postulate 7 - Environment-first (P7): The last postulate of the HES framework [133] suggests to start with a comprehensive analysis of the environmental systems. The assessment of the material-biophysical environment helps first to understand the magnitude of potential climate change impacts and limits of environmental services before developing adaptation strategies.

In this research, the HES and its postulates are used as a conceptual framework and basis for the analysis for climate change adaptation of smallholders in developing countries in the following way: farmers are decision makers with the primary goal doing agriculture for livelihoods. Experts are actors influencing farmers in decision making and promote adaptation strategies, i.e., to practice climate-smart agriculture. Both, experts and farmers have perceptions about risks from climate change in HES. Farmers make decisions for adopting or not adopting adaptation strategies. This decision will have an impact on their livelihoods, e.g. increase production, become resilient to climate shocks or reduce emissions from their agricultural production. Awareness of long-term climate change, e.g. global warming, sea-level rise or shifts in rainfall patterns, and shocks from short-term climate variability, e.g. droughts, flooding or heavy rains, influences farmers' decision making. The different levels in the human and environmental systems are essential conditions for enabling the process of implementing strategies, like spatial distribution of impact gradients, the policy environment and different actors in the planning and implementation of local adaptation strategies (Figure 4.3).

Chapter 5

Methods and procedures

This study is embedded in the ongoing research activities of CCAFS, a strategic collaboration among 15 research centres to address challenges of global warming and food insecurity (for further infor see www.ccafs.cgiar.org. The CCAFS program started its activities in 2011 and created CSVs in different tropical regions including East Africa, West Africa, and South Asia. Each CSV sites represented the size of a 10 per 10-kilometre raster grid and was selected based on the climate change impact-gradient (see objective 1), socio-economic characteristics, and strategic research partnerships. They serve as a playground to implement CSA in collaboration between experts and farmers and benchmark future transformative changes in agriculture as a response to a changing climate [145]. In 2014, CCAFS added new CSVs in two regions, Latin America and South-East Asia. The CSV in Cauca Colombia in Latin America was selected for the more comprehensive case study.

The theoretical HES framework was used to frame the adaptation process in a dynamic, coupled system with feedback loops between the human and environment system, and interferences from different decision-makers. In Figure 5.1, we show a schematic representation of the HES framework and illustrate the methods that we applied during the research. Table 5.1 shows how research methods and publications are related to goals and the HES postulates.

5.1 Geospatial Simulation Modeling (GSM) for assessment of impact-gradients

For objective one of this research a widely tested series of simulation models for crop systems were used and applied spatially. Its routines were repeated for different spatial locations based on a regular raster. A method to identify spatial patterns and crop response variability under different management options was developed and used to identify hotspots (see Figure 5.2).

Research objective one was first applied to the region of Central America. Results and impact-gradients of long-term climate change were part of CCAFS selection of relevant sites for the CSVs in Central America. Second, methods of objective one were used to simulate

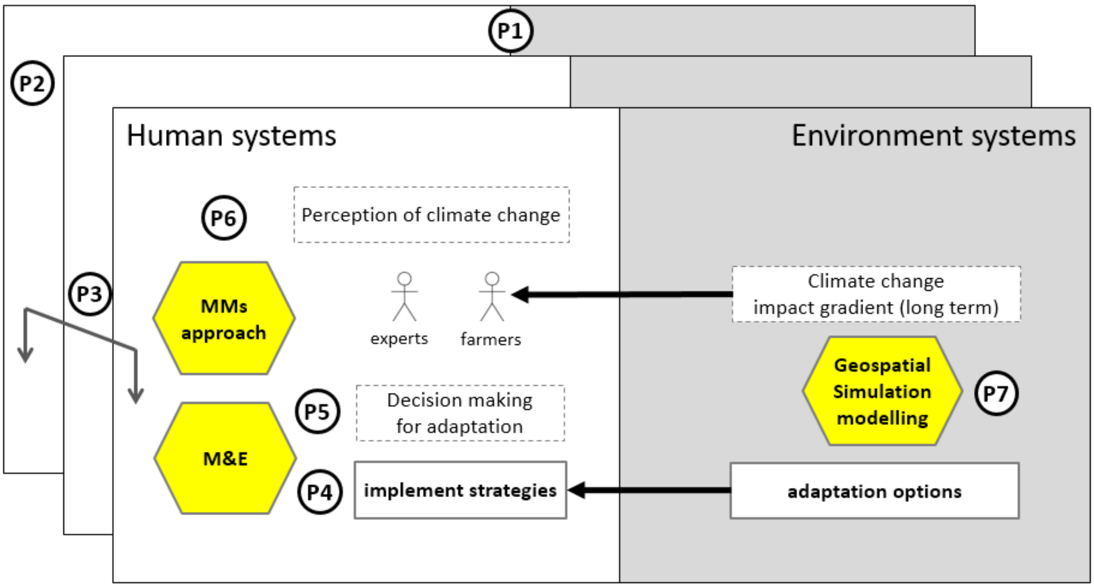

Figure 5.1: Research methods applied in the context of HES and climate change adaptation.

Phase	Goal	HES	Research methods	Publications
Obj.1	Spatial assess impact-gradients and simulate crop yield of different options for adaptation	(P1) (P2) (P7)	Simulation modelling using climate model predictions and crop models	Eitzinger et al., 2015; Eitzinger et al., submitted
Obj.2	Understand climate-risk perceptions of relevant actors and create a systemic view of multiple-risks in the farmers' livelihood system that may hinder the implementation of adaptation strategies.	(P1) (P2) (P5) (P6)	Interviews, qualitative and quantitative analysis, network of actors analysis, systems dynamics	Eitzinger et al., submitted; Eitzinger et al., submitted
Obj.3	Develop and test new tools for monitoring and evaluation to measure and track the evidence of farmers' adoption of adaptation strategies	(P3) (P4) (P5)	Indicator-based monitoring and evaluation, internet communication tools (ICT)	Eitzinger et al., submitted

Table 5.1: Overview of research methods and procedures

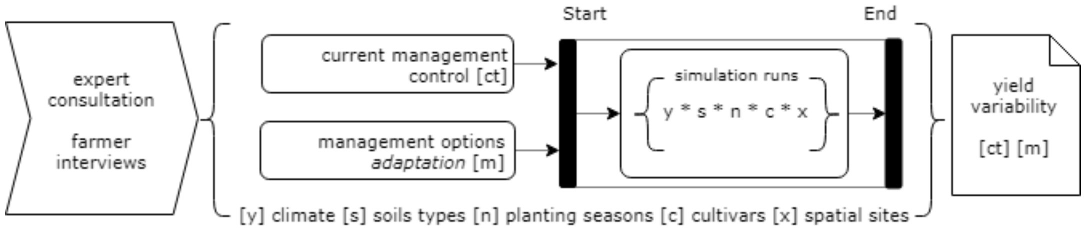

Figure 5.2: GSM modelling steps and simulations domains.

adaptation options simulated under a scenario of climate variability using historical climate data for East Africa.

5.1.1 Decision Support System for Agrotechnology Transfer (DSSAT)

DSSAT is a crop model that simulates all stages of plant development under prescribed or simulated management options [71, 63]. It uses specific sub-models for crop types. For this study, the sub-model BEANGRO [64] were used for dry beans (Phaseolus vulgaris L.), and the grain cereal simulation model CERES [23] for maize (Zea mays). DSSAT incorporates a detailed understanding of crop physiology, climate, soil and agronomy and simulates crop water balance, photosynthesis, growth, and development in a daily time step. Both sub-models BEANGRO and CERES have been validated many times, and they reflect the phenological development and yield of cultivars in DSSAT that have been calibrated by field experiments [27, 126, 106].

5.1.2 Climate data and climate model predictions

One of the main limitations to run the crop model DSSAT for regions in the tropics is data availability, especially climate data on daily time steps. Historical datasets from weather station networks often provide a monthly total of precipitation solely and mean monthly minimum and maximum temperature.

For the DSSAT simulations in Central America, the WorldClim database [60] were used to represent the current climate. For representing the future climates, a set of Global Circulation Models (GCMs) from the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR4) [137], downscaled to the same spatial resolution as WorldClim (30 arc seconds, approximately 1 kilometres), were used. For both current and future climate data, a final step of producing daily weather data using the MarkSim weather generator [76] was applied.

In East Africa, a high-resolution meteorological dataset [139] for a historical period of 27 years (1979-2005) was used to simulate climate variability. The dataset is based on reanalysis of rainfall data from the National Centers for Environmental Prediction (NCEP) and the National Center for Atmospheric Research (NCAR), merged monthly gridded temperature data from the University of East Anglia Climate Research Unit (CRU) and an elevation model from NASA Langley Surface Radiation Budget (SRB) (Sheffield et al. 2006). The dataset was available as downscaled data to 0.1-degree spatial resolution (approximately 10 kilometres) and was used in this study as daily climate data input for the DSSAT model without modification.

5.2 Using a Mental Model Approach to understand perceptions

A mental model approach (MM) was used to respond to the research questions from objective two. The research design followed the idea of a structured mental model approach (SMMA) by Binder and Schöll [16] and contextualised it for perceptions of climate change risks in the environment of multiple risks that farmers face in agriculture.

5.2.1 SMMA applied for climate change risk perceptions

The SMMA aims for understanding differences in perceptions between experts and farmers. Compared to other approaches used for analysing risk perceptions [97, 7, 34], it focuses on misunderstandings between experts and farmers, and it considers various risks in the farmers' livelihood system. Risks need to be studied as part of a livelihood systems dynamics [131], especially risks from climate events as they are not new to farmers and they are used to the short-term variability of climate. The SMMA combines the MM approach with the sustainable livelihood framework (SLF). It is described in [16], in brief, it suggests the following three steps:

- Define and rank livelihood capitals
- Analyze dynamics in the livelihood system
- Develop agent networks to define the social capital

In this study, four questions were developed to assess experts and farmers views on the farmers' concerns, risks, barriers to taking action, and enablers to take action. The following questions were asked of experts and farmers:

- What are farmers' main livelihood concerns?
- Which risks do farmers face in agricultural production?
- Which are farmers' barriers to adaptation to climate change?
- What enables (motivates) farmers to take action?

From the individual rankings of concerns, risks, barriers, and enablers, a weighted average based on the ranking of each element for the four questions was calculated. Then, the averages of experts' and farmers' rankings were compared. From a hierarchical clustering approach, typologies of risk perception were obtained from farmers' rankings.

The SLF concept [135] defines sustainable rural livelihood strategies depending on livelihood resources that consist of five different types of capitals, i.e., natural, human, physical, financial and social capital. In this study, the social capital was analysed by elaborating, visualising and comparing a farmers' actor-network with both groups, experts and farmers. The remaining capitals and its interactions were studied applying methods from systems dynamics [20, 154]. Concrete, a causal loop diagram (CLD) from farmers' explanations of interactions between capitals was developed. By applying the CLD approach [147], an integrative perspective of farmers' livelihood system was obtained, and the relationships between the different variables in the livelihood system were visualised. Studying the CLD, critical feedback loops were identified as positive (reinforcing) and negative (balancing) feedback loops influencing the livelihood system of farmers in the case study area Cauca.

Figure 5.3 presents the conceptual framework and methods for addressing research questions of objective two of this study. Farmers' perceptions regarding climate risks are shaped by their knowledge about the causes of climate change, their beliefs, social norms, and values and as well as through their experience with climate-related information and past events. Farmers have goals concerning their livelihood capitals and make decisions about investments and strategies. Based on perceptions, farmers will make decisions on adaptation strategies. In applying our approach, experts' external views of farmers' perception were captured and compared to the farmers' internal views. The interactions between capitals regarding the farmers' livelihood system were analysed.

5.2.2 Sampling and data collection

Qualitative semi-structured interviews were carried out to examine experts and farmers perceptions about farmers' livelihood risks and barriers for adaptation in the context of climate change. The interviews were carried out in three main steps. First, open interviews with 13 experts were carried out to obtain a holistic view of experts' perceptions. Second, based on the collected and ranked perceptions of experts, the farmer interviews were prepared. Third, 58 semi-structured interviews with farmers from five different villages in the municipality of Popayan were carried out.

5.3 Monitoring and Evaluation of climate change adaptation using ICT

The third objective of this research focuses on how the implementation of adaptation strategies can be monitored and efficiently evaluated [36]. Methods that are used in this objective include ICT tools for data collection and crowdsourcing of farmers' perceptions.

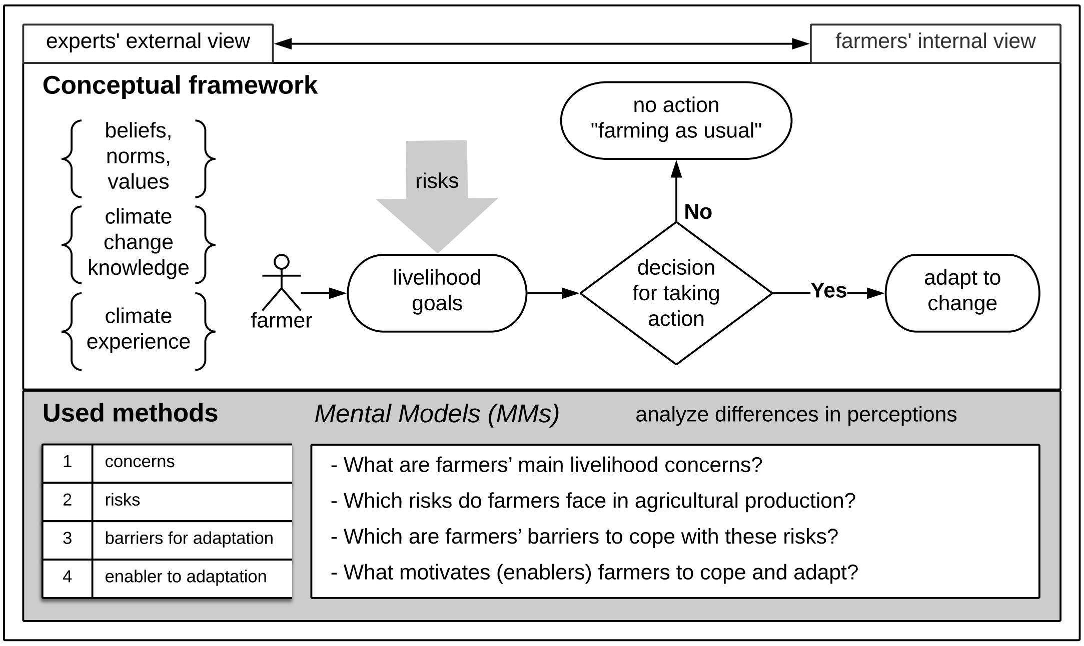

Figure 5.3: Overview of the conceptual framework and methods that were used to study the differences in perceptions between experts and farmers.

A prototype of an ICT application system was developed and tested to address the third objective of this research. The primary purpose of providing this system was to allow interactive feedback between farmers and experts in a spatial context. Using the system, farmers can report and communicate interactively with experts while adapting changes in technology and practices. Experts can use the system for cost-effective monitoring of ongoing implementations of adaptation strategies with farmers.

5.3.1 Development of ICT tools in the context of smallholder agriculture

The use of ICT-based approaches for M&E in agricultural development projects is more cost-effective as compared to employing traditional approaches. Such ICT-based approaches can incorporate feedback mechanisms using short surveys and build evidence in a structured way. Digital agriculture and ICT tools for data collection and knowledge transfer to farmers are considered to be promising for overcoming some of the impediments that farmers have always been facing in agriculture, i.e. the efficient access to relevant knowledge and sharing of information.

5.3.2 Development of a prototype as GeoFarmer application system

GeoFarmer was designed and developed based on the GeoCitizen framework, a geospatial system that allows for participatory community management based on a transparent and structured communication process [8]. The framework is applied as a social geoweb platform that combines social media with geospatial technologies allowing citizens to plan as a virtual community their living environment at a local level. In this study, the GeoCitizen framework and geospatial web-platform were adapted for the context of agriculture and climate change adaptation. For reasons of efficiency of code development and systems interoperability, GeoFarmer were integrated with the GeoCitizen geoweb platform, using existing modules that were modified to fit the purpose (Figure 5.4). Another reason to argue for building on an existing technological platform was that the technological platform development is not the primary goal of this research and was limited to a minimum.

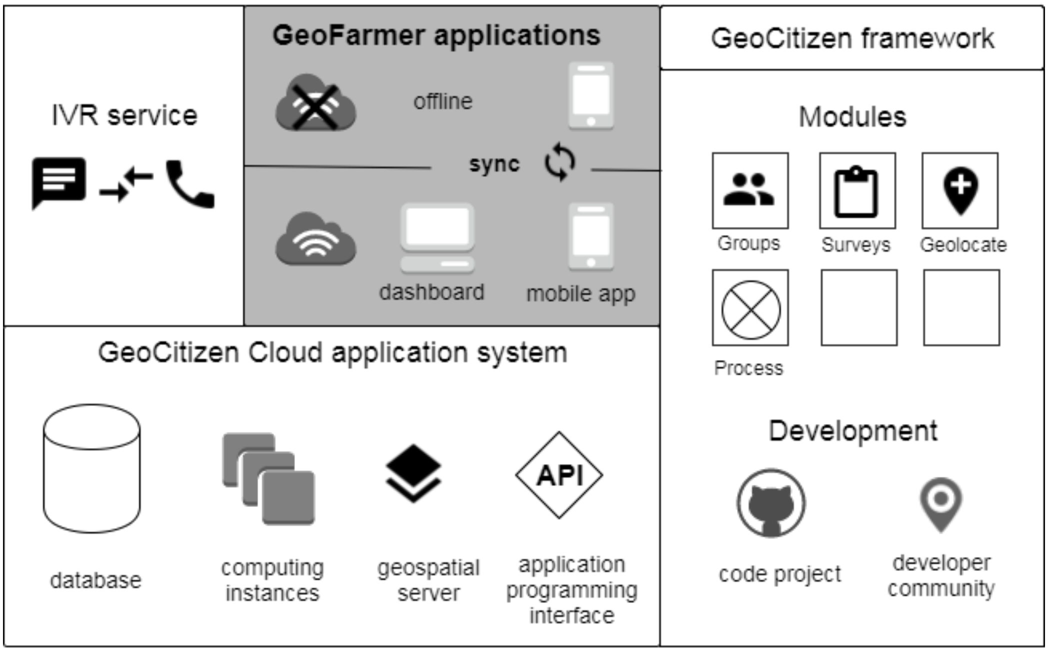

Figure 5.4: Overview of GeoFarmer application systems' architecture, developed based on the GeoCitizen framework.

The GeoFarmer prototype integrates different means of interaction (web-dashboard, a smartphone application, interactive-voice-response (IVR) call services and cloud-based backend for data integration). The platform enables interactive feedback in a spatial context between experts and farmers during the implementation of adaptation strategies and allows for active M&E of implementation and farmers adoption. The four main tasks of GeoFarmer are:

- Reporting

- Communicating
- Solving
- Monitoring

The following modules were designed on the GeoFarmer platform:

- Spatial collection of point-observations through LEF, VFT, and farmers
- Interactive feedback loops between experts and farmers as questions and answers
- Voting mechanism to make best practice knowledge for climate change adaptation evident
- Simple survey and data-collection tools for M&E of implemented adaptation strategies

In the design process, a use-case diagram was developed to relate functionalities, user interfaces, and user roles. Developers emphasised for simple functionalities for users that have a low level of ICT literacy. The design was implemented as code development of different modules, application components, and the systems' backend functionalities.

A systems performance evaluation of GeoFarmer were carried out and used to improve design and functionalities in an iterative process with experiences and field testing in four different pilots. The pilots were located within the geographical scope of this research and applied to projects implemented in the CCAFS CSVs; in Tanzania, Uganda, Colombia, and Ghana.

5.3.3 Performance evaluation of GeoFarmer

The system's performance was evaluated through transect-walks and field testing, training and use by LEF and VFT and carrying out surveys with farmers to measure perceptions and performance-based indicators that can build evidence of impact coming from implemented agricultural technologies and practices.

The different focuses of GeoFarmer in the four pilots were:

- 1st pilot in Lushoto in Tanzania: Training sessions were carried out with local experts (LEF and VFT) on how to use the application. The the first prototype of the smartphone application was evaluated in transect walks. In the following weeks after the training sessions and transect walks, LEFs registered farmers for further M&E activities and collected a demographic baseline survey with each of the registered farmers in face-to-face interviews. Finally, two IVR phone calls were operated with registered farmers at intervals of three months. The IVR calls were operated as simple surveys on automated phone calls in a crowdsourcing exercise. IVR surveys were using the concept of asking five simple questions in decision-tree structured questions around knowledge, attitudes and skill for practice (KAS), called the 5Q approach (Jarvis et al. 2015). The analysed data from surveys demonstrated perceptions and change of the adoption rate of CSA options at the CSV level.

- 2nd pilot: The primary focus of the second pilot in Nwoya Uganda was to repeat the first pilot and test the system in a different context. The site was characterised by lower ICT literacy of the farming community and low availability of mobile data network coverage (internet access). Quite the opposite to Lushoto, the Nwoya pilot was characterised by the low adoption of improved farming techniques on vast idle lands, low seed quality, and climate variability as critical challenges constraining agricultural production. The pilot was carried out with farmers from returning young generations of families that left the area twenty years ago because of the civil war in northern Uganda, with a low level of experience in farming.

- The 3rd pilot in Cauca Colombia: GeoFarmer was tested for crowdsourcing of farmers' perceptions about climate risks and decision making in the context of other risks in their livelihood systems. This pilot was linked to the second research objective and was applying parts of the farmer interviews that were first carried out with 58 farmers in five villages across the entire Cauca department. A total number of 1240 farmers in Cauca were included in the crowdsourcing exercise. The interviews were carried out as pre-recorded IVR calls and the same four questions from objective two about concerns, risks, barriers to taking action, and enablers to take action against risks were used.

- The 4th pilot in Jirapa-Lawra Ghana was implemented in one of the CCAFS CSVs in West Africa. In this pilot, new functionalities of GeoFarmer were tested, i.e., offline data collection with delayed data synchronisation and the systems' capacity to operate in a productive environment of complex decision-tree surveys (six surveys with total 546 questions) measuring performance based indicators more systematically.

Chapter 6

Results

This chapter emphasises the most relevant findings, sorted by the successive research objectives and questions (see chapter 3). The full research results can be found in the individual publications (see part II – Manuscripts).

6.1 Climate Change Impact-Hot-Spots

The first research objective focused on a comprehensive analysis of the environmental systems exposure to climate change (HES postulate 7) and the spatial distribution of impact gradients using a geospatial simulation model. It was addressed by responding to two research questions. The first question needed to resolve the spatial distribution of expected impact gradients from climate change on specific crop systems. The first research question was: **Where (location) are high-impact hotspots of climate change?** The answer to this question was provided in **Publication I** of this dissertation.

A simulation model for crop systems, the Decision Support System for Agrotechnology Transfer (DSSAT) model, was used and adapted by adding a programming routine, to spatially repeating its procedures of plant growth simulation on a regular raster. Both a current climate baseline and future multi-model predictions were used together with treatments of agronomic management and soil characteristics, for running the model. Results of yield differences (future yield minus current yield) were obtained as a geographical raster grid. Distance statistics were applied to identify significant outliers, and high-impact hot-spots (HIS) were classified in three different impact gradients:

- Adaptation spots, from pixels whose negative z-values of spatial association were equal to or greater than one standard deviation of the mean (68%)
- Hotspots, from pixels whose negative z-values were more significant than two standard deviations of the mean (95%).
- Pressure spots, from pixels whose positive z-values are higher than one standard deviation of the mean and lie outside the current zone of crop production.

6.1.1 Impact-Hot-Spots for dry beans in Central America

The modelling approach was applied for dry beans (Phaseolus vulgaris L.) and an area that covers four countries in Central America (Guatemala, Honduras, El Salvador and Nicaragua). The adaptation spots and the hotspots all lie within the areas that currently grow dry beans, while the pressure spots mostly lie outside them. Hotspots (red negative HISs) are concentrated from Lake Nicaragua to the northern coast of Honduras along the Central American dry corridor. Other areas currently used for dry beans cultivation and identified as positive HISs (green within the hatched areas) are promising for future development of dry bean production in the region, i.e., Guatemalan highlands, central areas of Nicaragua towards Atlantic coast to where bean production has already expanded in recent years. However, pressure spots are often close to the current agricultural frontier, and in this areas, it will cause social and political pressure to allow agriculture to migrate into these areas. Some of this area classified as pressure spots are areas currently occupied by other land use activities or even are areas under environmental protection (see Figure 6.1).

The second research question asked for translating the model outputs into actionable adaptation strategies that can be implemented by experts and farmers. The second research question was: **How can crop yields for adaptation strategies be simulated in a model and outputs translated into actionable strategies for smallholders?** The answer to this question was provided in **Publication I** and **Publication II** of this dissertation.

Simulation domains of different management options were defined in DSSAT as factorial arrangements of climate scenarios, soil types, different planting seasons, different crop cultivars and spatial sites, to respond the second research question. The necessary information for designing model treatments was obtained from expert consultations and farmer interviews. The model treatments design represented a farmers' conventional crop management (control) and selected management options as adaptation strategies. Yield variability for control and management options (Figure 5.2) were obtained from the model and used to derive actionable adaptation strategies. The modelling approach was applied for dry beans (Phaseolus vulgaris L.) in four countries of Central America and dry beans and maize (Zea mays) in four CSV sites in East Africa.

6.1.2 Simulated options for adaptation strategies in Central America

In consultation with experts, model parameters were defined for dry beans in Central America: First, the sowing windows was defined for three planting seasons (called Primera as first, Postrera as second and Apante as third planting season). Changing planting dates/seasons would be an adaptation option if other growing seasons were to give a yield advantage in future climates. Second, one cultivar and one breeding line were selected as representative cultivars commonly used in Central America. Next, two generic soils from the DSSAT model, medium sandy loam, and medium silt loam, were selected as repre-

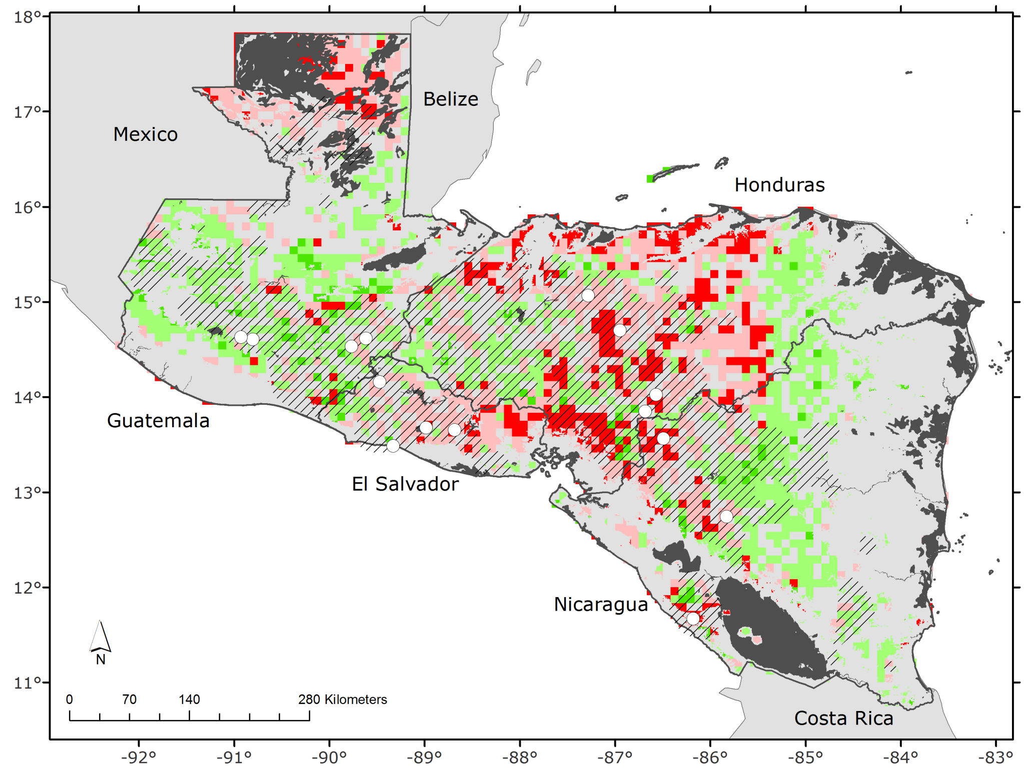

Figure 6.1: Outliers from yield change of dry beans in Central America in the first planting season (in Central America called Primera). Pressure spots are more than one standard deviation of the mean higher yield HIS (green), and hotspots are more than two standard deviations of the mean lower yield (red). Hatched areas are the main bean-growing areas; white points are the 15 selected bean production sites.

sentative for soils in Central America. Finally, three levels of fertiliser applications were simulated, no fertiliser application, fertiliser mix I and fertiliser mix II. All simulation options were run for current climate using worldclim data and future climate from downscaled CMIP3 multi-model predictions and daily weather data that were derived from monthly climate data using MarkSim (see section 5.1.2 for details on climate data) .

The design of simulation domains was, therefore:

$$\left\{ \text{ 2 y } \right\}\left\{ \text{ 3 n } \right\}\left\{ \text{ 2 c } \right\}\left\{ \text{ 2 s } \right\}\left\{ \text{ 3 m } \right\}$$

Where, y = years of climate, n = planting seasons, c = cultivars, s = soils and m = management option (fertilizer).

Findings for Central America show differences and yield variability for the selected management options (Figure 6.2) and comparison of alternative planting seasons (Table 6.1). Yields of Primera and Apante are likely to be more affected than Postrera planting season. Fertilizers give significant increases in yield, i.e., with no fertiliser option, yields were only 34% of those with F2.

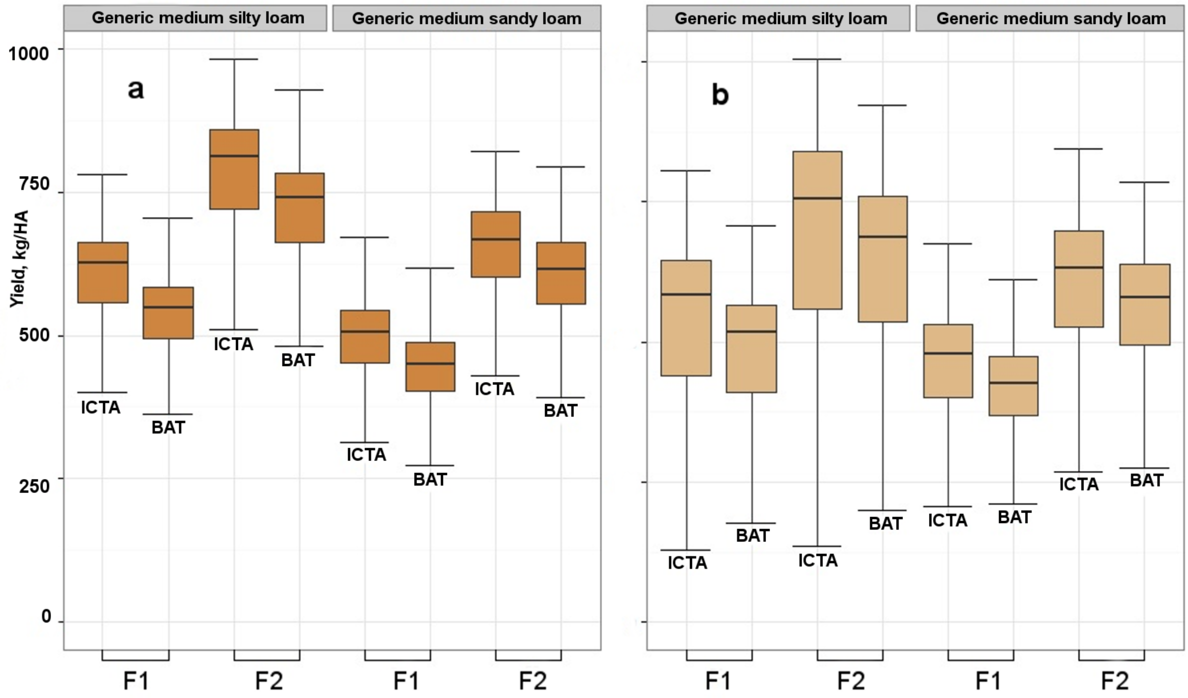

Figure 6.2: Yields from 4439 pixels in Central America for dry beans cultivars ICTA Ostua and BAT 1289 at two levels of fertiliser (F1, F2) and two soils (Generic medium silty loam, Generic medium sandy loam) with a current climate and b 2020s future.

Country	the average change in bean yield [%]		
	all municipalities	in municipalities accounting for 50% of total production	% of municipalities with expected yield loss gt 10%
El Salvador	-7 / -1 / -7	-6 / -1 / -10	33 / 0 / 25
Guatemala	+1 / +6 / -2	-2 / +5 / -8	10 / 0 / 20
Honduras	-9 / 0 / -4	-9 / -1 / -5	43 / 0 / 14
Nicaragua	-8 / +7 / -4	0 / +2 / -3	29 / 0 / 12

Table 6.1: Yield loss for the first season Primera, second season Postrera and third season Apante by country predicted for the 2020s.

6.1.3 Simulated options for adaptation strategies in East Africa

A similar modelling approach was applied in four different landscapes across East Africa: i) Lushoto in the Usambara Mountains in Tanzania, ii) Rakai in the Kagera basin in the southwestern region west of Lake Victoria, iii) Hoima in southwestern Uganda in the western part of the Great Rift Valley, and iv) Nwoya in northern Uganda. The DSSAT simulation framework was used to assess four different management options and compare them with a farmers' conventional crop management. For preparing the simulation domains, semi-structured surveys were carried out with experts and farmers. A total of 128 surveys were carried out in two sites, Lushoto in Tanzania and Hoima in Uganda. Compared to Central America where future multi-model predictions were used to compare yield variability between current and future climate scenarios, in this analysis data of 27 years (1979-2005) of historical climate (see section 5.1.2) were used to analyse current climate variability and how it affects yield levels. For soil variables, data from the Land Degradation Surveillance Framework (LDSF), a spatially stratified hierarchical sampling design aimed at assessing essential land and soil health metrics across diverse landscapes, were used. LDSF provided soil data at plot level for 16 samples each site and data could be used to calculate soil variables as input for DSSAT, instead of using generic soil characteristics like for Central America.

Four alternative management options as simulation domains were designed for the simulations: (i) organic fertilizer domain (OF), (ii) inorganic fertilizer domain (IF), (iii) combined organic and inorganic fertilizer domain (OI) and (iv) not taking into account the soil water balance by using the irrigation domain (IR). Finally, yield variability from the four management options was compared with yields from a farmers' conventional crop management (CT).

An example of findings is shown in Figure 6.3. Regarding dry bean yield variability and management options can be observed, that in Lushoto Tanzania in the first planting season (long rains) all management options reach yield levels above average (AA) in more than 50% of 27 years. The lowest level was 65% for CT and the highest of 82% of years for IR. Entirely the opposite can be observed for the second season (short rains) in Lushoto, where most years have yield levels below the average (BA), and no management option except IR can increase the number of years with average yield levels (AV) or AA yield levels.

In the other sites in Uganda (except Nwoya), the second season in Hoima and both seasons in Rakai, show a better model response to the other management options OF, IF and OI. Farmers' conventional crop management CT show for all sites higher share of BA years.

Findings show that yield response from management options vary between sites. Especially the combination of organic and inorganic fertiliser (OI) achieved highest yield levels for most sites and planting seasons. Based on this findings, specific recommendations for the four sites were developed:

Farmers in Lushoto Tanzania using OF, IF or OI as management option only improves yields of dry beans during the FPS (long rains). For dry beans in the SPS (short rains) as well as for both seasons of maize cultivation, the most effective management option in Lushoto would be IR. Variability between different soil domains in Lushoto was found to be higher than for the other three landscapes. Soil erosion and water availability are considered major limiting factors for crop growth according to the DSSAT model. Farmers need to implement soil conservation measures and increase water productivity on their farms to reduce the risk of years with potential low yields.

Simulations for Hoima and Rakai show that water is not the primary limiting factor for high yields, rather soil fertility. In Hoima, simulations of dry beans did not show a high response to management options in the FPS but indicate that all four options OF, IF, OI and IR would improve yield domains for the SPS. Simulations of maize yields show a high response to fertilisation. Especially OI would significantly increase AA years (up to 66% of AA years in FPS and 100% in SPS).

More findings for maize and yield variability related to soil types can be found in Publication II.

6.1.4 Crop exposure to climate risks in the case study area Cauca Colombia

The site selection of the CSV Colombia was carried out by CCAFS through vulnerability analysis, including impact assessment of climate change to cropping systems. The modelling approach using the DSSAT model was not applied for the case study area in Cauca, however, before starting our work of research objective two in Cauca, a crop exposure assessment was carried out using the empirical crop-niche-model Ecocrop. The modified model of the original Ecocrop approach [61, 42] is explained in Ramirez-Villegas [116]. Results of this impact assessment can be found in the Annex as online resource 1 of **Publication III**

6.2 Risk perceptions and decision making for adaptation

After assessing the biophysical exposure of farmers' crop production to climate change in the first research objective, enablers for farmers to adopt options to mitigate risks were examined. Thus, a mental models approach was used to understand differences in perception and systems dynamics were used to study dynamics in the farmers' livelihood system. The research objective was divided into two research questions; the third research question was: **What are the differences in perception between experts and farmers on climate change risks in the farmers' livelihood system?** The answer to this question was provided in **Publication III.**

Findings of analysing the mental models in Cauca show that experts and farmers perceived farmers' livelihood concerns and enablers for adaptation similarly, but risks and barriers to adaptation differently (see Figure 6.4). From a gender perspective, rankings showed that women more strongly agreed with experts than men. Women, much like experts, were worried about market opportunities and they ranked insufficient on-farm planning as a risk. Whereas men agreed with experts that insecure transport of products to the market is a risk and that adaptive capacity is a barrier to adaptation. Men saw economic interest as an enabler for adaptation; women ranked food security as an enabler for adaptation.

The cluster analysis of farmers' rankings revealed four typologies of farmers based on their perceptions:

- **Farmers are attributing risks to external factors:** These farmers are worried about poverty and lack of support from the government. They perceive critical risks for their future as their inadequate planning of farming activities and lack of access to social services from governmental programs. Their prerequisite is having access to weather forecasts to be able to adapt to climate change.

- **Production-focused farmers:** Such farmers are worried about having access to financial services. They perceive as the highest risks for them a failure in productivity due to uncontrollable factors, like pest and diseases, and they perceive to have low access to markets. Barriers to making changes to current agricultural practices are their low adaptive capacity and missing support from institutions. They are willing to adapt their current practices if the quality of life would improve for their families.

- **Vulnerable-anxious farmers:** This group of farmers in Cauca is worried about poverty and them seee risks in security-related issueses that affect their access to markets. Their barriers are a lack of access to formal credits and missing support from institutions. Motivations for adopting new practices are a traditional attachment to their land and region, and they want to improve their quality of life substantially.

- **Risk-aware farmers:** These farmers are worried about climate change, the lack of action by the government and increased insecurity from illegal mining activities in the region. As main risks, they see social vulnerability, and as barriers for adaptation, they ranked lack of access to weather and seasonal forecasts for planning their agricultural activities high. They feel traditionally attached to their land and also perceive their land to be suitable for agriculture.

For answering the fourth research question, the farmers' actors network was analysed as a significant element of the social capital for adaptation and a causal-loop diagram to identify feedback loops between the human, natural, physical and financial livelihood capital was developed. The fourth research question was: **What factors on the farm level of the agricultural production system can influence decision making and may hinder the implementation of adaptation strategies?** The answer to this question was provided in **Publication IV.**

Farmers in Cauca perceived actors from their social community network as being closer to themselves than actors from governmental institutions and actors from the agricultural value chain. Experts agreed with the view that actors from farmers' social community network were closest to farmers. However, they perceived actors from the agricultural value chain and governmental institutions closer to farmers than farmers themselves.

Smallholders' livelihood systems are complex, and they are characterised by interactions between livelihood capitals that often lead to unexpected feedback loops for farmers. In the causal-loop diagram of farmers' livelihood system in Cauca (Figure 6.5), interactions are shown as reinforcing and balancing feedback loops from experts and farmers explanations. Three main reinforcing feedback loops that were explained by farmers as interactions between human, financial, and physical capital were found. However, farmers did not see important interactions of the natural capital with the other livelihood capitals. The main and secondary feedback loops that control farmers' livelihood system in Cauca are:

- Perpetuating poverty loop (R1)
  - Opportunities for off-farm labour income (R2)
  - Assistance to training about farming practices (R3)
- Financial assets (R4)
  - Share of family labour compared to paid labour (B1)
- Farm productivity (R6)
  - Technological investment (R5)
  - Production risk control (B2)

6.3 Monitoring climate change adaptation using ICT tools

The third research objective focused on the implementation process of adaptation strategies at the local level. It reveals how evidence of successful implementation can be built up using geospatial technologies, ICT and modern M&E approaches. To answer both research questions of the third objective, a prototype application system called GeoFarmer was developed to explore interactive feedback in a spatial context between experts and farmers.

The fifth research question was: **How can the implementation of adaptation strategies be monitored and evaluated using an ICT based approach?** The answer to this question is provided in **Publication V.**

A use-case diagram (Figure 6.6) was developed drawing users interacting with the GeoFarmer application systems with means of interaction and use cases. Facilitators and farmers use the smartphone-application to register farmers (farmers can self-register as users), fill surveys, collect point information and participate in discussion processes with other farmers, facilitators and (often outside) experts. The role of the facilitators is to be a catalyst for farmers that are not using the system by themselves. A moderator is managing platform activities on a dashboard, he creates and administrates surveys and configures the GeoFarmer platform for specific projects and geographical sites.

Using the GeoFarmer on one of the four pilots in the CCAFS Tanzania CSV, farmers' adoption of the CSA practice manure compost was monitored for six months. After the demonstration/training session of the CSA practice carried out by the CCAFS team, 5Q feedback surveys [69] were carried out and KAS crowdsourced with farmers living in near villages. Data collection consisted of face-to-face surveys carried out by LEFs and operating automated IVR phone surveys with farmers (Figure 6.7).

The sixth research question was: **Can ICT tools be a cost-effective and scalable alternative for monitoring and evaluation of the implementation of adaptation strategies compared to traditional approaches?**

The answer to this question is provided in **Publication V.**

In the Colombian pilot, the GeoFarmer application system was used as a crowdsourcing tool to expand the range of farmers responding to the four questions (see section 5.2.1) on perceptions of climate risks in the context of other risks in the agricultural production system in Cauca. In total, 1,240 farmers in the Cauca department were reached using IVR calls through the GeoFarmer application system.

Running the pre-recorded surveys as parallel phone calls in the automated system took less than an hour (total duration of all single calls would be about 95 hours), the average call time per farmer was two minutes and 30 seconds, and the total operating costs of all calls were 511 US$.

Figure 6.8 shows the results of farmers' rankings of concerns, risks, barriers for and enablers to adaptation in Cauca. Comparing the results with Figure 10 from objective two (perceptions of farmers from five villages in the CSV Cauca in Popayan), it can be observed that farmers in Cauca rank access to credit first (third by farmers in CSV), while farmers in the CSV rank government policies first (third-ranked in Cauca). Poverty was ranked as a second concern by both farmers in the CSV in Popayan and the entire Cauca department. Regarding the risks in agriculture, farmers in Cauca rank unstable prices, and climate risks highest, while farmers in the CSV rank social vulnerability (lowest ranked in the Cauca department) and production failure highest (third-ranked as pest and diseases at department level). Rankings of barriers for adaptation were balanced at the department level with costs for adaptation ranked highest followed by weak institutional services. At the local CSV level, lack of climate forecasts and weak institutional services were ranked highest. For both the CSV and department level, the highest motivations and enablers to adaptation are family interests and improved quality of life.

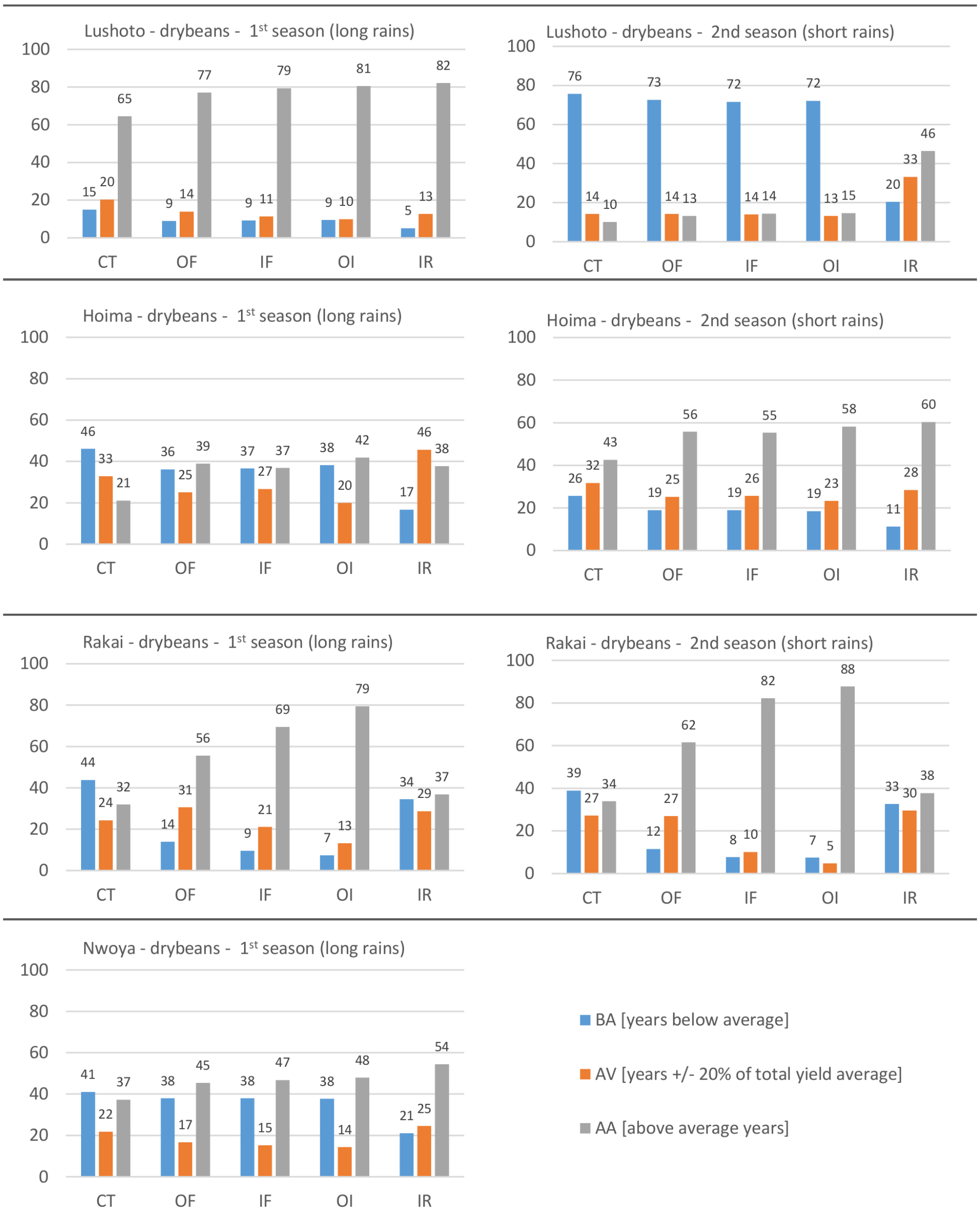

Figure 6.3: Yield domains show variability for different agronomic management practices of dry beans. AV is the percentage of years where DSSAT simulation outputs are within a range of +/-20% of the average of total simulation runs; BA is the percentage of years below, and AA is the percentage of years above the average AV. CT is simulated as control with farmers' typical agronomic management practices, for OF organic fertiliser was applied, for IF inorganic fertiliser and for OI both organic and inorganic fertiliser was applied in simulations. For IR, sufficient water availability during development (irrigation) was simulated.

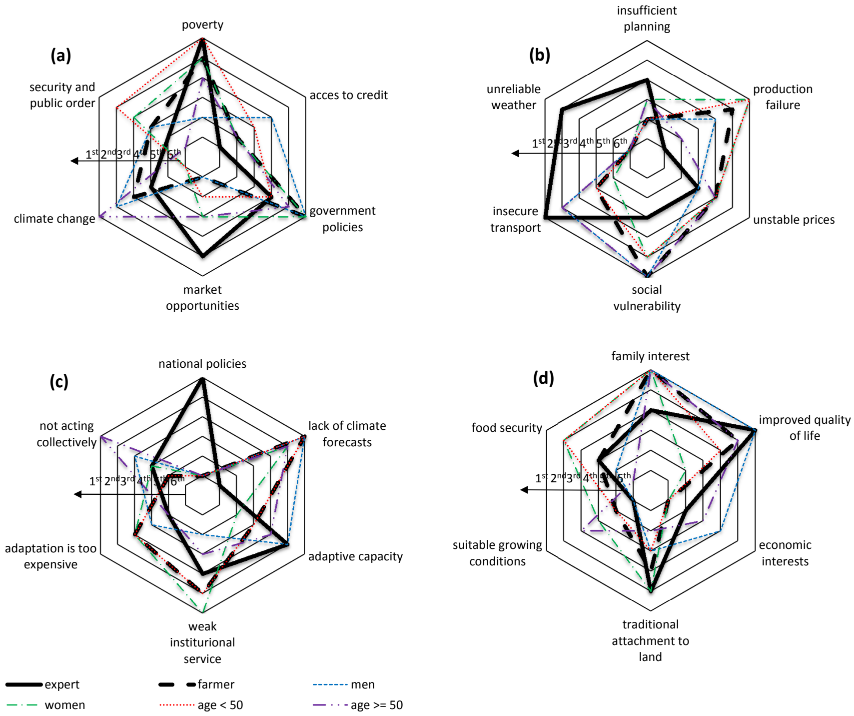

Figure 6.4: Differences in experts' (solid line) and farmers' (dashed line) rankings of farmers' (a) worries, (b) risks, (c) barriers to adaptation (d) enablers for adaptation. Rankings of male farmers (dashed blue line) and female farmers (dashed-dotted green line).

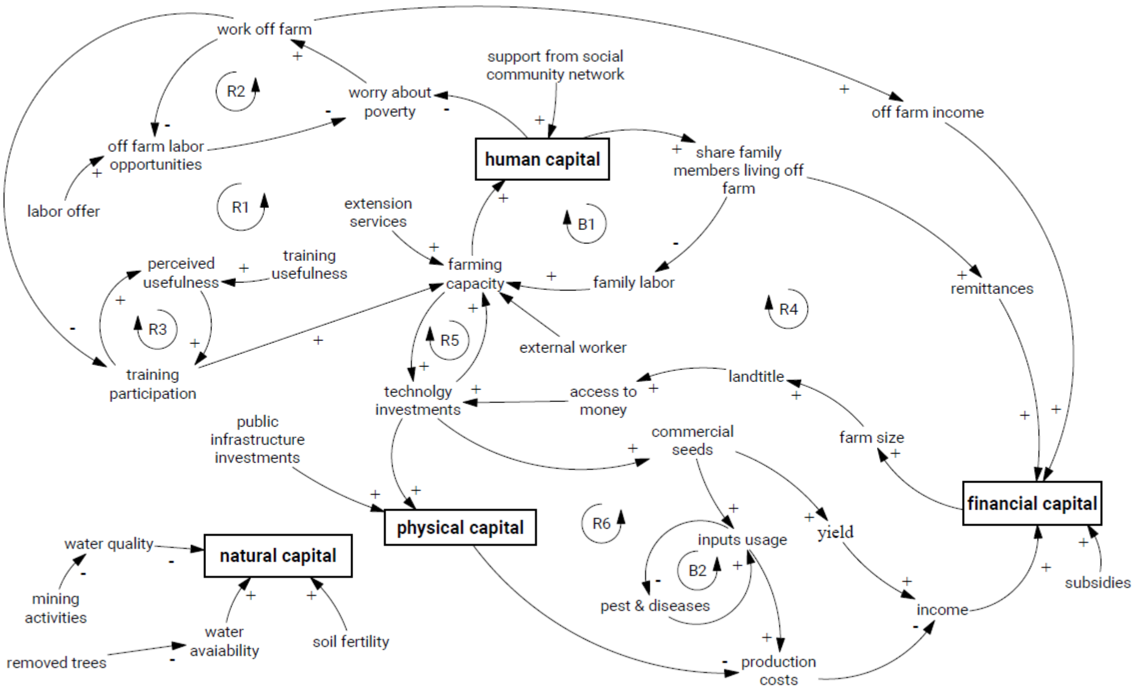

Figure 6.5: Perception of farmers in Cauca of livelihood dynamics, risks and feedback loops depicted as a causal-loop diagram. Balancing feedback loops are marked as B, and reinforcing feedback loops are marked as R.

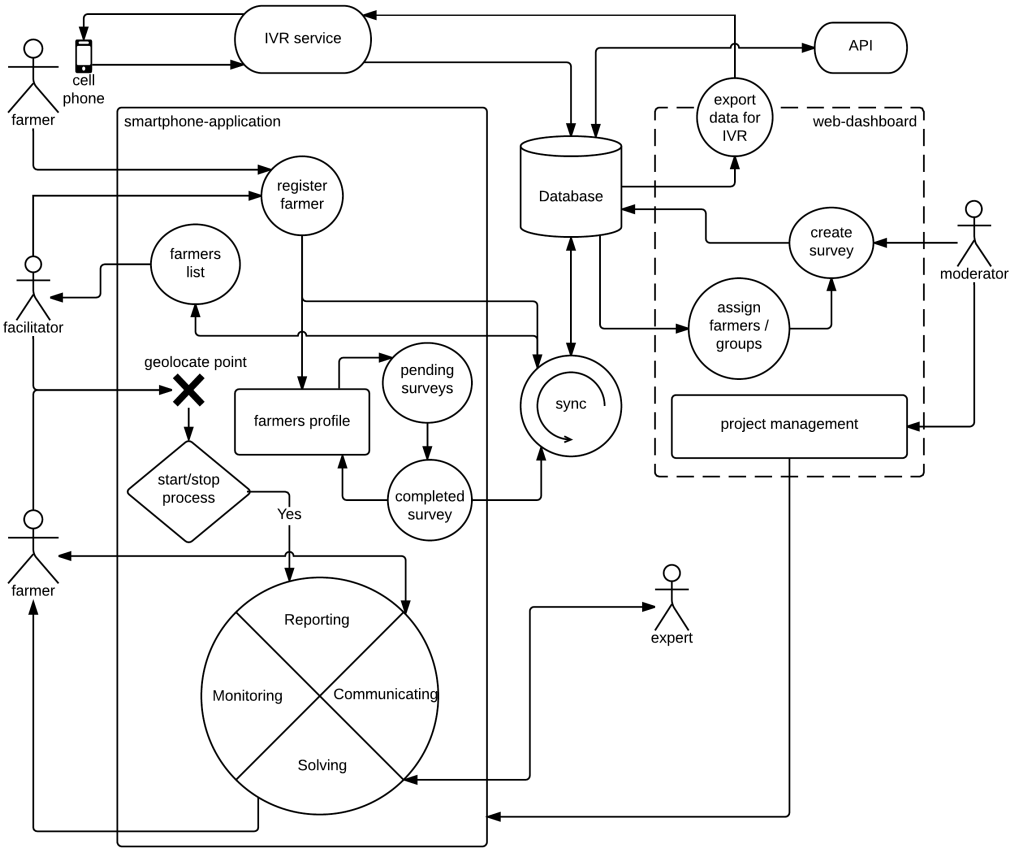

Figure 6.6: Use case diagram of GeoFarmer application systems, based on the GeoCitizen framework for monitoring of adaptation.

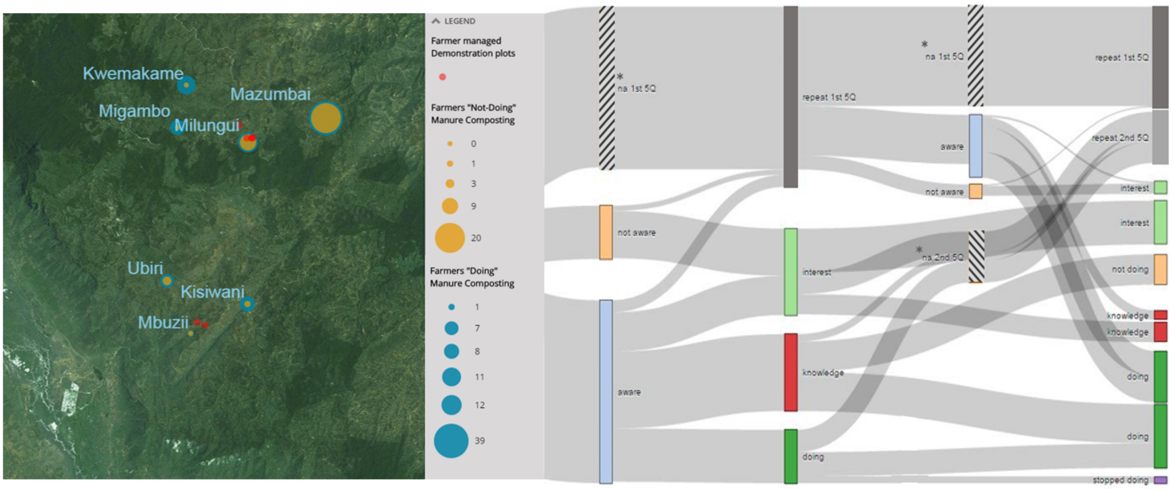

Figure 6.7: Farmers' adoption of the CSA practice manure compost in Lushoto. The diagram (on the right) shows the timeline of surveys carried out with 956 registered farmers in Lushoto. The first edge shows CSA awareness of farmers after the first survey. Edge two shows adoption of compost manure as KAS (knowledge, attitudes and skills for practice) and edge three and four show awareness and adoption rates after the second round of surveys after six months. The map (on the left) shows adopters and non-adopters of the CSA practice manure compost on the aggregated village level.

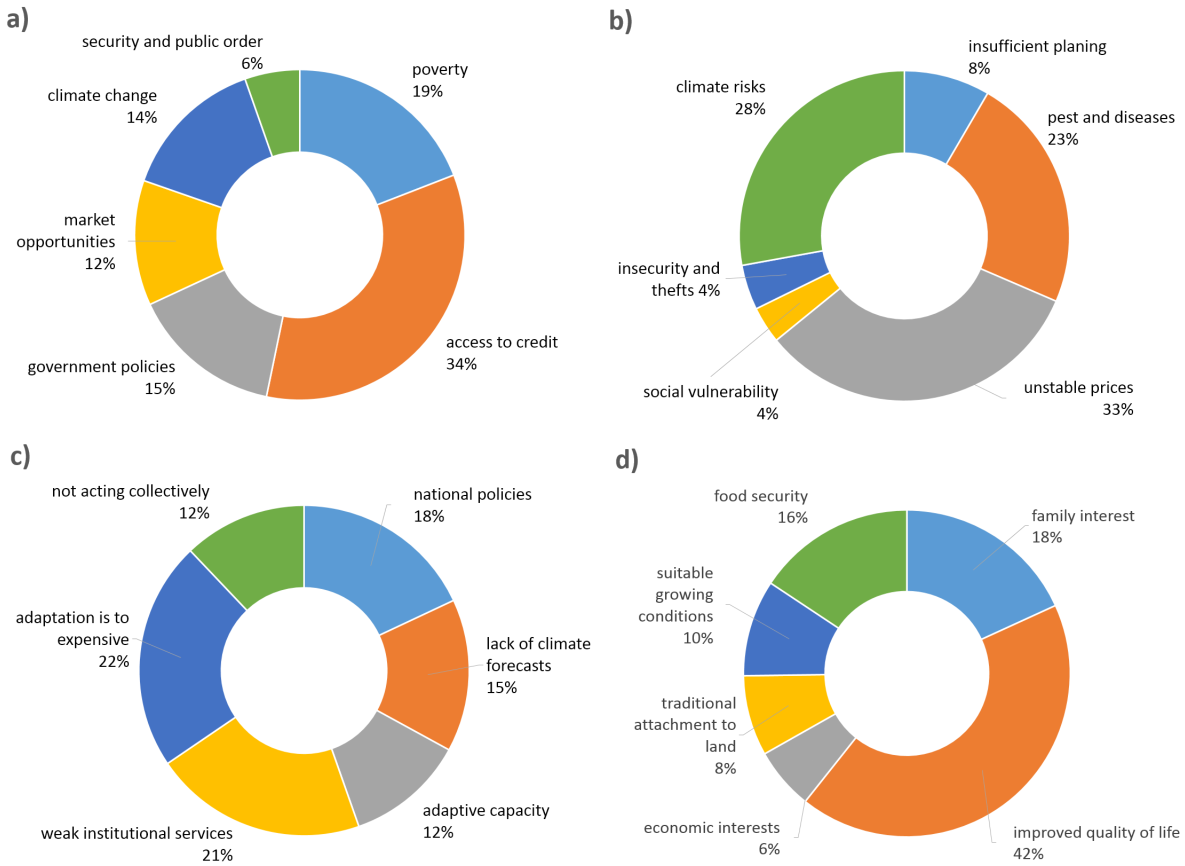

Figure 6.8: Results of crowdsourcing farmers' perceptions of climate risks through four questions: a) What are your main livelihood worries and concerns? b) What is the highest risk you face in agricultural production? c) What are the main barriers to the adaptation of coping strategies? d) What motivates you to adopt coping strategies?

Chapter 7

Discussion

This section discusses the relevance of the study for climate change adaptation (section 7.1), including the human environmental systems framework which was selected as a theoretical framework (section 7.2). Further, this section discusses the problem of climate change impact modelling for the local scale (section 7.3), the need of understanding perceptions (section 7.4), the importance of local actors in the co-creation process (section 7.5), and the need for rigorous monitoring and evaluation of adaptation (section 7.6). It presents strengths and weaknesses (section 7.7), and the issues which remain open, as well as recommendations for further research (section 7.8).

7.1 Relevance of findings for climate change adaptation

Climate change adaptation as science discipline is still emerging and the focus on science for adaptation (practice-oriented) and science of adaptation (understanding of the conditions for successful adaptation) needs a better balance [149]. In the future, adaptation science needs to be connected across scientific disciplines, and scholars need to couple science and practice and provide clear and simple stories for society; scientific results at the service of society [93, 18]. There is also a clear demand for collaborative and transdisciplinary research approaches, measurable progress in the form of outputs or outcomes, and learning and scaling-up of successful innovations [74]. The integrated approach presented in this study can partly fill this gap. It uses geospatial modelling to identify what are the biophysical constraints of adaptation options (spatial allocation of action), it provides a structured mental model approach to understand perceptions and who are the relevant actors for designing and implementing actions (understanding actors and adaptation processes), and it uses digital agriculture for communication, evidence-building and tracking of successful adaptation (feedback from co-learning).

The findings of this research are relevant for transdisciplinary processes of transferring scientific knowledge to local implementation of adaptation strategies, which requires interaction between science and society to achieve a sustainable transformation of HES [136, 93] under the threat of climate change. Same as in other studies [138, 119], it highlights the importance of community involvement in adaptation planning. However, Swart et al. [149] argue that a predominant focus on science for adaptation has some pitfalls, like putting untested heuristics to practice, using one-size-fits-all approaches and give scientists the role of problem-solvers. Thought, practical research is essential, but sustainable adaptation requires rigorous research for better understanding of the underlying theoretical frames and biophysical and social processes that would lead to better decision-making. Thus, climate change adaptation scientists need to be generalists and able to connect across disciplines [100, 74]; i.e. connect natural sciences and social sciences with applied science.

In the current climate change literature, adaptation is largely framed as policy intervention or a planned single action [40]. However, this interpretation of the adaptation concept has often been criticised in the scholarly literature [30, 40]. Climate adaptation is understood as actions taken by societies as they develop and change, the design of adaptation options should be done in a collaborative process, involving local actors in the development process of adaptation plans instead of operationalising adaptation measures top-down [160]. Also, successful adaptation comes from social processes [4]. Climate change adaptation practice has been criticised for lack of social science, instead, focusing on vulnerability assessments and intention to act, with little evidence of the extent to which adaptation is occurring, who is adapting and what drives adaptation [155].

Our integrated approach and findings support prior research on the importance of the social capital for the climate change adaptation process. Several authors frame adaptation as a social process [111, 72, 3], where the social capital facilitates collective action and trust [109]. Therefore, the findings suggest for the case study in Colombia, that local climate change adaptation plans should be designed using participatory bottom-up approaches to enhance the adaptive capacity of smallholders and they should be linked to top-down policies [17] without having dominant government agency representatives in the process.

Recently, real-world adaptations have increased rapidly, but evidence of successful cases is not well documented and cannot up-scale. Adaptation needs an integrated pathway-approach with coping strategies, systemic changes and options for transformative changes [117]. At first, it needs to address the socio-political roots of vulnerabilities and make a sustained effort over time [78, 12, 162]. Sustainability learning suggests to couple Human Information and Knowledge Systems (HIKS) with social-ecological systems (SES) dynamics [150]. Making adaptation socio-ecological sustainable requires to study the relation of the Human-environment system and build evidence from monitoring and evaluation of co-created and implemented strategies.

Several scholars call for re-framing adaptation science [99, 149, 40, 74, 155] to make it a more holistic approach. A key characteristic of adaptation science is that it has to be both, basic science including empirical evaluations and understanding of decision processes, and applied science that is problem focused and uses methods of co-creation between scientists and practitioners [99].

This research proposes using an integrated approach to study the adaptation process in a human-environment system, and to document human-environment interactions in spatial and temporal settings.

7.2 Appraisal of HES as a theoretical framework for climate change adaptation

The theoretical HES framework was used to frame the adaptation process in a dynamic, coupled system with feedback loops between the human and environment system, and interferences from different decision-makers. It provides a good starting point for understanding the complexity of the system, identifying research gaps and designing research questions. Prior research has not provided a thorough illustration of the use of the coupled human-environmental system for climate change adaptation research. Scholars used it for climate change vulnerability analysis [156] and systems dynamic modelling of expected systems change [57], but not explicitly to evaluate adaptation pathways and decision making in the context of multiple stressors in a HES. Findings of this study show that using the HES framework as integrated framework to combine approaches from spatial impact modelling, approaches for understanding mental models of decision-makers, and applied science tools for crowdsourcing and digital agriculture for monitoring and evaluation of the adaptation process, is novel and helps to integrate the components of adaptation, i.e. reduce socioeconomic vulnerability, address disaster risk, and support social-ecological resilience [155], in a holistic view.

As studying the HES is meant to start with a comprehensive analysis of the environmental systems (P7), our first objective focused on assessing the climate change impact on the cultural landscape, in our case study on smallholder farmers that are cultivating crops for their livelihood system. We used hotspot mapping to identify areas that are particularly vulnerable to future climate impacts [33], and show them as impacts from the secondary feedback of human interactions with the environmental system. The HES framework is especially useful to illustrate the hierarchy of causes and feedbacks coming from different levels of human interaction, and also that distant signals of initially global phenomena of climate change, e.g. melting of polar-ice-shields, changes of occurrence of ENSO events from changes in ocean temperatures, and among others, will impact local climates, and effect smallholders.

Once the environmental systems were analysed and the impact gradients and adaptation options identified, the coupled human systems (P1) needed to be understood, before bringing recommendations from scientific modelling and derived adaptation strategies to experts and farmers. Several authors recognise that the inherent complexity of decision making marks climate change adaptation at different levels and the occurrence of time-delayed feedback loops as risks across-scales [4, 45]. Primarily, the time-delay of feedback loops makes it difficult for people to anticipate the risks that are related to the variability-driven increase of extreme events and consequences from long-term shifts of climate patterns [148, 96]. Invisible and slowly progressing climate change as a risk makes it elusive for people [144], thus, understanding perceptions of climate risks is a priority in the adaptation process [99]. Because of delayed feedback loops (P4), potential impacts of climate change are difficult to perceive for individuals and actors at various levels (P2), and awareness and understanding for the need of action are heterogeneous among farmers and other actors that are part of the implementation process.

This study sought to made use of the mental models approach to understand perceptions as part of the HES. It examined differences in expert and farmers perceptions (P6) in the context of multiple risks in smallholder livelihood systems. Because ultimately, perceptions influence their decision making for adaptation (P5).

During the adaptation process, scientists and practitioners need to: i) assess vulnerabilities, ii) understand decision processes and information requirements of decision-makers, iii) improve knowledge about climate risks and relations to other stressors, iv) co-develop options to cope, change or transform the system, v) understand barriers and options for adaptation and select local-specific adaptation strategies; once the implementation process of adaptation is started, they need to: vi) monitor and evaluate ongoing experience from co-testing, vii) show evidence of successful adaptation based on performance indicators, and viii), document outputs and outcomes for development programs to up-scale adaptation.

Our findings show that the HES framework can provide a holistic framework to integrate models, approaches and fundamental concepts from different science disciplines into a single integrated framework for climate change adaptation.

7.3 The problem of the local scale for impact modelling

Similar to other work that focuses on climate change impact on crop production, we found limitations of data availability to make recommendations for adaptation planning on a regional or local scale [113, 84, 70]. A study by White [161] showed that many scholars use ecophysiological models to forecast potential impacts of climate change on current and future agricultural productivity. However, such assessments follow specific protocols and used approaches for model selection and vary to a certain extent, which increases the potential bias in projected impacts.

Though, most studies carry out climate change impact studies on crops on a global and regional scale and provide findings that are very useful for awareness building of policymakers at the regional and national level [75, 127]. Our modelling approach uses simulations to evaluate adaptation options that are linked to spatial units close to a local level. It is important to acknowledge that there are limitations of modelling results because they are cooked with uncertainties from climate multi-models, uncertainty from political emission pathways and lack of crop-model input-data for the tropics. Ramirez-Villegas and Challinor argue that using general circulation models (GCM) do not predict future climates well for particular sites, but can estimate conditions on a large scale. Thus, they cannot be used directly as input into plot-scale agriculture models. Higher resolution climate models can improve results if (i) models are matched in scale, (ii) the skill of the models is assessed and ways to create robust model ensembles are defined, (iii) uncertainty and model spread are quantified in a robust way, and (iv) decision-making in the context of uncertainty is fully understood [114].

In our study, we used GCMs for the HIS simulations in Central America on a regional scale and derived classification of impact-gradients that can be used for the development of national adaptation plans. For East Africa, we did not use GCMs. Instead, we used a high-resolution meteorological dataset generated from historical data to assess yield variability for crop management options on a 10-kilometre raster. The recommendations based on this findings can be used on the site level, in the case of this research study, for CCAFS CSVs, but not specifically for the farmer's plot level.

7.4 Why is it important to understand perceptions

In this study, we sought to understand differences of experts and farmers perceptions to risks from climate change in the context of multiple stressors in their livelihood system, and how it affects decision making for adaptation. It can be recognised in the growing literature on farmers' perception of climate risks, that most studies focus on climate risks only when they examine perceptions [68, 10, 85]. Morton explains why integrated analysis of risk is more suitable than an isolated analysis of climate change risks. He argues that farming systems of smallholders in the developing world are complex systems of location-specific characteristics integrating agricultural and non-agricultural livelihood strategies, which are vulnerable to a range of climate-related and other stressors [98]. Thus climate change should always be seen in the context of multiple stressors [95]. Looking solely at perceptions of climate risks can lead to misunderstanding of farmers mental models about climate change. An explanation for that statement in the literature is that farmers' long-term memory of climate events tend to decrease significantly after a few years; therefore, the importance of climate risks in farmers' perceptions may equally decline very quickly after disturbing climate events [22].

In the case of Cauca, inter-annual rainfall variability driven by the El Niño Southern Oscillation (ENSO) is high, and a challenge for farmers. The consequences of ENSO for farmers and agricultural production are prolonged droughts (El Niño) or intense rainfall over longer periods (La Niña). The assessment of the six most relevant crops in the study area revealed that variation in crop exposure to climate variability in Cauca is high. The mental model interviews were conducted in 2014, a year with ENSO neutral conditions, same as the two previous years. The comparison between experts and farmers perceptions showed clearly that farmers see the symptoms of social inequality (first rank of social vulnerability), agricultural production and market risks such as unstable prices or production failure. Contrastingly, the experts rather look at the root causes for the problem, i.e., insecurity and risks from climate. Farmers ranked climate risks low among their perceived risks in agricultural production, a perception that might change if the interviews would have taken place in a year affected by ENSO conditions. Our findings in the crowdsourcing experiment from 2016 showed that the perceptions of climate risks increase in years with stronger ENSO consequences for farmers, i.e. in 2016, with prolonged droughts and increased maximum temperatures.

Mental models (MMs) have been successfully employed in the past to study individuals' perceptions and compare perceptions between different groups of individuals [16, 131]. MMs provide an insight into perceptions and priority setting of individuals [97] and can help to understand risk perceptions and to inform the design of effective risk communication strategies. Findings in this study showed that in Cauca differences in experts' and farmers' perception and related farmers' concerns, risks, barriers and enablers for adaptation existed and could lead to miscommunication and consequently to a maladaptation to climate change. This was partly explained by the finding that experts agreed with farmers about main concerns for farmers, but disagreed about risks and barriers for adaptation, thus suggesting that the same view on a problem might not necessarily lead to similar action propositions.

Especially for countries like Colombia, where multiple stressors and rooted causes of social vulnerability act simultaneously on farmers' decision making, adaptive capacity to climate risks are constraint [120]. In Colombia, climate change, trade liberalization, and violent conflicts act simultaneously on farmers' livelihoods, but policies address them separately [44]. Thus, interdependencies require a systemic perspective on farmers' risks. If the implementation of policy actions is not coordinated, they might hinder each other or lead to failure. Understanding differences between experts and farmers mental models about risks is a first step to better design adequate policy actions for adaptation. An integrated view on perceptions and decision-making, presented in this study, might better capture the multitude of stressors for farmers, and the need for developing adaptation policies that are articulated to multiple stressors and targeted to farmers needs.

7.5 The importance of co-creation with local actors

Results from objective two demonstrate the importance of local actors in the development process of adaptation plans instead of implementing them top-down with dominating policies; an insight that is consistent with other work [86, 160]. The results suggest further that farmers trust local actors more and that understanding of farmers' perception of local institutions is essential to building adaptive capacity [13].

In particular, our findings in the case of Colombia suggest that actors from the social community network such as the members of the board of community leaders are the principal actors within the farmers' actors' network and should be included when developing adaptation strategies. Many studies have highlighted the importance of participatory work in climate change adaptation [110, 153], for example as community-based adaptation or co-creation of knowledge [93, 81]. Our findings in the case study Cauca underline the fact that community-based bottom-up approaches are often more likely to be successful in the implementation of adaptation strategies [119]. However, they need to be linked to policies [163] and monitored and evaluated by outside experts about their performance and possibilities for upscaling [29].

7.6 Need for better monitoring and evaluation of the adaptation process

If the HES framework is applied for the context of climate change, the adaptation process in the human system is a primary feedback loop as a reaction to the rebound of the environmental system, while the environmental reaction is a secondary feedback loop that was triggered by past human or natural cause. The primary feedback loop of the implementation of adaptation strategies alters the coupled human-environmental system and leads to more feedback loops. To better understand feedback loops, including their impacts on both human and environmental systems, there is a need for monitoring and evaluation of the process of implementing adaptation strategies and changes in farmers' vulnerability and resilience to risks from climate change. In objective three of this research, we focused on M&E approaches that can be used to measure the change of perceptions, adoption and indicators for trade-offs between productivity, farm resilience and agricultural emissions within the geographical scope of intervention.

The development of ICT tools for M&E in objective three is a first step to improve responsiveness and cost-effectiveness of M&E in the adaptation process [88, 36]. Most important for climate change adaptation, the application of M&E should include performance-based indicators, and it should be able to measures changes over space and time [55]. Tools for monitoring and evaluation should be capable of capturing different system levels of adaptation; collecting indicators at the farm level, perceptions at the community level, and enable processes of knowledge sharing through a network of actors at the global level and in between sites. Local expert facilitators (LEF) and volunteer farmer trainers (VFT) are playing a crucial role in the adaptation process and as facilitators for knowledge sharing. They are complementary to formal extension services [80]. Finally, several studies claim that tracking of the adaptation process is still insufficient in the current state of adaptation planning (Ford et al. 2015), findings and tools developed in this study might contribute to filling this gap.

7.7 Strengths and weaknesses of the approach

Besides the benefits of using the HES framework as an integrated framework to combine different approaches for understanding the adaptation process, there are also caveats that need consideration.

A strength of using the HES framework for the climate change adaptation process is to get a holistic view of how causes are related to effects in the human environment system. It provides a theoretical and conceptual understanding of decision making and the adaptation process. Thus, it provides a systems view of the ongoing adaptation process instead of linear thinking that starts with identifying a vulnerability and providing a single action as a solution. Instead, the HES framework helps to understand decision-making, feedback loops and the interlinked causes and effects between human and environment systems.

While the HES is helpful to frame relevant adaptation science and essential requirements, like understanding decision-making, identifying vulnerabilities, improves the foresight for stressors, and identifies barriers and develops adaptation options, as suggested by Moss [99], there are still gaps in applying theoretical frameworks and tools in policy and practice [100]. Also, it does not help to clarify the fundamental concepts of adaptation which are still inconsistent in the literature. Several authors discuss challenges of the emerging adaptation science, like missing a common theoretical language [100, 105], or inability to conceptually disentangle adaptation to climate change from adaptation to environmental change, and that we do not know how to evaluate adaptation successfully [149]. A weakness of using the HES framework is that it is more useful for the conceptual understanding of adaptation (the science of adaptation), but not for practice-oriented research (science for adaptation).

Though the HES framework serves as a holistic framework; it needs to be integrated with approaches and methods that can address the caveats mentioned above. In this work, we integrated several approaches into the HES framework to show the usefulness of an integrated approach to studying climate change adaptation. This work does not claim that these approaches are the best ones. Instead, it demonstrates the usefulness of the HES framework for adaptation science and stimulates to integrate other approaches.

7.8 Open issues for further research

There are also several issues which remain open after this research and needed to be followed up:

The first issue concerns the lack of available data and uncertainty of climate models that are used as input data for geospatial simulation modelling. Notwithstanding that this issue is well known and discussed in the literature, there must be more effort to close the data gap for studies in tropical regions. Often, the data are not usable because of missing shared data-infrastructures and interoperability of collected data from different sources, a restrained data sharing culture in many countries and lack of data update. Insufficient availability of data in developing countries include historical climate information, soil characteristics at the farm- and plot-level, systematic information about farmers crop management and practices; data quality and reliability is a further issue for modelling.

Better data availability could be achieved by involving farmers in field experiments as citizen science project, see [159, 152]. Having such a citizen science process started, volunteer farmers who participate in adaptation planning processes could collect and share data, or participate in simple modelling tasks as a citizen scientist.

The second issue concerns the representativeness of the case study in Cauca Colombia to understand how climate risks are integrated into the context of other risks in the farmers' decision-making process. We compared the experts' with the farmers' view and differentiated between concerns, risks, and barriers for, and enablers to adaptation. Though farmers in Cauca have relatively similar beliefs; the findings would be better sustained by repeating the mental model approach in more regions of Colombia.

By using digital agriculture, doing the rankings of risks through cost-effective ICT tools like interactive-voice-response (IVR) calls or engaging youth farmers to collect perceptions from farmers using surveys in mobile phone applications, this caveat could partly be overcome. In objective three we have tested such an approach successfully in the Cauca department with a higher number of farmers as we did in the farmer's interviews in objective two.

Future research could also use the outputs from mental models, typologies from clusters of farmers' rankings, and the developed causal-loop diagram of the farmers' livelihood system and develop an Agent-based model to simulate feedback loops in the HES. Such a model could be combined with choice experiments with farmers about adaptation options and simulate changes in the HES over time.

In the age of digital agriculture, there are new innovative ICT approaches and concepts that are now available to be used in rural areas of developing countries, like using crowdsourcing methods for monitoring and evaluation, or gamification elements in mobile phone applications with youth farmers for scaling the idea of two-way feedback loops of the GeoFarmer application that were presented in objective three. Further, gamification and role-playing game elements could be used to better communicate the scientific knowledge about climate change impact to farmers. Practitioners in participatory workshops with farmers often struggle in explaining scientific knowledge about possible climate change impacts to farmers.

Economic games have been used in land use planning and could be tested for climate change adaptation planning at the community level. Farmer typologies of similar perceptions, identified under objective two in this study, could be used to form focal groups and examine differences in decision making for adaptation, using game elements.

Finally, the GeoFarmer application system was designed as a prototype and needs to be further evaluated and improved. Initially, it was designed for two-way feedback loops between experts and farmers during the process of implementing and testing new practices. However, for monitoring and evaluation of the implementation of CSA options on CCAFS CSVs, this study only achieved to evaluate the tool for data collection and one-way information flow, from farmers to experts. The next step in evaluating GeoFarmer should be stimulating interactive feedback between experts and farmers and test the usability of ICT and digital agriculture for interactive, participative processes in climate change adaptation.

Chapter 8

Conclusion

Climate change is one of the significant issues concerning science and society, hitting economic livelihoods in developing countries hardest. Sustainable adaptation of smallholder agriculture in these countries requires new knowledge about impact-gradients, what type of adaptation strategies are needed and what shapes decision making for the adoption of adaptation options, because options chosen by farmers will alter the state of the coupled human-environmental system.

The next problem is, that for many people climate change is psychologically a distant problem, especially when they face multiple stressors in their livelihood system, they will put less attention to climate change. Thus, understanding the difference of perceptions of all actors that are relevant in the implementation of adaptation strategies, is crucial for successful adaptation on the most important spatial scale in agriculture, the community and farm level.

This research has demonstrated how needs to bring scientific knowledge to practical implementation on the local level can be better understood. It used the human-environment systems framework as a starting point and to structure the multidisciplinary research. Following the Environment-first postulate of HES, it started with a comprehensive analysis of the climate change impact on the environmental system and derived spatial accurate adaptation options for the farmers' cultural landscape.

Next, it contributed to better understanding of what influences decision making for adaptation at the local level, where farmers interact with different expert actors. Also, by capturing dynamics between elements of livelihood capitals, it illustrated the importance of understanding the farmers' complex livelihood system, which is composed of multiple risks and stressors that might hinder the perception of climate change risks. Therefore, this research highlights the importance of the social capital and to identify the relevant actors for the development of local adaptation plans.

Also, it provided new tools of digital agriculture that allow cost-effective monitoring and evaluation of climate change adaptation strategies at scale. The GeoFarmer application system was developed and evaluated on four pilots in three tropical regions where experts together with farmers test and implement climate-smart agriculture practices.

In conclusion, this research demonstrated that the sustainable implementation of adaptation strategies by smallholders could not be captured with one approach or tool. Instead, successful adaptation to climate change is a mix of identifying what works where (spatial allocation), understanding why (actors of implementation) and how can it be implemented on the scale (spatial adoption). It calls for transdisciplinary processes of transferring scientific knowledge to local implementers and tracking of adoption of practices and technologies by farmers. Tools for monitoring and evaluation should be capable of capturing different system levels of adaptation; collecting indicators at the farm level, perceptions at the community level, and enable processes of knowledge sharing through a network of actors at the global level and in between sites.

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Part II

Part TWO: Manuscripts

List of Manuscripts

Publication I

Anton Eitzinger, Peter R. Läderach, Beatriz Rodriguez, Myles Fisher, Stephan E. Beebe, Kai Sonder, Axel Schmidt. Assessing high-impact spots of climate change: spatial yield simulations with Decision Support System for Agrotechnology Transfer (DSSAT) model. Mitig Adapt Strateg Glob Chang. Mitigation and Adaptation Strategies for Global Change; 2017; 22:743-760. doi:10.1007/s11027-015-9696-2

Publication II

Anton Eitzinger, Beatriz Rodriguez, Leigh A. Winowiecki, Caroline Mwongera, Peter R. Läderach. Assessing crop response variability under different climate and soil domains across East Africa. PLOS ONE. in review.

Publication III

Anton Eitzinger, Claudia R. Binder, Markus A. Meyer. Risk perception and decision-making: do farmers consider risks from climate change?. Clim Change. Climatic Change; 2018; 151:507–524. doi:10.1007/s10584-018-2320-1

Publication IV

Eitzinger, A., Binder, C.R., Meyer, M.A. submitted. Understanding farmers' livelihood system and actors for effective climate change adaptation. in preparation.

Publication V

Anton Eitzinger, James Cock, Karl Atzmanstorfer, Claudia R. Binder, Peter R. Läderach, Osana Bonilla-Findji, Mona Bartling, Caroline Mwongera, Leo Zurita, Andy Jarvis. Geo-Farmer: A monitoring and feedback system for agricultural development projects. Comput Electron Agric. Elsevier; 2019; 158: 109–121. doi:10.1016/j.compag.2019.01.049

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ORIGINAL ARTICLE

Assessing high-impact spots of climate change: spatial yield simulations with Decision Support System for Agrotechnology Transfer (DSSAT) model

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Abstract Drybeans (*Phaseolus vulgaris* L.) are an important subsistence crop in Central America. Future climate change may threaten drybean production and jeopardize smallholder farmers' food security. We estimated yield changes in drybeans due to changing climate in these countries using downscaled data from global circulation models (GCMs) in El Salvador, Guatemala, Honduras, and Nicaragua. We generated daily weather data, which we used in the Decision Support System for Agrotechnology Transfer (DSSAT) drybean submodel. We compared different cultivars, soils, and fertilizer options in three planting seasons. We analyzed the simulated yields to spatially classify high-impact spots of climate change across the four countries. The results show a corridor of reduced yields from Lake Nicaragua to central Honduras (10–38 % decrease). Yields increased in the Guatemalan highlands, towards the Atlantic coast, and in southern Nicaragua (10–41 % increase). Some farmers will be able to adapt to climate change, but others will have to change crops, which will require external support. Research institutions will need to devise technologies that allow farmers to adapt and provide policy makers with feasible strategies to implement them.

Keywords Climate change · DSSAT drybean submodel · High-impact spots · Simulation modeling · Central America

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1 Introduction

Over the past decades, assessments of climate change impacts on agricultural crop production using empirical and process-based modeling have emerged for generating useful information and recommendations of adaptation strategies (Challinor et al. 2009). Several studies show the potential impacts of climate change on agriculture that may add significant challenges of ensuring food security and reaching global development goals (Morton 2007; Jarvis et al. 2011b; Teixeira et al. 2013; Rosenzweig et al. 2014). Jones and Thornton (2003) state a decrease in yield for maize by 2055 in Africa and Latin America due to progressive climate change will likely only be 10 %, but it represents equivalent losses of US$2 billion per year.

Smallholders will suffer most from climate change, and impacts will be locally specific and difficult to predict without remaining highly uncertain (Jarvis et al. 2010). To identify the geographical regions and spatial patterns of crop exposure to climate change is a crucial step in risk assessment and the development of the right adaptation strategies (Turco et al. 2015). Mechanistic models are widely accepted in agricultural research to understand crop-climate suitability and productivity (Ramirez-Villegas et al. 2011; Estes et al. 2013). Crop simulation models can also identify the potential impact of long-term changes of climate patterns on crop suitability and production (Jones and Thornton 2003; Beebe et al. 2011; Laderach et al. 2011; Jarvis et al. 2011b; Cortés et al. 2013). Keating and McCown (2001) reviewed biophysical simulation models that have evolved over the last 40 years. They recognized the strength of the generic grain cereal simulation model CERES and the CROPGRO model for grain legumes (Hoogenboom et al. 1994) to simulate crop yield responses to management factors. They also recognized their weakness to deal with integrated cropping systems. In recent years, these limitations were overcome in integrated modeling frameworks like the Agricultural Production Systems Simulator (APSIM) (McCown et al. 1996) and Decision Support System for Agrotechnology Transfer (DSSAT) (Jones et al. 2003). Simulation modeling has been used to highlight the impact of climate change on crop production and the vulnerability of farming communities (Jarvis et al. 2011a; Bellon et al. 2011; Baca et al. 2014; Eitzinger et al. 2014). Some of these studies used modeling to develop possible strategies to adapt to climate change in the region (Lobell et al. 2008; Ravera et al. 2011; Jarvis et al. 2011a; Ramirez-Villegas et al. 2012).

Drybeans (*Phaseolus vulgaris* L.) and maize (*Zea mays* L.) were the main food staples of the pre-Columbian civilizations in Central America. Drybeans remain part of the culture (Leterme and Muñoz 2002) and are an important subsistence crop in Central America. Consumption is higher than elsewhere in Latin America (FAO 2009) (Table 1), with Nicaragua's per capita consumption ranking third globally (FAO 2009) (Table 2). In El Salvador, Guatemala, Honduras, and Nicaragua, more than one million smallholder families depend on drybeans for their livelihood, with commercial production of 0.5 million tons per year (Instituto Interamericano de Cooperación para la Agricultura (IICA-Nicaragua) 2007). Consumption has changed little over the last 35 years in rural communities of Central America (Leterme and Muñoz 2002), reflecting tradition and their geographical isolation. Rural families depend on drybeans produced locally, which are not traded commercially.

Unlike the gene pool of Andean drybeans, which is adapted to cooler climates, the Mesoamerican gene pool is adapted to higher temperatures at low to medium altitudes (400–2000 m above sea level (masl)) (Beebe et al. 2011). Nevertheless, environments suitable for growing drybeans in Central America are most limited by maximum temperatures (Beebe et al. 2011). This limitation is likely to become more important as temperature increases through global warming.

Table 1 Consumption of drybeans in Latin America (FAO 2009)

Country	Drybean consumption kg/capita/year
Nicaragua	23.4
Brazil	16.3
El Salvador	15.2
México	10.3
Costa Rica	9.3
Honduras	8.7
Guatemala	8.3
Belice	6.4
Paraguay	5.8
Venezuela	5.3
Colombia	3.5
Perú	2.1
Panamá	1.8
Chile	1.6
Uruguay	1.1
Ecuador	0.4
Argentina	0.3
Suriname	0.3
Bolivia	0.2
Guyana	0.1

We developed a method to identify spatial patterns as hotspots by quantifying statistical outliers of predicted changes in future yields and tested the method on a pilot study in Central America, covering an area of four countries: El Salvador, Guatemala, Honduras, and Nicaragua. We used the drybean sub model of DSSAT to assess the impact climate change will have on drybeans. We show results of change in productivity for main drybean-producing regions, and derive conclusions for drybean breeding and adaptation.

Central America has five Köppen climate zones (Peel et al. 2007): tropical rainforest (Af), tropical monsoon (Am), tropical savanna (Aw), humid subtropical (Cwa), and dry (arid and semiarid) (Bw) climates. In Central America, drybeans are produced in tropical savanna climates, which have distinct wet and dry seasons of equal duration. In suitable areas, the wet season extends May–October, followed by a marked dry season. Annual rainfall is influenced by topography, with inter-annual variability as much as 750 mm (Ravera et al. 2011).

Precipitation in Central America is distributed bimodally, with less rainfall and higher temperatures during the dry spell in July and August between the two rainy seasons (called *canícula* in Spanish; Magaña et al. 1999). The canicula separates the two main growing seasons on the Pacific side of the isthmus where most of the population lives and where there is the most agriculture. The *primera* season May–mid July is followed by the *postrera*, September–November after the canicula. There is a third growing season, the *apante* (December–February), on the Atlantic side with Am climates (Costa Rica, south and southeast Nicaragua, eastern Honduras, and northern Guatemala). Planting in the *apante* has increased in the last two decades in response to the demand caused by the long dry season on the Pacific side.

Table 2 World consumption of drybeans (FAO 2009)

Country	Drybean consumption kg/capita/year
Rwanda	29.3
Burundi	26.0
Nicaragua	23.4
Cuba	16.6
Brazil	16.3
El Salvador	15.2
Tanzania	14.2
Benin	13.7
Korea	12.5
Cameroon	11.6
Kenya	11.1
Uganda	10.9
Togo	10.5
Mexico	10.3
Costa Rica	9.3
Honduras	8.7
Guatemala	8.3
Haiti	7.9
Angola	7.5
Timor-Leste	7.3

Central America has warmed over the last decades (Aguilar et al. 2005), with more extreme high temperatures that are spatially highly coherent. Rainfall increased somewhat over the last 40 years on most of the Caribbean side of Central America and southern Mexico. The canicula on the Pacific coast became more pronounced (Aguilar et al. 2005).

In view of the importance of drybeans for Central America, this study was conducted to assess spatial high-impact spots of climate change on crop production and provide general recommendations for priorities if strategies should focus on diversification, intensification of existing production systems, or conservation.

2 Methods and data

To analyze and understand potential impacts of climate change on crop production on a regional scale, we applied the following steps:

(a) We selected a range of model treatments that represent farming practices of drybeans in the target countries.
(b) We identified high-impact spots where climate change will impact drybean production in the first planting season of the year (in Central America called *primera*).
(c) We compared simulated impacts on drybean yields for the second (called *postrera*) and the third (called *apante*) seasons on selected sites within the different types of hotspots.

(d) We used data from multiple global circulation models (GCMs) for selected sites to assess uncertainty.

We used WorldClim (Hijmans et al. 2005) and downscaled GCMs (Ramirez-Villegas and Jarvis 2010) to provide monthly climate data for the climate baseline (current climate) and future climates. We generated daily climate from the monthly data, which we then used in the DSSAT drybean model (Fig. 1). We describe each procedure in more detail below.

2.1 Climate data

We used monthly total precipitation and mean monthly minimum and maximum temperature data as input to the MarkSim weather generator. For the climate baseline, we used the WorldClim database (Hijmans et al. 2005), which interpolated between observed data from more than 47,000 weather stations worldwide for the period 1950–2000 (Hutchinson 1995).

For future climates, we used the GCMs that the Intergovernmental Panel on Climate Change (IPCC) used for its "Fourth Assessment Report (AR4)" (Intergovernmental Panel on Climate Change (IPCC) 2007). We selected the GCMs' outputs for the A2 scenario from the IPCC's Special Report on Emissions Scenarios (SRES) (Intergovernmental Panel on Climate Change (IPCC) 2000). The A2 scenario describes a very heterogeneous world with high population growth, slow economic development, and slow technological change. It is commonly called the "business as usual scenario," and 13 years after publication of the SRES, it reflects the current situation.

The spatial resolution of the GCMs (1–2°) is inappropriate for analyzing the impacts on agriculture (Jarvis et al. 2010), which therefore needs downscaling to provide higher resolution surfaces. We used the delta method of downscaling (Ramirez-Villegas and Jarvis 2010), which is based on the sum of interpolated anomalies to 30″ monthly climate surfaces of WorldClim. The method assumes that changes in climates are only relevant at coarse scales and that relationships between variables will be maintained in the future.

We used downscaled data from all 19 GCMs from IPCC's AR4 for two different 30-year running-mean periods, 2010–2039 [2020s] and 2040–2069 [2050s]. We took means of the 30″ data (Ramirez-Villegas and Jarvis 2010) to produce 2.5′ and 5′ spatial resolution (roughly 5 and 10 km) for Nicaragua, Honduras, El Salvador, and Guatemala. We used the monthly data for each 2.5′ pixel as input to the MarkSim climate generator to produce daily weather data (Jones and Thornton 1993, 2000; Jones et al. 2002).

MarkSim uses a third-order Markov function to generate daily weather data that reflects the synoptic control of rainfall in the tropics by convection cells. It generates daily data of

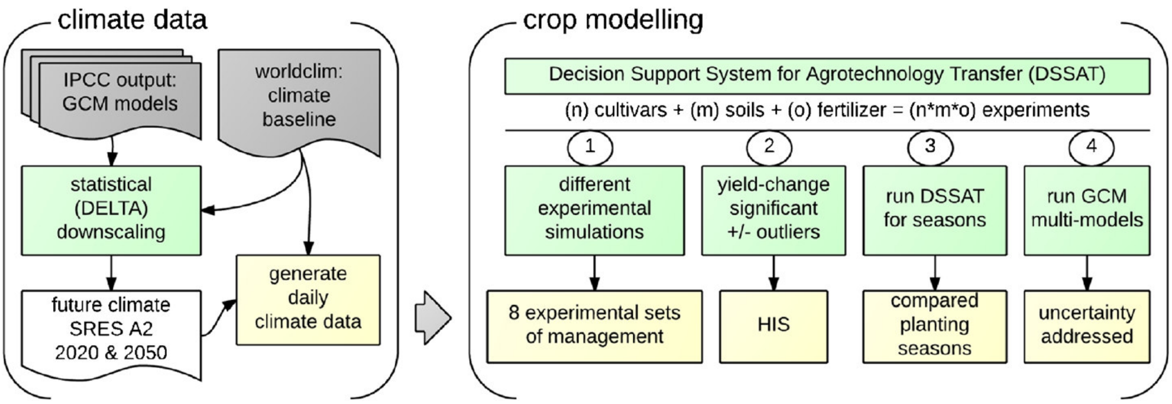

Fig. 1 The sequence followed in the simulation modeling

maximum and minimum temperatures, rainfall, and solar radiation for as many years as the user requires. We generated 99 replicate years of daily weather data for the climate baseline and for each of the 19 GCM models for the 2020s and 2050s for each pixel in the four countries. We automated this step by using the MarkSim 1.0 code compiled as an executable and running it from a command line under the control of a master FORTRAN procedure. In this way, we were able to run the process unattended as the run of MarkSim for each site was independent. The master procedure logged any failures of MarkSim but continued with the next site, which was not possible using MarkSim's shell routine in batch mode.

2.2 Crop modeling

DSSAT is a widely tested series of simulation models (Jones et al. 2003; Hoogenboom et al. 2010). It incorporates detailed understanding of crop physiology, biochemistry, agronomy, and soil science to simulate performance of the main food crops, as well as pastures and fallows. It simulates crop water balance, photosynthesis, growth, and development on a daily time step. DSSAT requires input of the soil water characteristics and genetic coefficients of the crop cultivar, plus any relevant agronomic inputs such as fertilizer and irrigation. It is driven by daily maximum and minimum temperatures, rainfall, and solar radiation.

BEANGRO is a simulation model for drybeans (*P. vulgaris* L.) that was integrated into the crop simulation module component of DSSAT (Hoogenboom et al. 1994). It simulates vegetative growth, reproductive development, and yield. It has been validated many times (see, for example, Oliveira et al. 2012) and accurately reflects the phenological development and yield of drybean cultivars (see, for example, Oliveira et al. 2012 and Fig. 2). Here, we used it to examine the difference between yields using the climate data described above.

We prepared DSSAT management files (FILEX) that included initial conditions at planting, cultivar selection, planting data, and row and plant spacing, among others. We consulted experts from the CIAT bean program and from national bean programs in the four countries in Central America on the appropriate management to apply.

We assessed final impact using the mean of the treatments and calculated the anomalies across sites (pixels) of future and baseline yields.

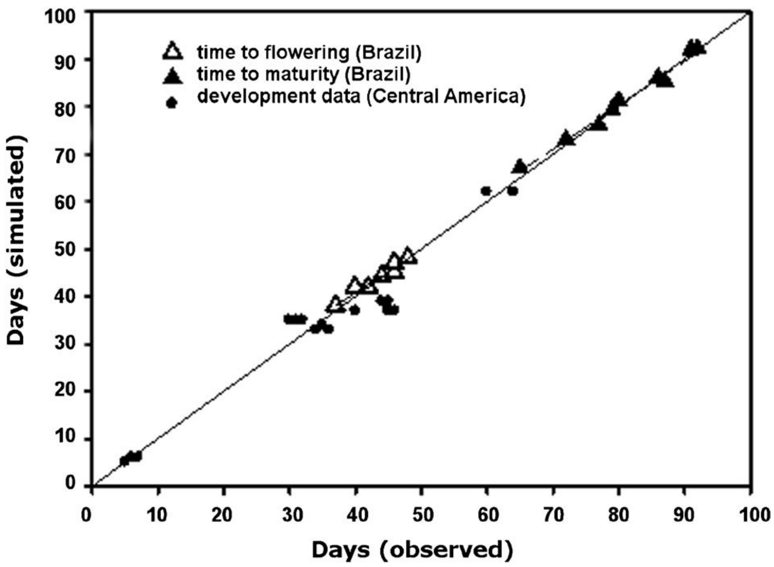

Fig. 2 Simulated compared with observed phenological data for drybeans grown in southern Brazil (Oliveira et al. 2012) and in ancillary experiments at three sites in Central America

2.3 Modeling steps

2.3.1 Simulations of bean management for the primera season

We defined a sowing window between 15 April and 30 June (the *primera* planting season) with a sowing trigger of 50 % available soil water in the top 30-cm layer of soil. The simulations started with available soil water (ASW) set at the lower limit (−1.5 MPa water potential) 60 days before the start of the sowing window to allow early season rain to accumulate in the soil. In consultation with experts, we selected one cultivar (black-seeded ICTA OSTUA) and one breeding line (red-seeded BAT1289) representative of cultivars commonly used in Central America. Because we could not obtain spatially distributed soil data, we used representative generic medium sandy loam and medium silt loam soils from the DSSAT package. We simulated two levels of fertilizer applications, 64 kg/ha 12-30-06 and 128 kg/ha 18-46-00 (N-P-K) at sowing, both with a side dressing of 30 kg N/ha as urea 22 days after sowing. The design was therefore a factorial arrangement of two cultivars, two soils, and two levels of fertilizer:

$$\left\{\begin{array}{c}\text{ICTA OSTUA}\\ \text{BAT1289}\end{array}\right\}\times\left\{\begin{array}{c}\text{generic medium silty loam}\\ \text{generic medium sandy loam}\end{array}\right\}\times\left\{\begin{array}{c}64\,\text{kg/ha 12-30-06}(F1)\\ 128\,\text{kg/ha 18-46-00}(F2)\end{array}\right\}$$

Equation 1: experimental design used in DSSAT

The lower level of fertilizer represents a typical farmer's management in Central America. A more advanced farmer might use the higher level, which also gives an estimate of the potential yields of the selected cultivars.

We used the averaged climate for the 19 GCMs as input data in a first step at 5′ resolution. After identifying high-impact spots (see below), we ran the simulations at 2.5′ using all 19 GCMs in step 4 (see Section 2.3.4).

2.3.2 Identify future high-impact spots

We calculated the yield change (future-baseline) from the yield outputs of the simulations (the mean of the eight treatments in step 1). We used the climate baseline and the ensemble of future climate data from the GCMs. We used distance statistics (Getis and Ord 1992) to identify the significant outliers and the high-impact spots (HISs).

Distance statistics analyze spatial association by measuring the degree of association within a population of weighted points. Spatial association is when the deviation of the variable of interest with respect to the mean (*z*-value) is greater than some specified level of significance. Here, we used a robust version of the root mean square (Darrouzet-Nardi and Bowman 2011) to scale the data and identify points that lie outside positive and negative cutoffs.

We used the HISs to identify priorities for diversification, adaptation, or conservation strategies. The three types of HISs were:

(a) Adaptation spots: We identified pixels whose negative *z*-values of spatial association were equal to or greater than one standard deviation of the mean (68 %). We expect that yields of drybean in the *primera* season in these pixels will decrease in the 2020s and even more in the 2050s.
(b) Hotspots: Pixels whose negative *z*-values were greater than two standard deviations of the mean (95 %). Yields will be so low that it will probably not be economic for farmers to continue to grow drybeans.

(c) Pressure spots: Pixels whose positive *z*-values are greater than one standard deviation of the mean are where the future climate will favor drybeans. Most of these pixels lie outside the current zone of bean production, but we did map them (see Section 3).

We identified hotspots and adaptation spots within the areas that currently grow drybeans. We overlaid the pixels on maps from the Bean Atlas for the Americas (Mejia et al. 2001) using a kernel density analysis (Silverman 1986). By this means, we also identified the pressure spots outside the areas that currently grow drybeans.

2.3.3 Comparison of different growing seasons for selected sites and estimation of fertilizer responses

Changing planting dates would be an adaptation option, if alternate growing seasons were to give a yield advantage in future climates. We therefore ran the same set of treatments for the *postrera* and *apante* planting seasons and compared results with those for the *primera*. Then, within the identified hot- and adaptation spots, we selected 15 communities within municipalities that produce drybeans, distributed across all four countries. We selected pixels that lay within 15 km of the selected communities that intersected with the bean-growing areas identified in the Bean Atlas. We constrained the selection to those pixels whose elevation lay within 100 m of the elevation of the selected community. In total, we selected 171 points for the comparison between seasons (Table 3).

We defined the planting date windows 15 April–30 June for the *primera* season, 20 August–30 September for the *postrera*, and 25 October–5 December for the *apante*. We also ran the model without simulating nutrient options to assess the fertilizer response on each site. We estimated the yield with no fertilizer increase by disabling the fertilizer application in the simulation control options. We did this for the 15 selected sites using current and climate input data for climate baseline and GCM ensembles for the 2020s and 2050s.

2.3.4 Run data from multiple GCMs on selected sites for the primera season to assess the prediction uncertainty

Uncertainty in climate projections raises doubts as to their applicability in crop models (Asseng 2013). Acknowledging that uncertainty exists is the first step towards being able to quantify it (Challinor et al. 2009; Ramirez-Villegas et al. 2013). We used data from all 19 GCMs on the 171 points selected in the previous step to generate daily data for the 2020s and calculated the change of yield for each GCM. For each point, we estimated the uncertainty of the simulated yields for the predicted future climates:

(a) The yield change of the GCM ensemble mean
(b) The standard deviation (SD) of the yield change
(c)The agreement among the model simulations using the 19 GCMs' climate projections, calculated as the percentage of the model outputs predicting changes in the same direction

3 Results

We present the data as maps for El Salvador, Guatemala, Honduras, and Nicaragua.

Table 3 Selected municipalities and points used from the Bean Atlas for simulating different planting seasons

Country	Municipality	Points	Elevation range (masl)	Country	Municipality	Points	Elevation range (masl)
El Salvador	Apastepeque (AS)	30	278–375	Honduras	Alauca (HS)	3	567–639
	Candelaria (AS)	11	524–575		Danli (AS)	12	716–798
	Comasagua (AS)	14	482–574		Orica (HS)	10	811–900
	Texistepeque (AS)	28	603–702		Yorito (HS)	5	743–791
Guatemala	Ipala (AS)	14	793–857	Nicaragua	La Conquista (HS)	11	229–320
	Jalapa (AS)	5	1491–1556		San Dionisio (AS)	9	305–393
	Parramos	4	1755–1801		Totogalpa (HS)	11	664–696
	Patzicia	4	2104–2185				

HS hotspots, *AS* adaptation spots

3.1 Impact on yields for the first season *primera*

Figure 3 shows simulated yields averaged over all sites in the four countries, comparing the current climate with the ensemble of GCMs for the 2020s. Mean yields decrease slightly but become a lot more variable.

In Nicaragua, the most decrease in yield in the 2020s will be in the departments of Granada (−38 %) and Carazo (−25 %). The greatest impact in tons produced is predicted for Nueva Segovia, Estelí, and Madriz. Constant or even improved yields are predicted for the eastern slopes of the central highlands, Jinotega and Matagalpa, which are the main bean-growing areas in Nicaragua (Fig. 4, Online Resource 1).

The corridor of yield decrease continues in Honduras through El Paraiso (−12 %), Francisco Morazan (−13 %), and Yoro (−10 %) departments. In southwest Honduras close to the El Salvador border, we expect high impact for the 2020s in Choluteca (−32 %), Cortes (−17 %), and Valle (−20 %) departments. We expect increased yields only in Ocotepeque department (Fig. 4, Online Resource 1).

In El Salvador, the simulations show reduced yields in the southeastern departments of Cuscatlan (−12 %), Cabañas (−10 %), and San Vicente (−14 %) in the 2020s. We expect yields to increase only Ahuachapan department (Fig. 4, Online Resource 1).

In Guatemala, drybean production in the 2020s will increase in San Marcos (+15 %) and Totonicapán (+16 %) departments. In contrast, Peten (−10 %) department, where there is now enough rainfall to support opportunistic *apante* sowings, will suffer the highest yield decrease for the *primera* sowings (Fig. 4, Online Resource 1).

3.2 Identified high-impact spots

We mapped the different categories of HISs so that we could suggest likely interventions at the farmer and national levels. The adaptation spots and the hotspots all lie within the areas that

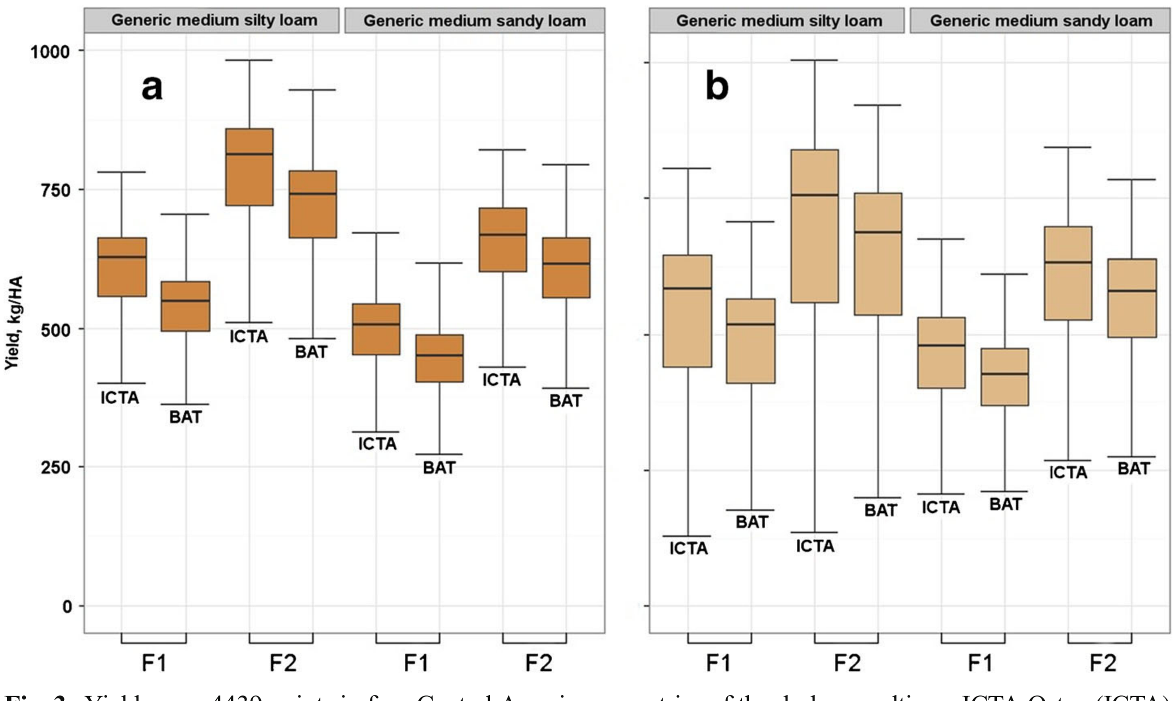

Fig. 3 Yields over 4439 points in four Central American countries of the drybean cultivars ICTA Ostua (ICTA) and BAT1289 (BAT) at two levels of fertilizer (*F1*, *F2*) and two soils (Generic medium silty loam, Generic medium sandy loam) with **a** baseline climate and **b** 2020s future (using the GCM ensemble)

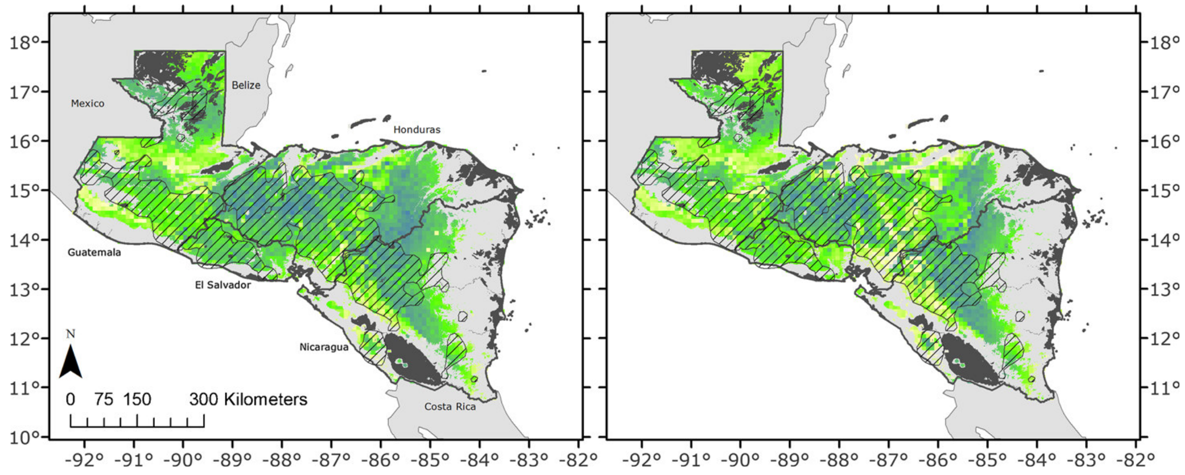

Fig. 4 Mean simulated yield of eight treatments in the *primera* season in **a** baseline conditions and **b** 2020s future (using the GCM ensemble). Areas are colored from blue (high yields) to *yellow* (low yields)

currently grow drybeans (hatched areas in Fig. 5, taken from the Bean Atlas), while the pressure spots generally lie outside them.

Negative HISs are concentrated from Lake Nicaragua to the northern coast of Honduras along the Central American dry corridor. Other areas currently used for drybean production and identified as positive HISs (green within the hatched areas) seem to

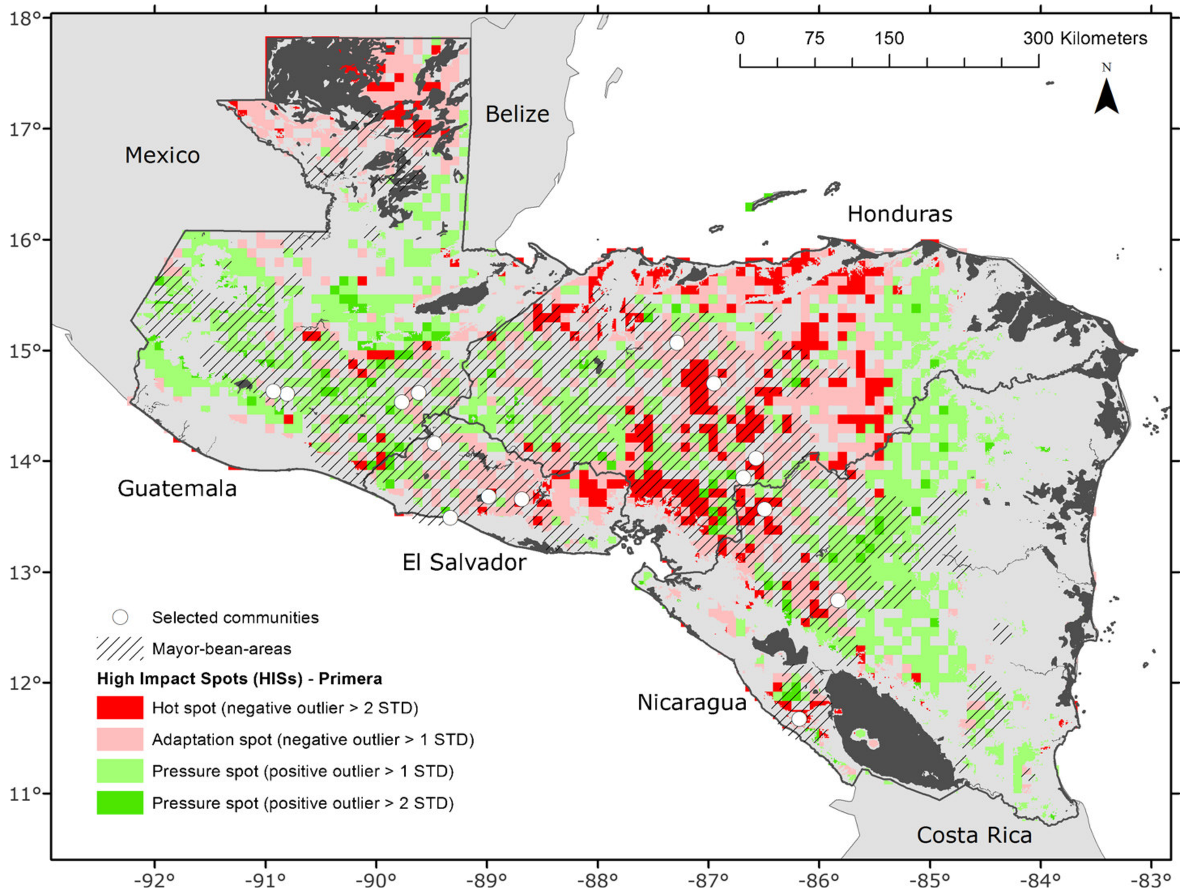

Fig. 5 Outliers from yield change of drybeans in Central America in the *primera* planting season. Pressure spots are more than one standard deviation of the mean higher yield HIS (*green*), and hotspots are more than two standard deviations of the mean lower yield (*red*). Hatched areas are the main bean-growing areas; *white points* are the 15 selected bean production sites

be promising for future development of drybean production in the region (Fig. 5, Online Resource 2).

Further analysis of the detailed data shows yield changes for the 2020s using all 19 GCMs for all 15 sites (Fig. 6). Using the HIS analysis, we identified Alauca (s5), Orica (s7), Yorito (s8), La Conquista (s9), and Totogalpa (s11) as hotspots. At these sites, production of drybeans will probably not be possible in the future and farmers will need a strategy to diversify their crops.

Ipala (s1), Jalapa (s2), Danli (s6), San Dionisio (s10), Apastepeque (s12), Candelaria (s13), Comasagua (s14), and Texistepeque (s15) are adaptation spots in the main production areas. In these areas, drybean systems can be adapted if suitable measures are taken in the near future. Results are based on simulations only for the *primera* season. We selected adaptation and hotspots only within the current main production areas. Areas outside these are not used or not important for drybean production in the main seasons, although some of them are important for the *apante* season. We did not include sites of pressure spots, although Parramos (s3) and Patzicia (s4) in Guatemala showed small gains in productivity in the future scenarios.

3.3 Comparison of alternative planting seasons

Simulations of different planting seasons for Guatemala show little change by the 2020s, even slight increases except for the *apante* season (Table 4). But El Salvador and, more severely, Honduras can expect up to 9 % yield loss in the *primera* planting season in municipalities that currently produce half the countries' commercial beans. The *postrera* season shows little loss in all countries, and even some gains. In El Salvador and Guatemala in the *apante* season, 25 and 20 % of municipalities respectively will have losses greater than 10 %.

Yields for the 171 points within the 15 selected sites show that the *primera* season is likely to be more affected (16 % less by the 2020s and 23 % less by the 2050s) than either the *postrera* or *apante* season (Fig. 7). The *postrera* may therefore become more important for farmers than the *primera* although the *postrera* yields will also decrease by 6 % in the 2020s and 16 % in the 2050s. The *apante* season, with yields of only 200 kg/ha, is only cropped

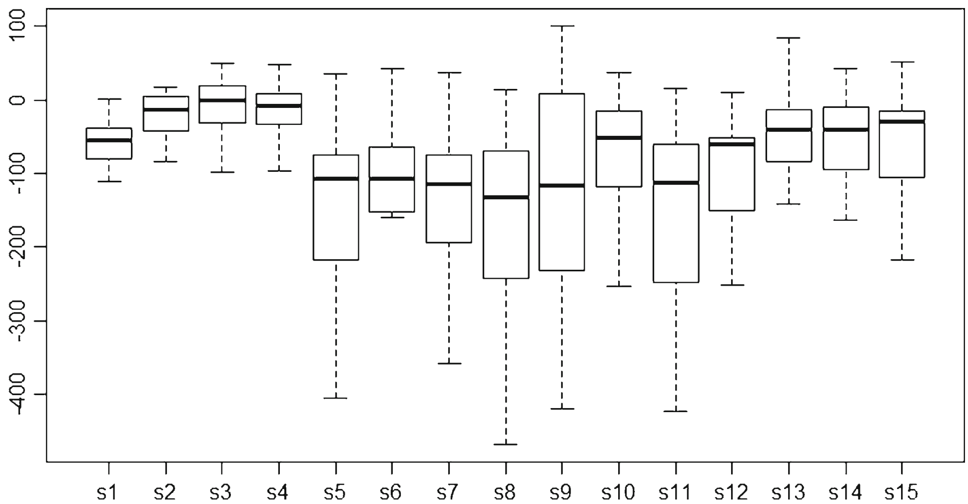

Fig. 6 Yield change for 15 sites using 19 GCMs; Ipala (*s1*), San Dionisio (*s10*), Apastepeque (*s12*), Candelaria (*s13*), Comasagua (*s14*), and Texistepeque (*s15*) are adaptation spots (small negative yield change); Alauca (*s5*), Danli (*s6*), Orica (*s7*), Yorito (*s8*), La Conquista (*s9*), and Totogalpa (*s11*) are hotspots (large negative yield change). Yields at Jalapa (*s2*), Parramos (*s3*), and Patzicia (*s4*) are not expected to change

Table 4 Yield loss for the first season *primera*, second season *postrera*, and third season *apante* by country predicted for the 2020s

Country	Average change in bean yield [%]		% of municipalities with expected yield loss >10 %
	All municipalities	In municipalities accounting for 50 % of total production	
	Primera/postrera/apante	*Primera/postrera/apante*	*Primera/postrera/apante*
El Salvador	−7/−1/−7	−6/−1/−10	33/0/25
Guatemala	+1/+6/−2	−2/+5/−8	10/0/20
Honduras	−9/0/−4	−9/−1/−5	43/0/14
Nicaragua	−8/+7/−4	0/+2/−3	29/0/12

opportunistically and will change little. The yields over the 15 sites were somewhat lower than those for the whole region (800–1000 kg/ha).

Fertilizer gives large increases in yield, and with no fertilizer, yields were only 34 % of those with 128 kg/ha 18-46-0. The yield response to fertilizer might be diminished by less favorable climates in the future. Fertilizer has only a small effect in the low-yielding *apante* season.

3.4 Uncertainty of the GCM results

Here, we consider the skill of the GCMs to forecast climate as it affects bean yields in the *primera* growing season. To do so, we used the predictions of each GCM separately as input to the DSSAT drybean submodel for all 171 points within the 15 selected sites. Simulated yields

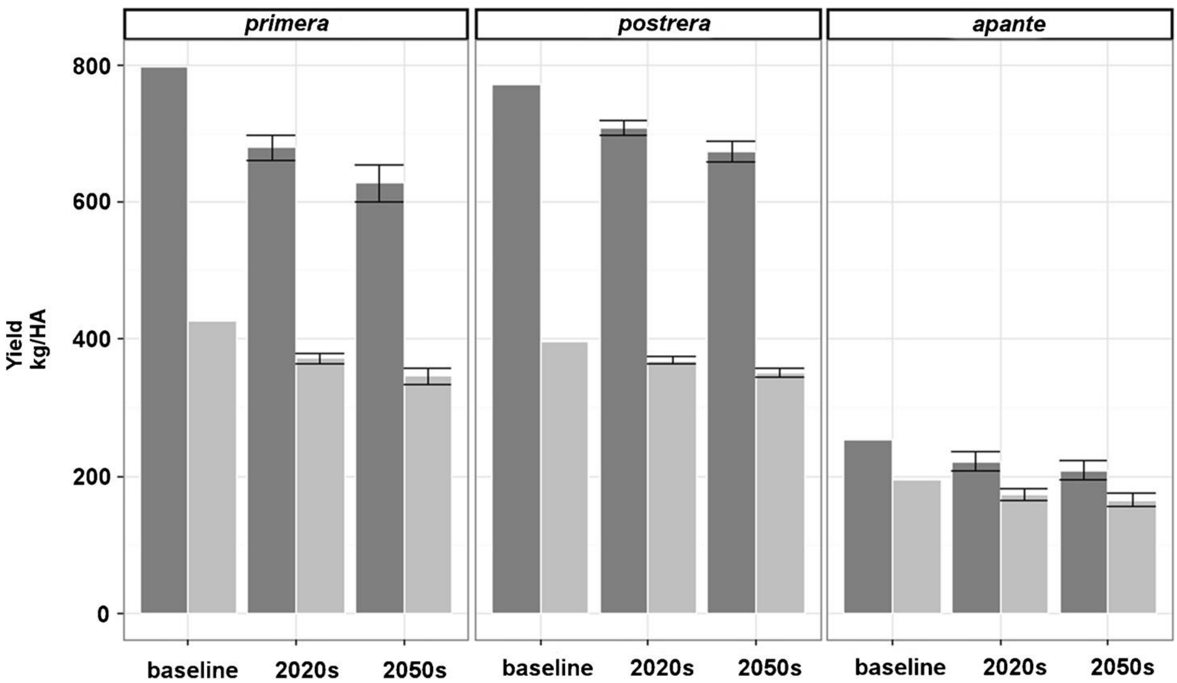

Fig. 7 Mean yields of drybeans at 15 sites (171 points) for three planting seasons for baseline and future climates; *dark grey bars* show yields with higher fertilizer (F2); *light grey bars* show yields with nutrients not simulated. Standard deviations are for all 19 GCMs for 2020s and 2050s

using the 19 different GCMs varied widely (Fig. 8). The change in the simulated yields using the 19 different GCMs varied widely across sites (Fig. 8a), but in general, the GCMs agreed in the direction of yield change (Fig. 8c). The SDs of the means of change in yields for the future climates for each site are a measure of the confidence of the predictions. Where the SDs are high, the uncertainty of prediction of the variability is higher (Fig. 8b) as for sites identified in light blue colors in Guatemala and El Salvador. In contrast, in Honduras and Nicaragua, where it is only locally lower, the sites with lower uncertainty should confront climate change with more certainty, although they must be combined with data of yield changes, which indicate whether yields in the future will be better or worse.

We can discern some geographical separation. The more mountainous sites (s5–s11) appear to have greater uncertainty in the prediction of yield change. We must caution that this may not be just the GCMs themselves, but the uncertainties introduced by the downscaling, by WorldClim and by MarkSim.

4 Discussion

Global food systems require locally specific urgent action to reduce vulnerability of a highly sensitive agriculture in the face of climate change (Vermeulen et al. 2011). Hotspot mapping can help to identify regions that are particularly vulnerable to future climate impacts, with the goal of drawing policy-maker attention to target adaptation measures (de Sherbinin 2014).

For our study area Central America, the general analysis identified adaptation spots and hotspots where climate change will cause modest and severe reductions in yield. In pressure spots, there will be modest yield increases. The more detailed analysis showed differences between planting seasons and the uncertainties between the GCMs. These analyses met our overall goal to differentiate areas that will require different measures for farmers and policy makers to cope with climate change.

Farmers in adaptation spots will have to adjust their management if they are to continue growing drybeans in the future, for example, by sowing better-adapted cultivars. In hotspot pixels, farmers will need to diversify their livelihoods because it will likely be uneconomic to grow drybeans. Future strategies might be to diversify to other crops, seek off-farm income, or leave agriculture.

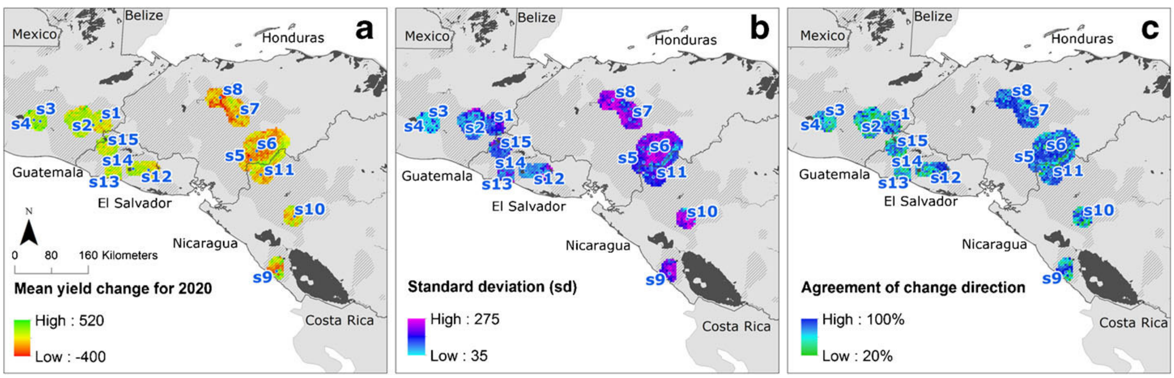

Fig. 8 Predicted changes in yields of drybeans and the range of uncertainty of the GCM outputs: **a** mean yield change for 2020s for the ensemble of 19 GCMs, **b** SD of the mean of yield change for the 19 GCMs, and **c** percentage of GCMs agreeing in the direction of simulated yield change. *Hatched areas* are main drybean-growing areas. The *subfigures* correspond to the categories described in Section 2.3.4

Pressure spots mostly lie outside the current bean-growing zone. They are often located in forest reserves or at higher altitudes, or are close to the current agricultural frontier. There will be social and political pressure to allow agriculture to migrate into these areas. Identifying pressure spots is important so that national and regional decision-makers can either develop them in an ecologically sustainable way or protect them.

The more specific analysis differentiated planting seasons and the potential of fertilizer to increase yields in the selected municipalities. In the future, the *postrera* planting season will become more important in these municipalities. Fertilizer still increased yields with climate change, although the cultivars ICTA OSTUA and BAT1289 that we used appeared to become somewhat less responsive to fertilizer. Beebe (Beebe et al. 2014) argues that edaphic factors will become important as climate change will bring more frequent droughts. A more comprehensive study using site-specific soil data and data from field experiments on the effects of fertilizer and improved varieties is necessary to verify this argument.

We focused first on likely effects of climate change on drybean production in the *primera* planting season. We then assessed the potential for the *postrera* planting season at adaptation spots and hotspots defined in the *primera*. For many of these sites, the *postrera* planting season will be more favorable. We included the *apante* season, which is largely on the Atlantic coast where droughts are rare but production is opportunistic and yields are low. The *apante* crop grows in a period of falling temperatures so that climate change may make the crop more attractive. Bean production has expanded on the Atlantic coast and will likely continue as production in the *primera* season becomes less favorable elsewhere. Further studies of climate change should include this region to test this hypothesis.

There is a great potential to improve insights on future production constraints using multiple GCMs and a wider range of scenarios for spatially distributed DSSAT simulations. Using a dataset containing historical daily weather data and daily future predictions would be another refinement of the methodology we present here. In areas where detailed soil data are available, they should replace the generic soils we used in our simulations.

We also need physiological and phenotypic data on the growth and development in the field of regional and promising cultivars to determine their crop-specific coefficients for DSSAT. With these data, we could generate virtual varieties with heat and drought tolerance, which could help identify the potential of genetic improvement to adapt to climate change. It would also allow us to evaluate strategies of crop management oriented towards adapting current bean production to future climates.

We caution that the fertilizer utilization in the three different seasons needs to be investigated in more detail. The research should consider wider ranges of treatments and the effect of P, which is not implemented in the current DSSAT drybean submodel. Future work should also include the CO_2 fertilization response, for which we need more experimental data on which to base the modeling.

GCMs do not predict future climates well for particular sites but rather estimate conditions on a large scale. GCM estimates can therefore not be used directly as input into plot-scale agriculture models (Ramirez-Villegas and Challinor 2012). Higher resolution climate models can improve results if (i) models are matched in scale, (ii) the skill of models is assessed and ways to create robust model ensembles are defined, (iii) uncertainty and model spread are quantified in a robust way, and (iv) decision-making in the context of uncertainty is fully understood (Ramirez-Villegas and Challinor 2012). It is therefore necessary to address uncertainty of the climate prediction models used. Methods of impact assessment are sensitive to uncertainties. We attempted to assess the inherent uncertainty by using 19 credible GCMs used by the IPCC in its AR4 (Jarvis et al. 2012). GCMs continue to improve their skill with regard to temperature, but unfortunately, their skill with regard to precipitation is progressing more slowly (Ramirez-Villegas et al. 2013).

Based on the results of this study, we make the following general recommendations to address future climate change in Central America:

1. Breed drybeans for improved adaptation to heat and drought stress (Beebe et al. 2011, 2013).
2. If economically viable, extend production into the dry season with lower temperatures using irrigation and water-harvesting systems combined with improved soil fertility management (Fox et al. 2005).
3. Start building farmers' awareness of adaptation to climate change and stimulate adaptive behavior in a social-learning process (Grothmann and Patt 2005; Grothmann et al. 2013).

All the above assume that farmers will use optimal management of abiotic stress and biotic constraints. The development and implementation of adaptation strategies to face progressive climate change will depend also on the participation of all actors in the bean sector in Central America. Research institutions and policy makers will need to provide feasible strategies too.

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Assessing crop response variability under different climate and soil domains across East Africa.

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Abstract

Farming households in East Africa are often food insecure, and climate change will add significantly to the development challenges of ensuring food security. In Tanzania and Uganda, drybeans (Phaseolus vulgaris L.) and maize (Zea mays) are essential components of the diets and farming systems. Climate variability and low soil quality have always been a primary factor of variability in crop yields. Thus, adjustments in management practices at the field scale across varied landscapes are needed to decrease the adverse effects of climate variability and soil degradation. Crop simulation models are widely used to estimate the crop yield potential, often for controlled locations such as experimental research station or particular farmer's field. In this study, we use crop models to quantify drivers of drybean and maize yield variability in complex smallholder production environments in two sites in Tanzania and Uganda. We combined data from farmer surveys with systematic soil surveys to parameterize the Decision Support System for Agrotechnology Transfer (DSSAT) model. We defined simulation domains using a farmers' conventional crop management and four improved management alternatives from the DSSAT model for yield comparison. Findings show that yield response for management options vary across landscapes depending on climate and soil. While in the Tanzania site, intra-site variability is higher and water limitations drive yield variability, especially in the second planting season, in the Uganda site, water limitations and soil fertility are drivers for yield fluctuations. We conclude that assessments of yield domains using different management options for climate and soil variability across landscapes are essential to identify adequate and site-specific options for ensuring food security of farm households in East Africa.

Keywords:

Simulation model
DSSAT
Crop yield
Maize
Dry beans
Climate variability
Soil-health
Crop management
Site specific
East Africa

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1. Introduction

Heterogeneity in soil fertility and soil degradation prevalence, caused by both natural variability of soil properties as well as poor agricultural practices of farmers, has been observed in many parts of SSA [1,2], which further exacerbates farmers' risks in food production. Recent advances in the spatial assessments of soil properties and land health at scales, relevant for decision making, has significant implications for climate change, crop management and understanding drivers of land degradation. Also, land degradation, climate change, and farming system management are inextricably linked. Thus, adjustments in management practices at the field scale across varied landscapes are needed to decrease the adverse effects of evironmental risks [2,3]. Besides, managing for soil properties such as increasing Soil Organic Carbon (SOC) has the potential to mitigate climate change, reduce land degradation and improve the long-term sustainability of the production systems and resilience of farming systems [4–7].

Drybeans (Phaseolus vulgaris L.) and maize (Zea mays) are essential components of the diets and farming systems in East Africa [8]. Economically, these crops are of great importance, contributing significantly to the national gross domestic products in each country, with an overall value of $1.2 billion for common beans and $8.2 billion for maize for East Africa [9]. In Lushoto in Tanzania, one of the two study sites, an average household faces five food deficit months per annum [10], both maize and drybeans are essential crops for households' food security in Lushoto. Climate change is estimated to affect the drybeans and maize yields by 2050 negatively and will add significantly to the development challenges of ensuring food security in East Africa [11]. Although simulation models show that the average decrease in yield for maize by 2055 in Africa and Latin America due to progressive climate change will be 10%, it represents an equivalent loss of $2 billion per year [12]. The predicted economic impact of climate change on total maize production for SSA, from estimated production risk using historical crop production and weather data, shows a 22% adverse change until the 2050s [13]. These studies point to significant adverse impacts on food security and livelihoods in these regions and urgently call for context-specific adaptation measures. Acknowledging that these predicted yield decreases will not be homogenous across landscapes, instead, they will vary across and within sites, districts, countries, and regions [11]. In the two different landscapes in Tanzania and Uganda used for this study, factors limiting growth and yield of drybeans and maize production are related to climate risks from erratic rainfall, less rainfall and increased drought frequency [14] and soil constraints, including high prevalence of soil erosion and declining soil fertility [10,15].

Using crop simulation models is a robust method to analyze landscape-specific yield domains in space and time. Assessments of yield domains are essential for farmers' sustainable intensification of agricultural production, to reduce risks from yield variability and improve food security [16]. Crop growth simulation models have been used to assess the performance of cropping systems under different biophysical and management conditions, for example the Agricultural Production Systems Simulator (APSIM) [17], the Erosion Productivity Impact Calculator (EPIC) [18] and the Decision Support System for Agrotechnology Transfer (DSSAT) [19]. While EPIC uses a single equation to simulate the production of many crops; DSSAT and APSIM provide a simulation framework that combines several crop sub-models, including the generic grain cereal simulation model CERES and the CROPGRO model for grain legumes [20]. A comparison of crop system simulators by Resop et al. [21] recognizes the strength of crop growth models that simulate process-level physiological plant responses, like APSIM and DSSAT, to simulate yield responses to management factors. In contrast, generic crop models like EPIC use one model for all crop types and have limited sensitivity to crop-specific responses. Also, EPIC is more suitable for higher-scale studies at the national scale and less for regional or site-specific assessments. However, most crop simulation models are limited to assessing crop response on a particular farmer's field or even research station while rarely addressing the spatial variability that exists across landscapes and villages. This research aims to address this gap and utilize spatially specific field data collection as input into a well-accepted crop simulation model to better understand factors affecting drybean and maize production in East Africa across diverse landscapes.

In this paper, we use the DSSAT simulation framework to assess four improved agronomic management options as alternatives (Alt) in comparison with the farmers' conventional crop management (Conv), soils and climate variability conditions, and across two different landscapes in Tanzania and Uganda. Considering the availability of accurate input data, both sub-models in DSSAT, BEANGRO, and CERES, have been validated many times in previously published works [22–24], and they reflect the phenological development and yield of cultivars in DSSAT that have been calibrated by field experiments carried out in this studies. Specific objectives include i) simulate crop yields using four Alt, in comparison with Conv crop management; ii) demonstrate the utility of accounting for the spatial variability in soil properties in crop simulation models, and iii) analyze yield domains for Alt options and provide landscape-specific recommendations.

2. Materials and methods

The study was conducted in three main steps. In Fig 1, we show a model of components and techniques that we used to structure the modeling process. First, we collected and converted input data that were necessary for running the DSSAT model. Second, we defined simulation domains using input data and several management options that come with the model. Finally, we analyzed yield probabilities, i.e., years of yield above and below average yield, for different management options and compared yield domains across landscapes.

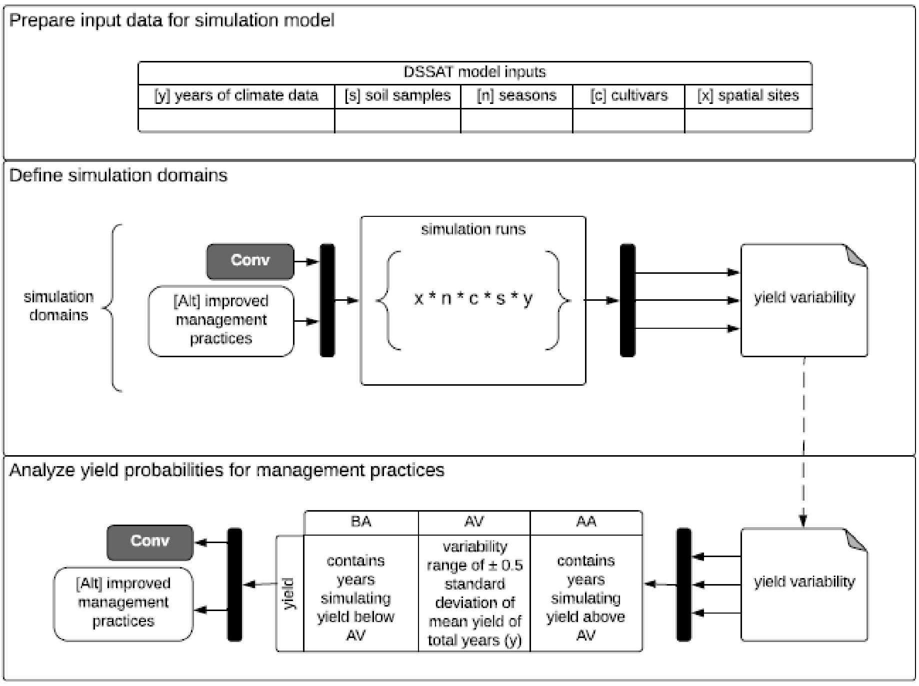

Fig 1. Model of components and methods. We compared a farmers' input data as conventional crop management (Conv), in comparison with four improved agronomic management options as alternatives (Alt) and analyze three classes of yield variability across years of weather data input and intra-site soil characteristics.

2.1. Study sites

Simulation of yield domains under Alt options was applied in two different landscapes in East Africa. Both sites, Lushoto (Tanzania) and Hoima (Uganda), are part of the Climate-Smart Village (CSV) agricultural research for development (AR4D) approach by the CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS). Field studies were carried out under the Regional Program of CCAFS in East Africa, and permissions for field studies were requested and issued by local government district offices for each site. Semi-structured surveys in Hoima and Lushoto were implemented with the Hoima District Farmers' Association (HODFA) in Hoima and the Selian Agricultural Research Institute (SARI) in Lushoto.

2.1.1. Hoima, Uganda

The site is recognized as a biodiversity hotspot and is characterized by a steep rainfall gradient from highland agroforestry, mid-hill coffee/tea systems and small-scale mixed farming to dryland small-scale agriculture and agro-pastoralism along the lake. The principal crops are maize, pulses and root crops. Hoima has highly degraded landscapes contributing to decreasing soil fertility. Increasing rainfall variability impacts are already seen with increasing drought and excessive rainfall [25].

2.1.2. Lushoto, Tanzania

This site in the Usambara Mountains is a global hotspot for biodiversity with different micro-ecozones within a relatively small area. It is a mixed crop-livestock area with intensive farming systems at a higher elevation and agro-pastoral farming systems in lower height [26]. Deforestation and poor land management pose a threat to agricultural production [15,25,27–29]. The most important cultivated crops are Irish potato, beans, maize, vegetables (cabbage, carrots, tomatoes) and fruits [30,31]. Soil erosion by water and tillage in mountainous areas have been identified as a significant constraint to generating enough food to feed the escalating population [15,32–36].

2.2. Input data for the simulation model

2.2.1. Crop management data

Data of crop management and associated yields were taken from semi-structured surveys with farmers. A total of 128 questionnaires were carried out at two sites, Lushoto in Tanzania and Hoima in Uganda [37]. These surveys aimed to assess a typical farmers' crop management for maize and drybean production in the region and use it to define crop management for the Conv simulation domain. We collected data on planting dates, names of used varieties, planting distance on the field, plant development stages in days after sowing and practices on fertilizer management, among others.

2.2.2. Climate data

For our simulations, we used a high-resolution meteorological dataset for a historical period of 27 years (1979-2005), covering 20°W to 60°E and 5°S to 25°N of the African continent. The dataset was generated by the Princeton University [38,39] and was provided through the Climate Change, Agriculture and Food Security (CCAFS) research program. The dataset is based on reanalysis of rainfall data from the National Centers for Environmental Prediction (NCEP) and the National Center for Atmospheric Research (NCAR), merged monthly gridded temperature data from the University of East Anglia Climate Research Unit (CRU) and an elevation model from NASA Langley Surface Radiation Budget (SRB). Spatial downscaling was applied to this dataset, and climate data of 0.1-degree spatial resolution (approximately 10 kilometers) were obtained. To meet the DSSAT requirements for climate input data, we performed data conversions and prepared 27 years of daily data for solar radiation, precipitation, and maximum and minimum temperature.

We compared the 0.1-degree rainfall data that we used for this study with as monthly averaged data of 30-second spatial resolution from the worldclim data [40] to validate the consistency of the climate data that we used for this study (Table 1).

Table 1. The calculated difference (diff) of climate data used for this study with the Worldclim long-term average. It shows 12 monthly precipitation data (prec 01 to prec 12) with a spatial resolution of 0.1-degree used in this study (PRC) for a period between 1979 and 2005, and averaged climate data from a 30-seconds spatial resolution of the worldclim dataset (WC2) for the period between the years 1970 and 2000.

	Lushoto			Hoima		
Monthly precipitation	PRC 0.1-deg	WC2 30 sec	diff	PRC 0.1-deg	WC2 30 sec	diff
prec 01	55	87	-32	34	33	1
prec 02	47	66	-19	49	30	20
prec 03	125	78	**46**	103	92	10
prec 04	184	190	-6	170	150	20
prec 05	176	147	30	139	124	16
prec 06	56	42	14	87	76	11
prec 07	36	30	6	85	79	5
prec 08	59	22	**37**	135	164	-29
prec 09	40	27	13	153	129	24
prec 10	96	55	**41**	159	166	-7
prec 11	106	107	-1	136	148	-12
prec 12	106	121	-15	52	55	-3

2.2.3. Soil data

We applied the Land Degradation Surveillance Framework (LDSF) [41–43] to assess the soil fertility status and provide the soil data needed for the DSSAT model. The LDSF is a spatially stratified hierarchical sampling design (see Fig 2) aimed at evaluating essential land and soil health metrics across diverse landscapes. The two LDSF sites were surveyed as follows: Lushoto in November 2012 [44], and Hoima in March 2012 [37].

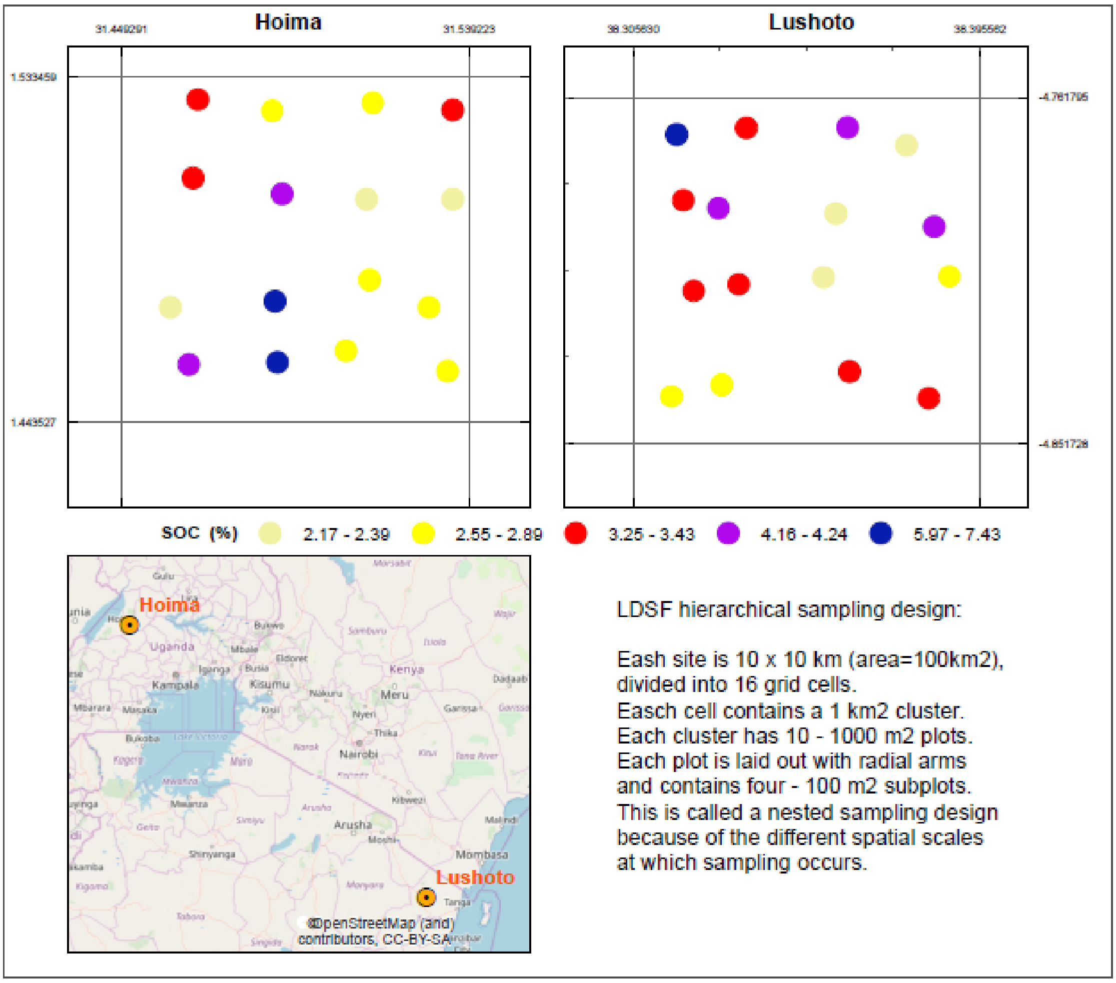

Fig 2. The LDSF sampling design used for Lushoto an Hoima. It shows the 16 soil sample clusters with mapped SOC classes for Hoima and Lushoto.

Observations were made at both plot-level (1,000 m2) and subplot-level (100 m2). At each 1,000 m2 plot (n=160) observations of the slope, vegetation structure, topographic position, land management, and land use history were made. While inspections of erosion, as well as tree and shrub densities, were conducted within each 100-m2 subplot, soil samples were collected at each of the four subplots per plot and composited to comprise one topsoil sample (from 0-20 cm) and one subsoil sample (20-50 cm) from each plot. For this study, one reference plot per cluster was used for a total of 16 soil profiles to parameterize the DSSAT model.

Soil samples were analyzed at the Crop Nutrition Laboratory Services in Nairobi, Kenya. Exchangeable bases were extracted using a Mehlich-3 method [45]. Total N and OC were measured by dry combustion using an Elemental Analyzer Isotope Ratio Mass Spectrometry (EA-IRMS) from Europa Scientific after removing inorganic C with 0.1N HCl, at the Iso Analytical Laboratory located in the United Kingdom. The sand content was measured using a Laser Diffraction Particle Size Analyzer (LDPSA) from HORIBA (LA 950) after shaking each soil sample for four minutes in a 1% sodium hexametaphosphate (Calgon) solution, at the World Agroforestry Centre (ICRAF) Soil-Plant Spectral Diagnostics Laboratory in Nairobi, Kenya.

Most soil variables collected using the LDSF were inputted directly into DSSAT without modification. However, we had to estimate field capacity, permanent wilting point, saturation soil water content, and bulk density. For evaluating these, we utilized appropriate pedotransfer functions (PTF) (Table 2). Due to the well-established differences in physical properties of tropics soils as compared with soils from temperate regions, we used PTFs that were proven suitable for tropical soils. For saturation, we implemented the methodology described in [46], which was based on a certain percentage of the porosity [47] and dependent on the United States Department of Agriculture (USDA) soil texture classes. For sand, loamy sand and sandy loam, we used 93% for estimation of saturation; for loam, silt loam, silt, sandy clay loam, and sandy clay we used 95%; and for clay, clay loam, silty clay and silty clay loam we used 97% [46]. To estimate bulk density, we compared four different methodologies for estimating the missing data that were used in similar studies [48–51] and used the mean bulk density of these four estimations.

Table 2. Pedotranfer functions used for estimation of soil parameters for input into DSSAT.

Variable	Author	Functions
Lower Limit of plan extractable soil water	[52]	LL= 7.95 + 0.86*OC + 0.4*Clay-0.004 〖*(Clay-37.7)〗^2
Drained upper limit	[52]	DUL=56.6-7.49*BD-0.34*Sand
Saturated upper limit	[49]	SAT=0.97*POR
Bulk density	[52]	BD= 100⁄((OM⁄BDom))+(100-OM⁄BDmin)
Bulk density	[53]	BD=1.524-0.0046(Clay)-0.051(OC)-0.0045(pHwater)+0.001(Sand)
Bulk density	[54]	BD=1.578-0.054(OC)-0.006(Silt)-0.004(Clay)
Bulk density	[55]	BD=1.660-0.318* 〖OC〗^0.5

Variable descriptions and units: LL = Lower limit soil water content (cm3 cm-3); OC = Organic content (%); Clay/Sand/Silt (%); DUL = Drained upper limit soil water content for soil layers (cm3 cm-3); BD = Bulk density of soil (g cm-3); SAT = Saturated soil water content in layer (cm3 cm-3); POR = Porosity (%); BDom = Organic matter bulk density (g cm-3); BDmin = Mineral bulk density (g cm-3) ; OM = Organic matter (g kg-1).

2.3. Simulation of yield domains

2.3.1. Decision Support System for Agrotechnology Transfer (DSSAT)

We used the DSSAT framework-model to simulate plant growth and crop yields of drybeans and maize. DSSAT is a crop model that simulates all stages of plant development under prescribed or simulated management options. The model considers changes in soil water, carbon, and nitrogen that take place under the cropping system over time [19,53,54]. DSSAT uses specific sub-models for crop types. It uses the simulation model BEANGRO [20] for drybeans (Phaseolus vulgaris L.) and the grain cereal simulation model CERES [55] for maize (Zea mays).

DSSAT has been used for several studies to highlight the potential impact of climate change on crop production [12,56,57]. Here we used it to examine the difference between yields using historical climate variability, a set of clusters for soil parameters and different management practices, including a farmers' conventional crop management as control yield domain.

2.3.2. Definition of parameters and simulation design of DSSAT

We used crop management, climate, and soil data that we collected and prepared during the previous step (see chapter 2.2), and we added other information from the AgTrials platform [58] and other case studies carried out for East Africa [59].

Based on the obtained information from the semi-structured surveys we defined planting windows, plant density and type and amount of applied fertilization for the DSSAT model. Most sites in East Africa have a bimodal distribution of rainfall and account for two planting seasons. Based on the planting dates reported by farmers in the surveys, we performed initial model runs for defining the simulated planting window in DSSAT. We kept the planting window wide to avoid failures of simulation outputs due to small sowing windows. To trigger the start of simulation in DSSAT, we defined that the soil water must be at least 50% of field capacity in the top 30 cm. The final simulated sowing window was set between February 15th to April 15th for the first planting season (FPS), and July 15th to late October for the second planting season (SPS).

We did not include field experiments and calibration of site-specific cultivars in our design of DSSAT simulations. We used instead collected physiological variables about cultivars from the semi-structured surveys and compared them with already calibrated cultivars in other studies, which are available in DSSAT. We did so by carrying out expert consultations and review of data from grey literature [11,60], and we selected calibrated cultivars common within the DSSAT framework. We selected Canadian Wonder and Calima cultivar for yield simulations of drybeans. For maize, we used the same cultivars chosen by Rosegrant [61], H. Obregon and FM 6, which were used in a study to simulate worldwide growth and development of different maize cultivars to test various agricultural practices such as irrigation and different fertilization strategies.

We defined the simulation design as a factorial arrangement of:

Y [years of climate] * s [soils] * n [seasons] * c [cultivars] * x [spatial sites]

2.3.3. Definition of simulated yield domains

The main objective of simulating different yield domains was to compare a typical farmers' crop management under spatial variations of biophysical conditions. In the following, we call it the farmers' conventional crop management (Conv). To compare Conv with alternative crop management options (Alt), we selected several options of agronomic management practices offered by the DSSAT model, including change of cultivars, different planting date windows, amount of applied inorganic or organic fertilizer, different kind and level of tillage practice and the use of irrigation. For our purpose we selected four improved agronomic management options as alternatives (Alt): (i) organic fertilizer domain (OF), (ii) inorganic fertilizer domain (IF), (iii) combined organic and inorganic fertilizer domain (OF+IF) and (iv) not taking into account the soil water balance by using the irrigation domain (IR).

In Table 3, we describe yield domains of agronomic management practices — each of the four selected management options OF, IF, OF+IF and IR were compared relative to the control yield domain Conv. Fertilization levels for organic fertilizers were taken from Lekasi et al. [59]. Farmers' practice on plant spacing and application of inorganic fertilizer have been extracted from survey data [37], recommended application rates have been provided by researchers from the Pan African Bean Research Alliance (PABRA).

Table 3. Selected agronomic management practices for simulations of drybeans and maize yield levels in DSSAT.

Trait/scenario	Conv	OF	IF	OF+IF	IR
Organic fertilization*	0	2 t/ha manure, 1.5 t/ha mulch		2 t/ha manure, 1.5 t/ha mulch	0
Inorganic fertilization*	0	0	For drybeans: 125 kg/ha of DAP (16-46-0) at planting date. For maize: 50 kg/ha of DAP (16-46-0) at planting date and 50 kg/ha of UREA 45 days after planting time	For drybeans: 125 kg/ha of DAP (16-46-0) at planting date. For maize: 50 kg/ha of DAP (16-46-0) at planting date and 50 kg/ha of UREA 45 days after planting time	0

Irrigation	0	0	0	0	Taking into account the water balance in simulations
Tillage	No	No	No	No	No
Simulated sowing window FPS	February 15th to April 15th	February 15th to April 15th	February 15th to April 15th	February 15th to April 15th	February 15th to April 15th
Simulated sowing window SPS	July 15th to late October 30th	July 15th to late October 30th	July 15th to late October 30th	July 15th to late October 30th	July 15th to late October 30th

* We initiated fertilizer conditions in the DSSAT model 25 days before the defined planting window to ensure that the manure and mulch are incorporated into the soil when plant growth starts.

2.4. Analysis of yield variability across different domains

Taking into account improved agronomic management practices, farmers can reduce year to year yield variations and cope with increasing climate variability [62,63]. To quantify domain variability influenced by climate, soil clusters, and management options, we ran simulations for 27 years of weather data, 16 clustered soil samples, two different planting seasons for each site, two cultivars for each crop, five management options and across two landscapes in East Africa. In total, we ran approximately 17 thousand simulation runs for each location. We calculated statistical means for each site and yield domain and the fraction of years with a yield below or above the long-term average for each yield domain. Finally, we defined three classes to illustrate our results. The first class AV, contains years within a variability range of ± 0.5 standard deviation (SD) of mean yield of total years (y) within the same planting season, for the FPS and SPS respectively and each site. The second class BA contains years simulating yield below AV, and the third class AA, contains years simulating a yield above the AV class.

3. Results

Our findings show that yield variability between Conv and Alt domains is high and different across the two sites in East Africa. We first present the results of estimating soil parameters for DSSAT using the LDSF soil data. In the following, we give results from DSSAT simulations of yield domains and show temporal and spatial variability.

3.1. Estimation of missing soil parameters

We used soil data from the LDSF soil survey that were carried out for the two landscapes separately. The analyzed soil samples in Lushoto show that average SOC is 4.14% (SD 3.22), average pH is 6.05 (SD 0.96), N content 0.43 (SD 0.36). For Hoima, the analyzed soil samples show average SOC of 3.44% (SD 1.44), average pH is 6.16 (SD 0.5), and the average N content is 0.28% (SD 0.1).

For using the soil data in DSSAT, we had to estimate some soil variables based on information that was obtained from the literature. We estimated bulk density (BD), the Lower limit of plant extractable soil water (SLLL), the drained upper limit (SDUL) and saturation upper limit (SSAT). As shown in Table 4, soil variables varied widely both between and within the sites.

Table 4. Summary statistics of the soil properties used as input variables to DSSAT for two soil for the two landscapes in Uganda and Tanzania.

Variable	Units	Layer 1 (0-20 cm) Mean	Max	Min	SD	Layer 2 (20-50 cm) Mean	Max	Min	SD
Hoima-Uganda									
SLLL	cm3 cm-3	0.334	0.361	0.292	0.020	0.339	0.372	0.307	0.016
SDUL	cm3 cm-3	0.441	0.468	0.394	0.022	0.446	0.473	0.411	0.021
SSAT	cm3 cm-3	0.598	0.705	0.549	0.040	0.573	0.686	0.515	0.038
BD	g cm-3	1.02	1.15	0.723	0.110	1.08	1.24	0.777	0.104
Organic C	g kg-1	34.4	74.3	21.7	14.4	25.0	64.4	8.5	13.2
Clay	%	64	83	50	9	73	89	55	10
Silt	%	22	27	10	4	16	27	7	6
Sand	%	14	25	6	6	11	20	4	5
Lushoto-Tanzania									
SLLL	cm3 cm-3	0.306	0.357	0.190	0.047	0.311	0.368	0.161	0.053
SDUL	cm3 cm-3	0.424	0.477	0.358	0.041	0.425	0.485	0.318	0.054
SSAT	cm3 cm-3	0.602	0.718	0.503	0.061	0.573	0.759	0.485	0.065
BD	g cm-3	1.00	1.28	0.647	0.174	1.08	1.33	0.533	0.187
Organic C	g kg-1	41.4	134.1	9.2	32.2	31.5	156.1	7.8	35.9
Clay	%	55	86	16	21	61	84	16	22
Silt	%	26	41	10	9	21	45	10	10
Sand	%	19	43	4	13	17	46	0	15

We show mean, median, standard deviation (SD), Pearson's second Coefficient of Skewness (Sk2) and Kurtosis (Kurt) for all soil variables, which we estimated from input data of 16 soil samples each site, and used as input soil data for DSSAT simulations.

3.2. Yield domains for drybeans and maize in East Africa

3.2.1. Validation of yield simulations

To validate our simulated yields by the DSSAT model with farmer's yields, we compared simulated yield domains of the Conv management option with farmers' yields that were obtained from the surveys. For the comparison, we used mean, and as suggested by Lobell et al. [64], the maximum farmers' yield from the surveys; because the best yield achieved by a farmer within a homogenous landscape may give a good idea of what can be achieved from the site's edaphoclimatic conditions.

Results from farmer surveys in Lushoto show a mean and maximum drybean yield of 0.34 t/ha and 0.53 t/ha (SD 0.15) respectively. In comparison, drybean yields of Conv (the simulation domain without fertilizer application) are simulated by the model as mean yield of 0.69 t/ha (SD 0.22) for FPS and 0.24 t/ha (SD 0.1) for SPS. Similar results were obtained for maize crop, where farmers reported mean and maximum maize yields of 0.86 t/ha and 1.24 t/ha (SD 0.27) respectively, while DSSAT simulated 1.17 t/ha (SD 0.32) for FPS and 1.30 t/ha (SD 0.45) for SPS.

In Hoima, farmers reported 0.53 t/ha (mean) and 0.84 t/ha (max) for drybeans and 1.74 t/ha (mean) and 2.16 t/ha (max) for maize. From the DSSAT simulations of the drybeans Conv option, we obtained 0.62 t/ha (SD 0.15) for the FPS and 0.77 t/ha (SD 0.17) for the SPS. For maize, we obtained 2.09 t/ha (SD 0.42) for the FPS and 3.1 t/ha (SD 0.8) for the SPS.

Climate has a strong effect on yield. We found that climate accounts for 14% to 96% of the variability in simulated yield. The highest simulated yield variability from climate was observed for the second planting season in Lushoto for both crops, maize and drybeans and the first planting season for maize. The lowest variability from the climate in simulated yield was the second planting season in Hoima for maize (Table 5).

Table 5. Climate response variability in the DSSAT model. Values show the coefficient of variance CV of the Conv yield domains on 16 different soils S(n) within each of the two sites and for two planting seasons FPS and SPS, using 27 years of different climate input data in the DSSAT simulation model..

Drybeans		S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S11	S12	S13	S14	S15	S16	Mean
Lushoto	FPS	.26	.22	.32	.30	.46	.20	.28	.42	.35	.20	.18	.32	.26	.21	.43	.27	.29
	SPS	.66	.81	.96	.98	1.2	.68	.72	.96	.71	.67	.83	1.1	.75	.57	.94	.90	**.84**
Hoima	FPS	.24	.32	.30	.33	.31	.37	.32	.26	.37	.43	.26	.28	.36	.30	.41	.42	.33
	SPS	.22	.21	.29	.40	.39	.32	.28	.24	.34	.34	.21	.25	.41	.24	.29	.39	.30
Maize		S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S11	S12	S13	S14	S15	S16	Mean
Lushoto	FPS	.77	.68	.90	.83	.84	.67	.80	.84	.85	.92	.65	1.0	.88	.67	.90	.55	**.80**
	SPS	.80	.91	.93	.95	1.0	.73	.75	1.4	1.1	.83	.88	1.4	.96	.76	1.1	.84	**.96**
Hoima	FPS	.45	.36	.34	.33	.40	.48	.42	.30	.39	.49	.41	.39	.42	.40	.29	.39	.39
	SPS	.14	.07	.12	.16	.19	.14	.14	.11	.17	.13	.13	.13	.20	.16	.09	.15	**.14**

3.2.2. Drybeans yield domains

For Lushoto in Tanzania, simulations show that for drybeans in FPS, recognized by farmers as long rains, 31% of the Conv simulation domains are BA yield domains (Fig 3), resulting in simulation results below 0.5 standard deviations of all years. All Alt options (OF, IF, OF+IF and IR) show a reduction of BA years compared to the Conv domain. In contrast to FPS, the SPS shows 38% of BA years and no reduction of BA years for the first three Alt options, OF, IF and OF+IF respectively. In regards to the fourth option IR, which is not taking into account the water balance in the model, shows that all years are simulated to be AV or AA years. That is most likely because of insufficient water availability for drybean growth in SPS in Lushoto, which can only be overcome by farmers through irrigation of crops in SPS.

For Hoima, results show homogeneous AV, BA and AA yield domains in the FPS. Like Lushoto, in Hoima IR seems to be the most promising strategy to reduce BA years and increase the fraction of AV and AA years up to 88%, while selecting OF, IF and OF+IF as management option could increase AV and AA years to 71% and 73% respectively. For SPS in Hoima, yield improvements could be achieved by all Alt options (Fig 3). Overall, DSSAT simulations for drybeans in Hoima show lower annual, seasonal, and landscape variability of yields.

Fig 3. Results of annual variability of yields for conventional crop management (Conv) and alternative model traits (Alt) for drybeans. AV (orange bars) contains years within a variability range of ± 0.5 standard deviations (SD) of mean yield of total years (n), BA (blue bars), contains years simulating yield below AV, and AA (grey bars) contains years simulating a yield above AV; Conv is simulated as control with farmers' typical agronomic management practices (without fertilizer), for OF we applied organic fertilizer, for IF inorganic fertilizer and for OF+IF we applied both organic and inorganic fertilizer in simulations; for IR we simulated sufficient water availability during development

In Fig 4, we show for the Lushoto landscape simulated yields of Conv and Alt options and their variability between 16 soil samples, and for different years of climate. For drybeans in 1979, in Fig 4 used as example of a frequent weather scenario in Lushoto, results demonstrate that the model simulated very low yields in the SPS compared to the mean of all simulations for drybeans in Lushoto. More drastically for the year 2005, the models did not even show a successful crop development for drybeans in SPS in Lushoto. For years with weather data similar to 1979, while the FPS shows higher yield levels for Conv and Alt management options, irrigation (in DSSAT the IR trait) is the only option to achieve reasonable yields in the SPS. The majority of all modeled years in Lushoto, namely 20 out of 27 years, show similar results of high difference between FPS and SPS, and low yields for all management options in SPS, except for IR.

Nevertheless, some years show similar conditions and higher yield levels for both drybean planting seasons in Lushoto, FPS and SPS (see the year 1997 in Fig 4). For the year 2000, the model simulated low yields for both planting seasons and most management options, except the IR model trait.

Find results of simulated yields of Conv and Alt options and their site-specific variability between soil samples for both sites, Lushoto and Hoima respectively, in the supplementary material (S1 Fig).

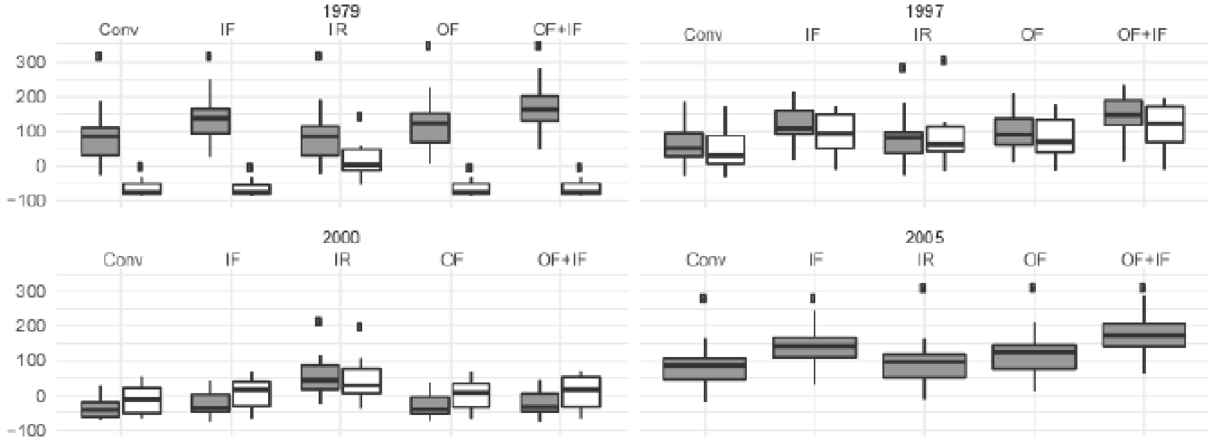

Fig 4. Relative drybean yield variability between 16 soil samples and Conv and Alt model traits in Lushoto. Grey boxes show the first planting season; white boxes show second planting season.

Results in Fig 5 show relationships between edaphoclimatic variables and yield performance. It confirms that increased yield performance for Conv and Alt options in the FPS in Lushoto is related to the increased amount of available water from rainfall. It also shows that increased SOC has a positive effect on yield in the FPS, but not in the SPS, were insufficient rain seems to be the most limiting yield factor. However, the IR model trait shows a positive effect in SPS from both, increased SOC and increasing amount of rainfall during the crop cycle.

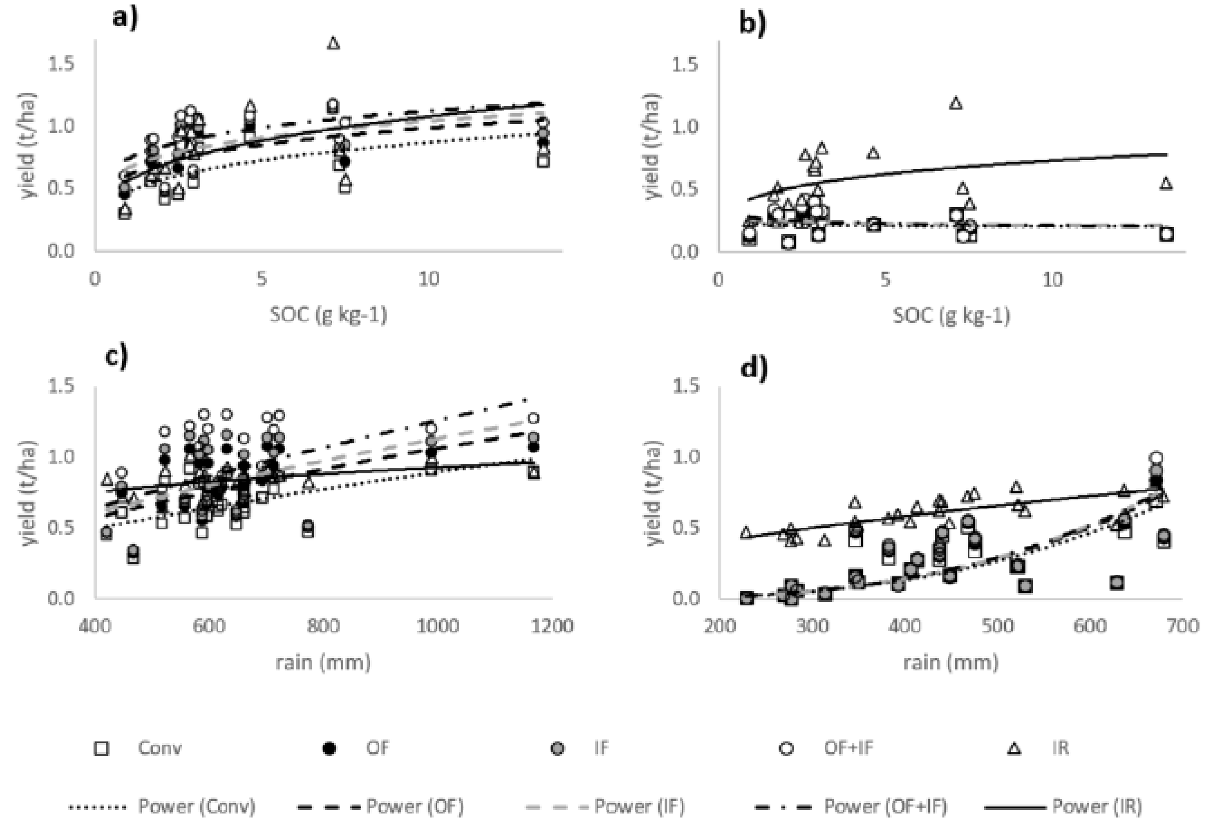

Fig 5. The comparison of edaphoclimatic conditions and drybean yield performance across the Lushoto landscape. SOC and yield in the FPS (a), SPS (b); Amount of rain during crop cycle and yield in

the FPS (c), and SPS (d); points in a and b show results for 16 soil samples (SOC) across the Lushoto landscape and c and d show 27 years of rain from historical climate, in relationship to simulated yields from DSSAT for Conv and Alt options OF, IF, OF+IF and IR.

Find all results from a comparison of edaphoclimatic conditions and yield performance in the supplementary material (S2 Fig).

3.2.3. Maize yield domains

Simulations of maize yield domains in Lushoto show yield variability, with yield varying between BA, AV and AA years. (Fig 6). In FPS and SPS, the model shows that Alt options OF, IF and OF+IF would not reduce farmers' risk of BA years, however, IR seems to be a solution for increased yield levels for maize production in Lushoto for both planting seasons, FPS and SPS respectively.

Results for Hoima show that not only IR but also OF, IF and OF+IF, could reduce the fraction of BA years. For maize in the SPS in Hoima, OF, IF and OF+IF seem to be even a better option as IR, by reducing BA years and prevent farmers from the possibility of BA years.

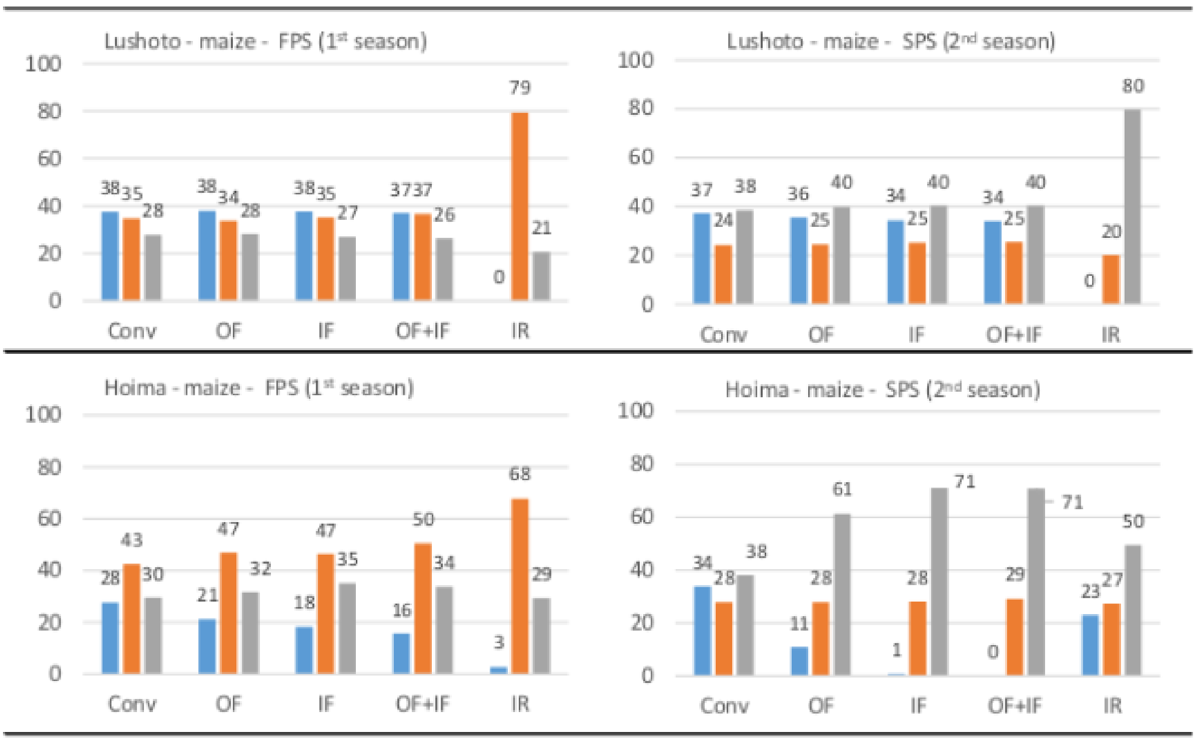

Fig 6. Yield variability of yields for conventional crop management (Conv) and alternative model traits (Alt) for maize. AV (orange bars) contains years within a variability range of ± 0.5 standard deviations (SD) of mean yield of total years (n), BA (blue bars), contains years simulating yield below AV, and AA (grey bars) contains years simulating a yield above AV; Conv is simulated as control with farmers' typical agronomic management practices (without fertilizer), for OF we applied organic fertilizer, for IF inorganic fertilizer and for OF+IF we applied both organic and inorganic fertilizer in simulations; for IR we simulated sufficient water availability during development (irrigation).

In Fig 7, we show for the Hoima landscape simulated yields of Conv and Alt options and their variability between 16 soil samples and time series. Results show again overall differences between FPS and SPS and its yields of simulated management options compared to the mean maize yield in Hoima, whereas some years (1986 and 1998 in Fig 7) show higher differences between FPS and SPS. Overall, the model simulated higher yields for the SPS, and IR did not result to be the most important model trait to improve yield levels. The best option, however, seems to be the application of fertilizer in most years, where OF+IF harvested highest model yields in almost all years and planting seasons. Years with conditions similar to 1986 show further higher variability between different sites from soil samples across the Hoima landscape.

Find results of simulated yields of Conv and Alt options and their site-specific variability between soil samples in the supplementary material (S1 Fig).

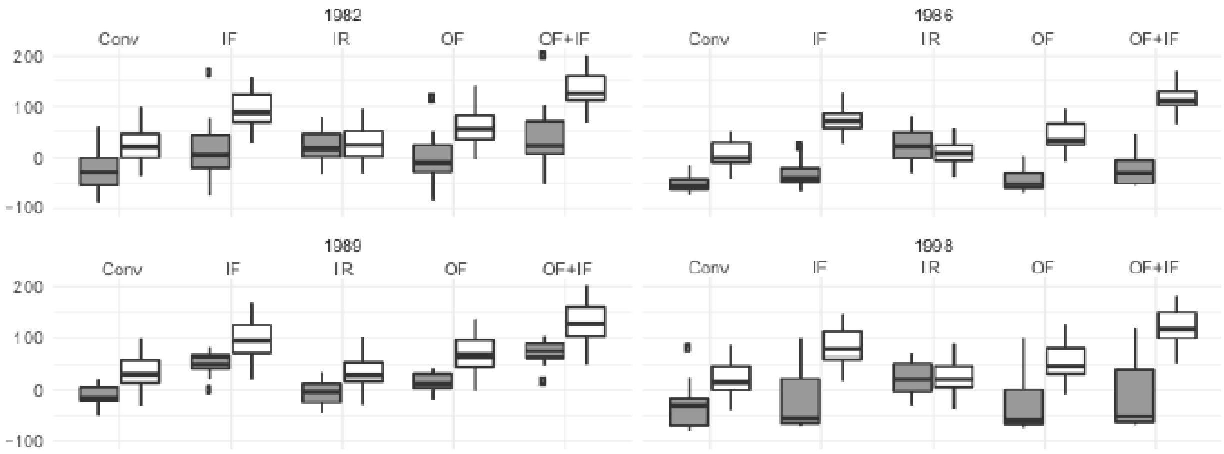

Fig 7. Relative maize yield variability between 16 soil samples and Conv and Alt model traits in Hoima. Grey boxes show the first planting season; white boxes show second planting season.

Results in Fig 8 show relationships between edaphoclimatic variables and yield performance for maize in Hoima. It shows that the relationship of increased SOC and yield is less than for drybeans in Lushoto. Besides, increased rainfall during the crop cycle is related to a higher yield in the FPS only (Fig 8c).

Find all results from a comparison of edaphoclimatic conditions and yield performance in the supplementary material (S2 Fig).

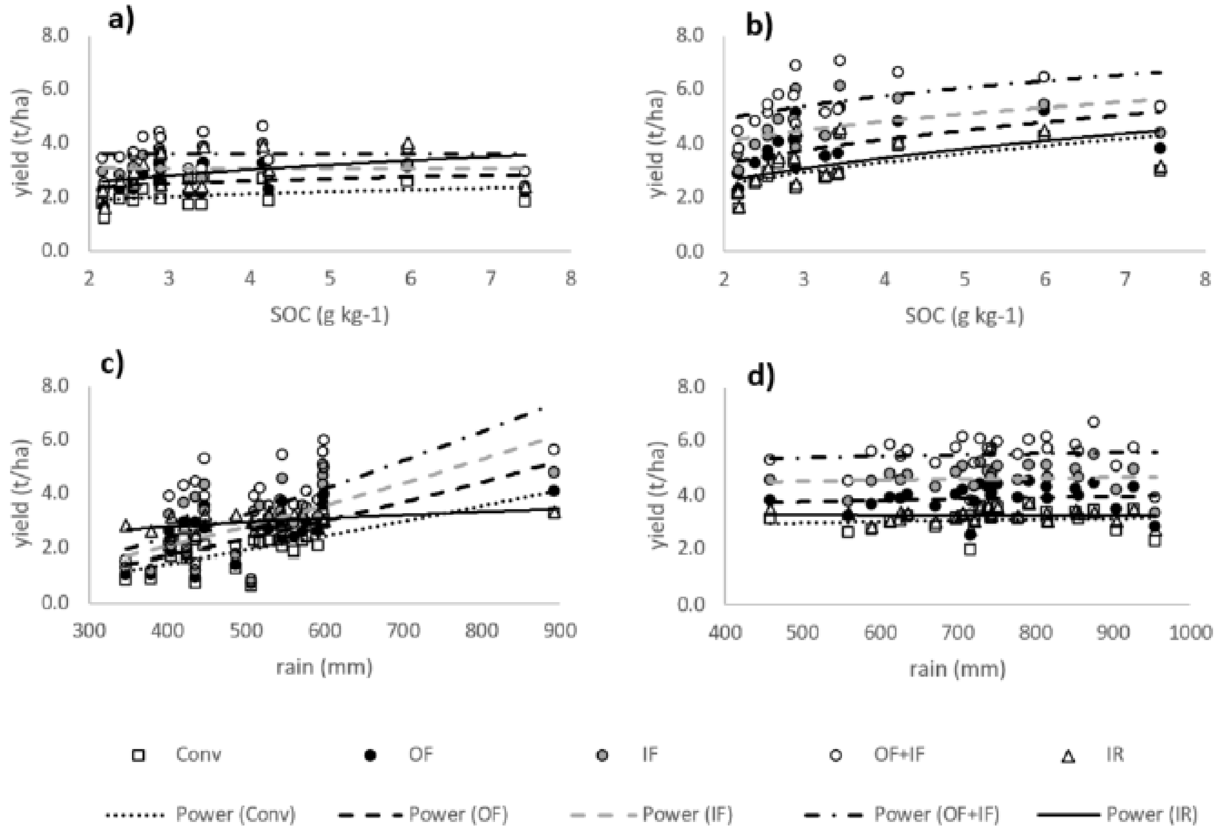

Fig 8. The comparison of edaphoclimatic conditions and maize yield performance across the Hoima landscape. SOC and yield in the FPS (a), SPS (b); Amount of rain during crop cycle and yield in the FPS (c), and SPS (d); points in a and b show results for 16 soil samples (SOC) across the Hoima landscape, and c and d, 27 years of rain from historical climate, in relationship to simulated yields from DSSAT for Conv and Alt options OF, IF, OF+IF and IR

4. Discussion

This research analyzed drybeans and maize yield domains for improved agronomic management options as Alternatives (Alt) compared to a farmers' conventional crop management (Conv) under scenarios of inter-annual variability of weather and intra-site soil variability for two landscapes in East Africa. While in the Tanzania site, intra-site variability is higher and water limitations drive yield variability, especially in the second planting season, in the Uganda site, water limitations and soil fertility are drivers for yield fluctuations. Thus, the assessments of yield domains using different management options for climate and soil variability across landscapes are essential to identify adequate and site-specific options for ensuring food security of farm households in East Africa.

4.1. Variability in space and time

Our findings show yield variation across the two sites. In Lushoto, results show high variability between the two seasons and between years, especially in the second planting season. Irrigation (IR simulation trait) is the only management option that can improve yield in most simulated years (see Figs 3 and 4). In addition, the climate has a stronger effect on yield in Lushoto (see table 5), and the simulations show a higher intra-site variability (Fig 4) than in Hoima. The variation between the two sites can be explained partly by their agro-ecological potential. Winowiecki et al. [44] found that soils in Lushoto have high variability and the current cultivation practices, which are often taken place in steep slopes, have led to erosion and land degradation. Jambiya [65] describes that soils in the mountainous Lushoto area depend on the landform, with deteriorating soils in higher slopes from extensive use, fertile soils being located in foot slopes and suitable soils for irrigation in the valleys. However, cultivation of food crops such as maize and beans is taking place on steep slopes, because the irrigated valleys are often used for vegetables as cash crops. Thus, soil erosion mainly from steep terrain, deforestation, and population pressure is the main challenge in Lushoto [66,67]. A soil fertility survey carried out by Ndakidemi and Semoka [15] revealed that 90% of soils in Lushoto are constrained by P deficiency, followed by N deficit (73% of analyzed soils). Our simulation outputs agree with this other findings; especially, the low yield outputs in the SPS are most likely related to low water holding capacity of soils in steep slopes in Lushoto.

Other studies revealed that soil erosion is a constraint in Lushoto and that soil conservation measures and sustainable land management practices are crucial to increase crop yields in Lushoto [32,33]. For most farms in Lushoto, where soil erosion and water availability is considered a major limiting factors for crop growth, farmers need to implement soil conservation measures and increase water productivity on their farms to reduce the risk of years with potential low yields, as shown from the simulation outputs in Fig 4. To improve water availability, Rockström et al. [68] suggests solutions for farmers such as water-harvesting, conservation tillage, and drip irrigation. As shown by Wickama et al. [33], reducing soil losses and improving fertility can be achieved by sustainable land management measures such as terraces, grass strips as contour lines and adequate use of manure or other organic fertilizer options.

Hoima has similar climate conditions as Lushoto, but most likely due to its landform, it has a low overall erosion prevalence [37]. While in Lushoto, soils samples from cultivated plots had a significantly lower SOC than samples from non-cultivated plots [44], in Hoima there was less difference in SOC between cultivated and non-cultivated plots [37]. A study by Babel and Turyatunga [69], simulating future climate scenarios for maize production in Hoima, shows that supplementary irrigation will be needed for the FPS in Hoima in the future, and they suggest measures such as rainwater harvesting and earlier planting to meet future water demands for maize. In our study, we did not simulate future scenarios, but our simulations using 27 years of historical weather data, show the same finding for the first planting season from past climate variability, which will most likely increase from climate change [70].

Simulations for Hoima show that after the availability of water being the main constraint in simulations, improved management practices of fertilization increase the yield levels, especially for maize. According to Affholder et al. [71], reduced soil fertility is the second leading factor explaining the yield gap after water limitations. They further confirm, that biophysical constraints such as soil physical properties, are highly variable across landscapes and understanding its spatial distribution is required to assess yield potentials under rainfed conditions, but they are often out of farmers' control. Thus, variations due to crop management and best available and affordable technologies define the on-site yield potential of farmers. Low soil fertility and weed infestation were often the explanatory factors, and they are directly related to the farmers' purchasing power of fertilizer and herbicides. To reduce farmers production risks, Affholder et al. [71] suggest that farmers combine management practices to improve soil fertility and weed management while investing in water saving techniques at field level. Van Ittersum et al. [16] suggests to couple yield simulations with appropriate socio-economic analysis of constraints and to guide sustainable intensification of agriculture through yield gap assessments. Although, in our simulations we focused on biophysical conditions affecting yields of farmers, we agree that there are many other factors that need to be considered for selecting adequate and site-specific management options for farmers. Further research needs to be considered to systematically integrate all factors of yield levels in the context of farmers in the tropics.

4.2. Variability between crop species

Differences in simulations between drybeans and maize show more responsiveness of maize to improved fertilizer management(see Fig 5). While OF, IF and OF+IF only reduce BA years for drybeans in the FPS in Lushoto, improved fertilization alternatives reduces BA years in both planting seasons of Maize in Hoima. Since drybeans are nitrogen-fixing species that can support its own N needs, water availability from increased rain and increased SOC in soils, which improve water holding capacity of soils, were the determinants in drybeans simulations in Lushoto. It seams that as long as water availability is a major constraint, the plant is not benefiting from increased fertilizer inputs (see Fig. 5), only the FPS of drybeans in Lushoto show increased yield from improved fertilizer management practices. Maize, on the contrary, show reduced BA years from OF, IF, OF+IF, especially in the SPS of Maize in Hoima. However, the IR option is the most effective option to reduce BA years for both species, drybeans, and maize respectively. Based on a household survey carried out by CCAFS in 2011 in Lushoto, only 18% of farmers have started irrigating maize during the last ten years, while 72% of farm households have started using organic fertilizer [31] in the same ten year period.

4.3. Limitation of data and methods used

Due to the lack of validation of our simulations, we acknowledge that our model estimates of yield for the conventional management option may be subject to uncertainties. Nevertheless, the values obtained from our simulations are plausible compared to the data from farmer surveys, and also agree with other studies in the same geographical region and with comparable cultivars under similar environments. A study carried out by Van Ittersum et al. [16] show a farmer's average maize yield of 1.7 t/ha for Western Kenya and simulated potential yields of 5.4 t/ha for the same site. Besides, farmers reported in the surveys different management practices and often applied the practice of intercroping of drybeans with maize, or another second crop, which partly explains the lower yield levels of farmers compared to the simulated potential yields. Affholder et al. [71] affirm that in different study sites of potential yield simulations, the simulated potential yields were always considerably higher than maximum observed yields from field measurements on farmers' plots. Also, while our simulation shows large differences in yields between the two planting seasons in Lushoto, we did not ask farmers about different yields in different planting seasons.

Other authors pointed out that crop simulation models, even when scarcity of field data to calibrate cultivar-specific parameters prevails, appear to be more accurate in estimating differences between theoretical and actual farmers' yield levels compared to other methods [68,72]. We suggest that further research could simulate other management options that may increase yield levels without applying fertilizer, like shifting planting dates, heat and drought resistant cultivars, or soil conservation techniques, as suggested by Tittonell and Giller [73].

The innovativeness of this study is that we used crop models to quantify drivers of drybean and maize yield variability in complex smallholder production environments, and show variability in space and time. Instead of using data from controlled locations such as in experimental research station to calibrate the model, we used previously validated crop cultivars for both sub-models BEANGRO and CERES in DSSAT, and applied simulations in spatially distributed sites with different biophysical domains and information on farmers' crop management from surveys. We validated findings by comparing a simulated control yield domain (Conv) with data from expert surveys. We did not validate the DSSAT model itself, rather we relied on other scientific studies that validated DSSAT many times, and showed that it reflects the phenological development and yield of cultivars that have been calibrated by field experiments in research stations, and which we used for our simulations.

For this study, we used a meteorological dataset for a historical period that was constructed by combining observation-based datasets with near-surface meteorology and correction of rain day statistics [39]. Because of the lack of reliable historical climate datasets, previous studies often used weather generators to produce series of daily data as input for the DSSAT model [57,73,74]. Although we agree on using weather generators to get more reliable rainfall data, we used in this research a different approach of using the above mentioned meteorological dataset. However, we found that for Lushoto, which is characterized by vast variability in elevation, temperature data had little differences in values between pixels covering the studied landscape. To verify the input climate data for our DSSAT model, we compared elevation values of the Global Relief Model ETOPO altitude dataset [75], used by the authors for downscaling of climate surfaces, with data from the Shuttle Radar Topography Mission (SRTM) dataset [76]. We found that according to differences in elevation, the temperature lapse should be more between these two pixels and reported our observations to the authors of [39]. We conclude that the dataset is better suitable for similar topographies like Hoima and less for hillsides landscapes like Lushoto. However, we used the original data without correcting the temperature lapse for this study.

For soil data, instead of using the reliable datasets coming with DSSAT, we developed soil properties by using a subset of LDSF soil health measurements. As the primary purpose of LDSF was not producing soil data for crop models, we had to calculate and estimate some variables. We acknowledge that soil data that would have been measured for the primary purpose of crop models might be more accurate, but we decided to use the LDSF data because the soil samples were collected more recently and for precisely the two landscapes.

The identified yield domains in this study are mainly based on edafoclimatic conditions. Reliability of simulations would benefit from more accurate climate and soil data. Improvements of simulation domains could include the expansion of management options, i.e., shifting planting dates, heat and drought resistant cultivars, or soil conservation techniques, to better understand the many influences on yield domains. Also, future work could integrate the existing model of components for simulating yield domains with socio-economic models and include spatially different social limitations and adaptive capacity for implementing single management options by farmers.

5. Conclusions

In this paper, we have presented a model of components and methods to assess landscape-specific yield domains using the Decision Support System for Agrotechnology Transfer (DSSAT). The assessment of yield domains in space and time provides valuable insights for sustainable intensification of agricultural production, to reduce risks from yield variability and improve food security for farmers' households. We have applied simulations of yield domains in four sites across East Africa.

Our methods built on research using crop simulation models for estimating differences between theoretical and actual farmers' yield levels, even when scarcity of field data to calibrate cultivar-specific parameters prevails. To substitute for detailed DSSAT input data that would be available in experimental research stations, we combined data from expert surveys with systematic soil surveys and a high-resolution meteorological dataset of historical climate data to parameterize the DSSAT model. We defined simulation domains using a farmers' conventional crop management domain and selected four improved management alternatives from the DSSAT model for yield comparison.

Our findings show that assessments of yield domains by using different management options and taking into account climate and soil variability across landscapes are essential to identify site-specific management options. Simulated yield domains in space and time can be used as critical information to target site-specific adaptation measures for reducing farmers' risk from yield variability and improve households' food security.

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Supporting information

S1 Fig. Results of simulated yields of Conv and Alt options and their site-specific variability between soil samples for time series of 1979-2005. Grey boxes show first planting season; white boxes show second planting season.

S2 Fig. Comparison of edaphoclimatic conditions (SOC, Rain, TMAX) and yield performance.

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Risk perception and decision-making: do farmers consider risks from climate change?

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Abstract
Small-scale farmers are highly threatened by climate change. Experts often base their interventions to support farmers to adapt to climate change on their own perception of farmers' livelihood risks. However, if differences in risk perception between farmers and experts exist, these interventions might fail. Thus, for effective design and implementation of adaptation strategies for farmers, it is necessary to understand farmers' perception and how it influences their decision-making. We analyze farmers' and experts' systemic view on climate change threats in relation to other agricultural livelihood risks and assess the differences between their perceptions. For Cauca, Colombia, we found that experts and farmers perceived climate-related and other livelihood risks differently. While farmers' perceived risks were a failure in crop production and lack of access to health and educational services, experts, in contrast, perceived insecurity and the unreliable weather to be the highest risks for farmers. On barriers that prevent farmers from taking action against risks, experts perceived both external factors such as the national policy and internal factors such as the adaptive capacity of farmers to be the main barriers. Farmers ranked the lack of information, especially about weather and climate, as their main barrier to adapt. Effective policies aiming at climate change adaptation need to relate climate change risks to other production risks as farmers often perceive climate change in the context of other risks. Policymakers in climate change need to consider differences in risk perception.

1 Introduction

Climate change poses major challenges to our society, especially in the agricultural sector in developing countries (Vermeulen et al. 2011). Experts have argued that adaptation and

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mitigation actions are urgently needed to pave climate-resilient pathways for the future (IPCC 2014a). One major challenge with the design and implementation of adequate actions is the complexity of the systems characterized by interactions between environmental and human dynamics at different scales (Turner et al. 2003). Delayed and unexpected feedback loops, nonlinearities, and abrupt rather than gradual changes render the climate system exceedingly hard to predict and the reactions of the exposed human system even less foreseeable (Alley et al. 2003). These entailed uncertainties make decision- and policymaking a difficult task.

The difficulties in climate-relevant decision- and policymaking in agriculture are further aggravated by differing perceptions of climate change by experts and farmers. Despite the scientific consensus about existence, risks, and possible solutions to climate change, nonspecialists largely seem to underestimate and misinterpret these causes and risks (Ding et al. 2011). This is partly due to two key facts: first, most people do not differentiate between weather and climate (Weber 2010) and are thereby unable to distinguish climate variability from climate change (Finnis et al. 2015). Second, most people still perceive the likelihood that climate change might affect them directly as low (Weber 2010; Barnes and Toma 2011; Lee et al. 2015). When taking decisions towards adaptation, people tend to relate possible actions to probable consequences in a linear manner without considering feedback loops, delays, and nonlinearities (Weber 2006). The success of agricultural climate policies relies to a large extent on farmers' awareness of climate change including their knowledge and beliefs regarding climate change and how it will affect them (Patt and Schröter 2008; Carlton et al. 2016).

Scholars have found that small-scale farmers in Latin America are highly vulnerable to climate change (Baca et al. 2014; Eitzinger et al. 2014). While farmers have adapted continuously to social and environmental change in the past, the magnitude of climate change strikes the already stressed rural population. In Latin America, inequality and economic vulnerability call for an approach that tackles the underlying causes of vulnerability before implementing adaptation strategies (Eakin and Lemos 2010). Without visualizing climate change as one of the multiple exposures, small-scale farmers rarely adapt their farming practices even if suggested by climate policies (Niles et al. 2015). This reluctance is greatly influenced by the farmers' beliefs and perception concerning causes and local impacts of climate change (Haden et al. 2012).

Furthermore, adaptive actions are driven by individuals and groups ideally supported by institutions and governmental organizations. In many countries in Latin America, the influence of governments has become weaker due to economic liberalization. Thus, governance mechanisms have lost their capacity to manage risks and to address issues of social vulnerability, especially in rural areas (Eakin and Lemos 2006).

"By 2050, climate change in Colombia will likely impact 3.5 million people" (Ramirez-Villegas et al. 2012, p. 1), and scenarios of impacts from long-term climate change will likely threaten socioeconomics of Colombian agriculture. In Colombia's southwestern department Cauca, the average increase in annual temperature to the 2050s is estimated to be 2.1 °C with a minor increase in precipitation (Ramirez-Villegas et al. 2012). In this region, coffee farmers face several challenges through climate change, like shifting suitable areas into higher altitudes, implying reduced yields and increasing pest and disease pressure (Ovalle-Rivera et al. 2015). Ovalle-Rivera et al. (2015) estimate a national average of 16% decrease of climate suitability for coffee in Colombia by 2050, mostly for areas below 1800 m a.s.l.

During the twentieth century, Colombia's agrarian reform was the best example of failed top-down approaches to promote self-reliant grassroots organizations in agriculture (Gutiérrez 2014), which might be more likely to adapt to climate change. Vulnerabilities in Colombia are structural and need to be addressed through transformative adaptation (Feola 2013). First, rural populations in Colombia, and especially resource-limited farmers, depend on natural resources and are particularly sensitive to environmental stress. Second, the level of human security is low and tied to deeply rooted socioeconomic and political inequality. Third, the institutional setting is a mix of formal and informal institutions that facilitate or impede building adaptive capacity of farmers (Eakin and Lemos 2010; Feola 2013).

For the successful adaptation of Colombian agriculture to agricultural risks from climate, the government should set up enabling policies and release funds for research and development to subsectors (Ramirez-Villegas and Khoury 2013). Adaptation options should be developed based on underlying vulnerability analysis and participatory processes with farmers and experts (Feola 2013). The interaction between grassroots organizations (bottom-up) and institutions (top-down) is crucial for transformative adaptation (Bizikova et al. 2012).

The development of adaptation options is hampered by the fact that experts often have an incomplete view of farmers' perceptions which might have vast implications for effective risk communication, e.g., regarding climate change, and during the participatory design process of adaptation strategies (Thomas et al. 2015). These findings imply that an improved, in-depth understanding of the differences in risk perception between farmers and experts is necessary for the design of more effective and successful policies to promote adaptation initiatives.

To gauge the prevailing perception of various groups, mental models (MMs) have been successfully employed in the past, for example, to elicit farmers' perceptions and underlying views on livelihood risks (Schoell and Binder 2009; Binder and Schöll 2010; Jones et al. 2011). MMs provide insight into perceptions and priority setting of individuals (Morgan et al. 2002) and can help to understand risk perceptions and to inform the design of effective risk communication strategies. In risk analysis, MMs have been used to identify how individuals construct representations of risk (Atman et al. 1994; Schöll and Binder 2010; Binder and Schöll 2010). Based on the mental model approach (MMA) (Morgan et al. 2002), Binder and Schöll (2010) developed the structured mental model approach (SMMA). The SMMA combines the so-called sustainable livelihood framework (SLF) (Scoones 1998)—a framework that shows how sustainable livelihoods are achieved through access to resources of livelihood capitals with the MMA (Morgan et al. 2002). The SMMA can help to understand how farmers perceive and balance livelihood risks for their agricultural practices (Schoell and Binder 2009; Binder and Schöll 2010).

This study aims (i) to understand how climate risks are integrated in the context of other risks in the farmers' perception and decision-making process for taking action, (ii) to identify differences between farmers' and experts' mental models regarding farmers' agricultural risk perception, and (iii) to elaborate on possible consequences for policies addressing farmers' livelihood risks and their agricultural adaptation strategies in the face of climate change.

The paper is structured as follows: *first*, we present material and methods on how we analyze climate risks in the context of farmers' livelihood risks and analyze differences in perception between farmers' and experts' MMs. Second, we present results from applying our approach to the Cauca Department in Colombia (South America) as an exemplary study for a region for small-scale farmers in a developing country. Finally, we discuss our findings concerning other literature and draw our conclusions.

2 Material and methods

2.1 Study area

The Cauca Department is located in the southwestern part of Colombia with a size of approximately 30,000 km^2. Cauca is composed of a lowland coastal region, two Cordilleras of the Andes, and an inner Andean valley. Agricultural land is concentrated in the inner Andean valley. According to the latest agricultural census (DANE 2014), 83% of the farmers in Cauca have a low educational achievement (elementary school only), 22% are illiterate, and 52% live in poverty according to Colombia's Multidimensional Poverty Index (Salazar et al. 2011). The main stressors for agriculture and farmers alongside climate change are trade liberalization and violent conflicts (Feola et al. 2015). Colombia has one of the longest ongoing civil conflicts and one of the highest rates of internal displacement, estimated to be 7% of the country's population and 29% of the rural population (Ibáñez and Vélez 2008). Cauca is one of the regions in Colombia with a high rate of violence from armed conflicts (Holmes et al. 2006). Especially for small farm households, weak institutional support and absence of the state in rural areas have led to unequal land distribution and lacking technical assistance as well as financial services for agricultural transformation (Pérez Correa and Pérez Martínez 2002).

Due to Cauca's proximity to the Pacific Ocean, the region is subject to inter-annual climate variability mainly driven by the El Niño Southern Oscillation (ENSO) (Poveda et al. 2001), a feature that has great influence on agricultural productivity and, in consequence, farmers' livelihood. A study by the CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS) shows that farmers in the study area are mostly affected by more frequent droughts, storm and hail events, more erratic rains, and landslides as a consequence of heavy rains (Garlick 2016). Even if uncertainty in future scenarios of extreme events is still high, changes in inter-annual climate variability are of high relevance for farmers; there is agreement that more intense and frequent extreme events are likely to be observed in the future (IPCC 2014b).

The Cauca region is particularly relevant for these types of analyses as (i) the region has a high potential of being affected by climate change, (ii) interventions for rural development by the government have been weak in the past, and (iii) because of the national and international efforts to implement the peace process, Cauca has caught attention for implementing development interventions. Many of these interventions could benefit from an in-depth understanding of farmers' perceptions regarding the climate and nonclimate risks affecting their livelihoods.

Exemplary for Cauca, we selected a geographical domain of 10 km^2 with altitudes between 1600 and 1800 m a.s.l. within the boundaries of the municipality Popayan. We conducted the interviews with experts and farmers in five rural villages and selected randomly 11 to 12 farmers each village (see details on sampling design in Chapter 2.4). The farm size of interviewees was between 1 and 4 ha, half of them (45%) possessed legal land titles, and 41% of farmers have started the legalization process recently. The average age of interviewees was 47 years old, 48% of them were women farmer, and the average household size was five people. Overall, 74% of farmers depend on coffee (*Coffea arabica*) as their main agricultural livelihood besides other crops and some livestock to complement income and for self-consumption. Other crops and livestock that are managed in the farming systems are cassava (*Manihot esculenta*), dry beans (*Phaseolus vulgaris*), maize (*Zea mays*), banana (*Musa* *acuminata*), cattle, and poultry. As the second most important crop, 19% of interviewed households depend on sugarcane (*Saccharum officinarum*) and the derived product *panela*, which is unrefined sugar in compact loaves of a rectangular shape. Most of farmers' income is coming from on-farm agricultural activities and also from off-farm day labor activities in the agricultural sector (harvest coffee in other farms). Generally, there are few job opportunities in the study area.

2.2 Assessment of climate risks

Before we started analyzing risk perceptions, we conducted an assessment of climate risks and impacts on main crops grown in the region and reviewed existing literature on the vulnerability of farmers in the study area. First, we compared anomalies of precipitation, maximum temperature, and minimum temperature in the study area with records about ENSO events. We used data of a local weather station from the Instituto de Hidrologia, Meteorologia y Estudios Ambientales de Colombia (IDEAM) and data of the Oceanic Niño Index (ONI) from the National Oceanic and Atmospheric Administration (NOAA) (NOAA 2014). Second, we used a simple climate envelope model to analyze the current and future climate suitability of six crops in the study area. Finally, we reviewed the existing literature on climate change impact assessment for Colombia. Detailed results of climate risk assessment in the study area are presented in Online Resource 1.

2.3 Analyzing mental models to understand perceptions

Figure 1 presents the conceptual approach of the study. Farmers' perceptions regarding climate risks are shaped by their knowledge about the causes of climate change, their beliefs, social norms, and values as well as through their experience with climate-related information and past climate-related events. However, farmers' decision-making is not only shaped by climate risks, but other agricultural production risks are also equal or even more important for farmers. Farmers consider the complete mental model of risks when envisioning goals concerning their livelihood strategy and make appropriate decisions about investments and adaptations of the agricultural production system. In applying our approach, we captured experts' external views of farmers' perception and compared it to the farmers' internal views.

To assess the importance of climate risks in the context of another risk in farmers' agricultural production system, we identified differences between the perception of farmers and that of experts regarding climate risks as placed in the context of other risks within the farmers' livelihood system by analyzing and comparing each group's MMs. The experts' perspective on farmers' perceptions represented the external view, whereas the perspective of the farmers themselves represented the internal one. We captured the external and internal views on climate risks with two sets of structured interviews with experts and farmers, and we used ranking techniques to show differences in perception.

2.4 Interviews with experts and farmers

A qualitative semi-structured interview study was conducted between June and September 2014 to examine perceptions of experts and farmers about farmers' livelihood risks and farmers' barriers for adaptation to cope with risks they face in agricultural production. In a first step, we conducted open interviews with 13 experts. In order to obtain a holistic view of

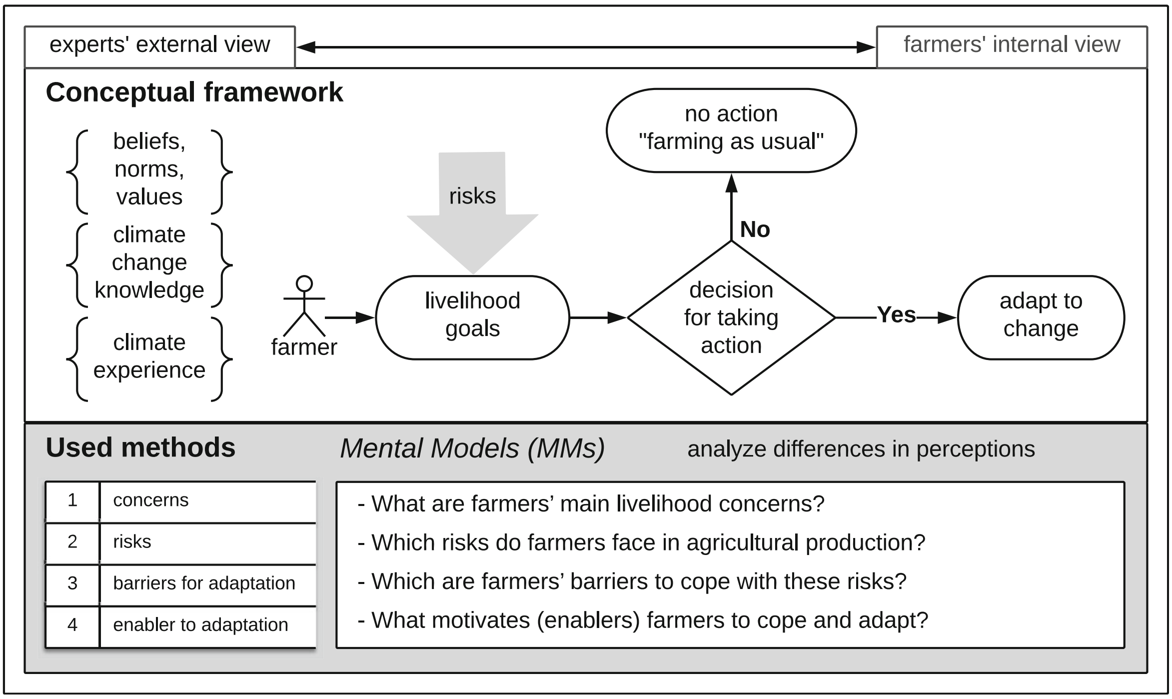

Fig. 1 Approach used for understanding climate risks in the context of farmers' livelihood risks

experts' perceptions, we included regional, national, and international experts from different fields of the analyzed agro-environmental system, namely four agronomists, three economists, one environmental lawyer, one public government administrator, one nutritionist, one climate change scientist, one ecologist, and one veterinarian. All experts have been regularly working with farmers in the study region during the last 5 to 10 yrs and have still been working with them at the time of the study. Following the expert interviews, we conducted 58 semi-structured interviews with farmers from five different villages in the municipality of Popayan, performing between 10 and 12 farmer interviews from different households and for each village. The total population of farmers of the five villages was 499 at the time of the interviews. We included farmers aged 20 to 60, and we designed the sample to ensure an equal representation of women and men. Morgan et al. (2002) judge a small sample for interviews within a population group that has relatively similar beliefs as reasonable. Schoell and Binder (2009) found for the case of small farmers in Boyacá, Colombia, that after 5–10 interviews, no more new concepts emerged (Binder et al. 2015). To avoid interruption from notes taken by the interviewer and to keep the natural flow of conversation, we recorded all interviews with the consent of the participants. Subsequently, we transcribed the records of the interviews for the analysis. The used guidebook for expert interviews can be found in Online Resource 2 and the guidebook for farmer interviews in Online Resource 3.

First, we assessed the experts' views on the farmers' concerns, risks, barriers for taking action, and enablers to take action by asking the following questions:

- What are the farmers' main livelihood concerns?
- Which risks do farmers face in agricultural production?
- Which are farmers' barriers to cope with these risks?
- What motivates (enablers) farmers to cope and adapt?

In the expert interviews, we received answers and explanations to the four guiding questions about farmers' concerns, risks, barriers for taking action, and enablers to take action when facing risks in agricultural production. We noted all answers of experts for each question on small cards. Answers from all experts were pooled after finishing all the interviews; we got 16 concerns, 10 risks, 13 barriers for taking action, and eight enablers to take action. Based on the pooled elements, we used an online survey tool to ask the same group of experts to rank all compiled elements according to the importance of the elements for farmers. The highest ranked elements by experts were then selected to start the farmer interviews.

Second, we carried out the farmers' interviews. After explaining the overall purpose of the study briefly as part of informed consent with farmers, we visualized the elements of the experts through drawings we created for each question and then asked farmers to rank them according to their priorities. After piloting the interviews with farmers, we decided to use only the six highest ranked elements by experts to keep the ranking exercise for farmers simple. In addition, we asked farmers at the end of each ranking if they would consider other elements to be more important for them that the ones we used for the ranking (see Online Resource 3). We did not mention climate change during the interviews for a specific purpose. Farmers should rank the card elements without being biased by knowing the purpose of the interview, namely to understand how they perceive climate risks in relation to other livelihood risks.

After finishing both interview series, we analyzed the differences in perception between experts and farmers. To aggregate the individual rankings, we calculated a weighted average based on the ranking of each element for the four questions. The overall ranking of experts and farmers was calculated separately as follows:

$$f_{\text{ranking}} = \frac{\sum_{i=0}^{n} (x_i \times w_i)}{n}$$

where w is the weight, x the response count of an answer choice of each question, and n the total number of answer elements. In our case of six elements per question, we calculated the average ranking using weights starting at 6 for the highest ranked element and decreasing towards 1 for the lowest ranked element.

We compared the average experts' rankings to farmers' rankings stratified by gender and age group and then applied the hierarchical clustering approach (Ward 1963) to the farmers' rankings to obtain groups of farmers with similar choices. The hierarchical clustering approach by Ward (1963) is a widely used data analysis approach for similarity grouping to determine distinct subgroups with similar characteristics (Vigneau and Qannari 2003). After obtaining groups of farmers from clusters, we described them based on high ranks using first and second ranked answers each question and demographic variables collected during the surveys.

3 Results

3.1 Climate change risks in the study area

Figure 2 shows that inter-annual rainfall variability is high. High variability in rainfall can be observed between October and February for long-term weather records since 1980. Inter-annual climate variations in the study area are mainly driven by the ENSO. The consequences of ENSO for farmers and agricultural production are prolonged droughts (El Niño) or intense rainfall over more extended periods (La Niña). The assessment of the six most relevant crops in the study area revealed that variation in crop exposure to climate variability in Cauca is high (see Online Resource 1). Farm households in the study area grow coffee, sugarcane, maize, dry

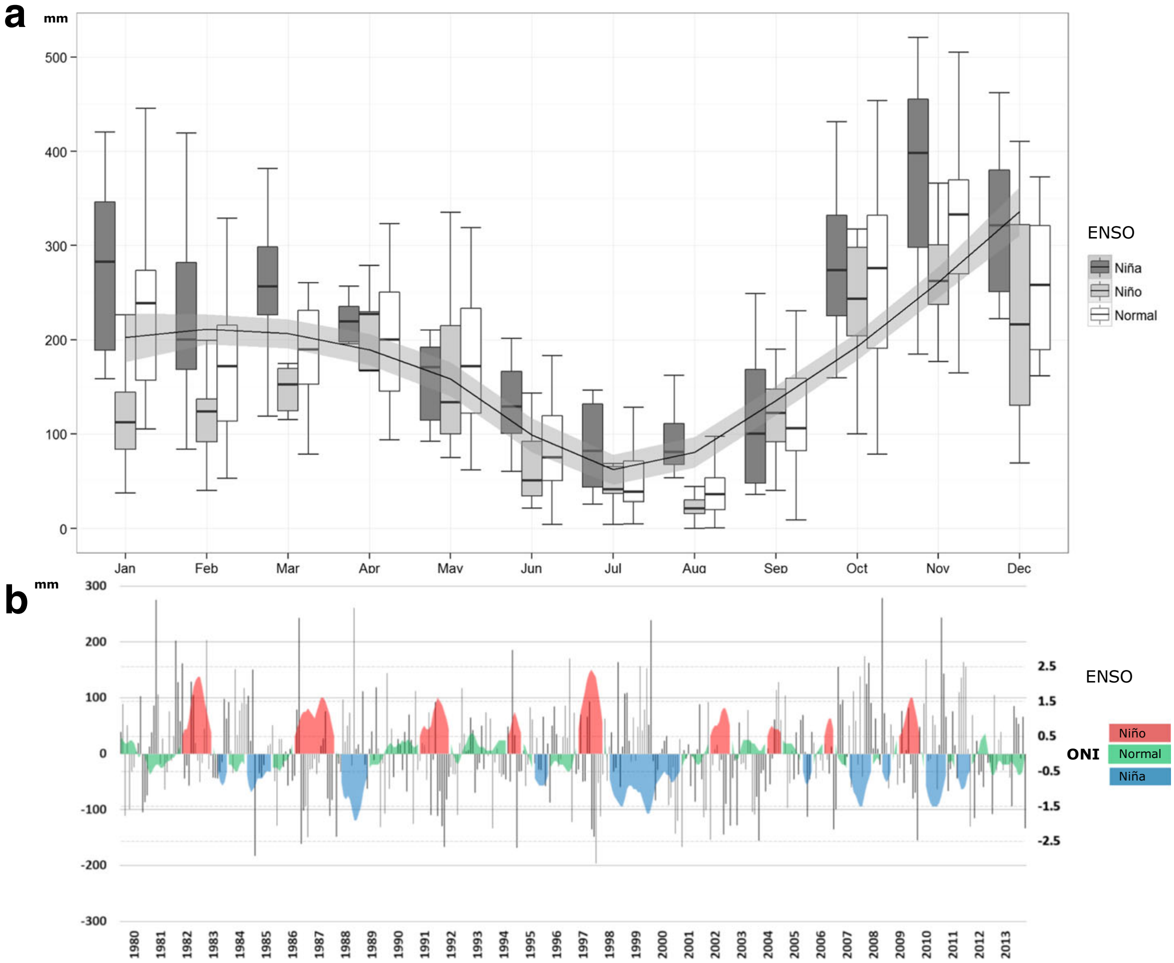

Fig. 2 **a** Inter-annual precipitation variability calculated from weather records from a station (Apto G L Valencia, elevation of 1749 m a.s.l.) in the study area, and **b** ONI and precipitation anomalies show the frequent influence of ENSO episodes

beans, banana, and cassava. While banana, sugarcane, and cassava can better cope with long-term climate change scenarios, dry beans and coffee are more likely affected by increasing mean annual temperatures. Production of coffee and dry beans represents an important livelihood for farmers in the study region but will likely face impacts through climate change in the future. See Online Resource 1 for more details on climate change risks in the study area.

3.2 Farmers' rankings and differences to experts' rankings

We found that experts and farmers perceived farmers' livelihood concerns and enablers for adaptation to agricultural production risks similarly, but risks and barriers for adaptation differently (see Fig. 3). Also, farmers agreed on the selected answers as the most relevant for them for each question; only a few farmers mentioned other elements. Beyond, the most mentioned elements by farmers were concerns about health (five times) and access to tap water (three times).

Older farmers are more worried about climate change than younger farmers but rank production failure low as risk (see Fig. 4). Interestingly, older farmers saw insecure transport as a major risk and production failure as a lower risk, whereas this was the opposite for younger farmers.

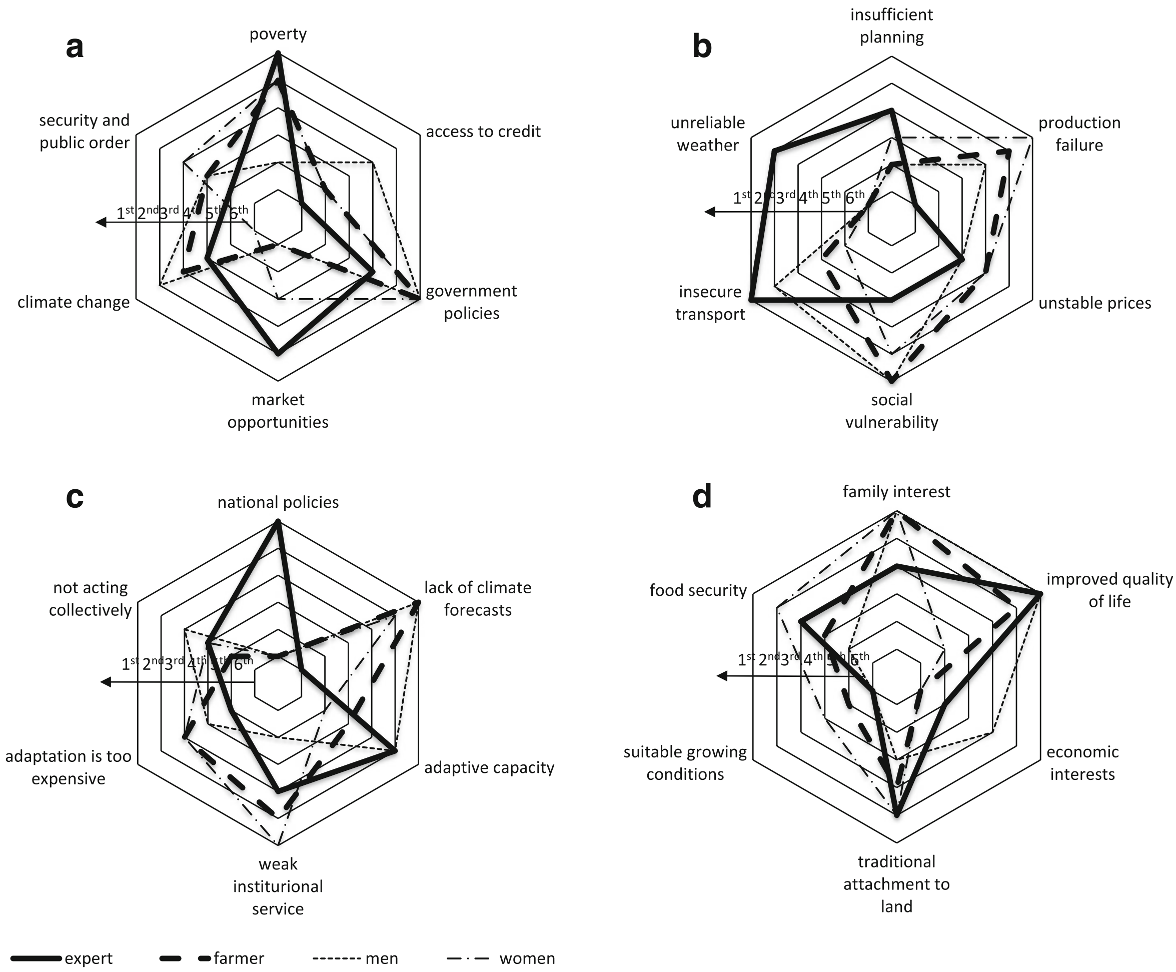

Fig. 3 Differences in experts' (solid thick line) and farmers' (dashed thick line) rankings of farmers' **a** worries, **b** risks, **c** barriers to adaptation, and **d** enablers for adaptation. Rankings of male farmers (dashed narrow line) and female farmers (dashed-dotted narrow line)

Regarding farmers' concerns (Fig. 3a), we found two issues experts and farmers agreed upon: poverty is a chief concern in this region (ranked first by experts and second by farmers) and neither climate change nor security problems are perceived to be relevant in the study area. The key differences in perceived concerns were related to government policies, access to credit, and market opportunities. Farmers were highly worried regarding government policies (rank 1). They argued: "The government in the capital, Bogota, is too far away and does not take into account the context of our region when making new laws" (farmer's interview, translated from Spanish, Colombia, October 2014). Experts ranked government policies lower with respect to concerns (rank 3), but they agreed in their explanations with farmers that: "The government is focusing on international trade agreements and is supporting medium-sized and large farmers, they are not investing in small-scale farmers' production" (expert's interview, translated from Spanish, Colombia, August 2014). Both male and female farmers were highly worried regarding their access to credit to be able to pay for labor and to purchase inputs for crop production (rank 3). Experts, on the other hand, did not perceive that farmers need to be worried about having access to credit (rank 6). In contrast, experts believed that farmers were worried about market opportunities—a perception shared more often by women than by men (see Fig. 3a).

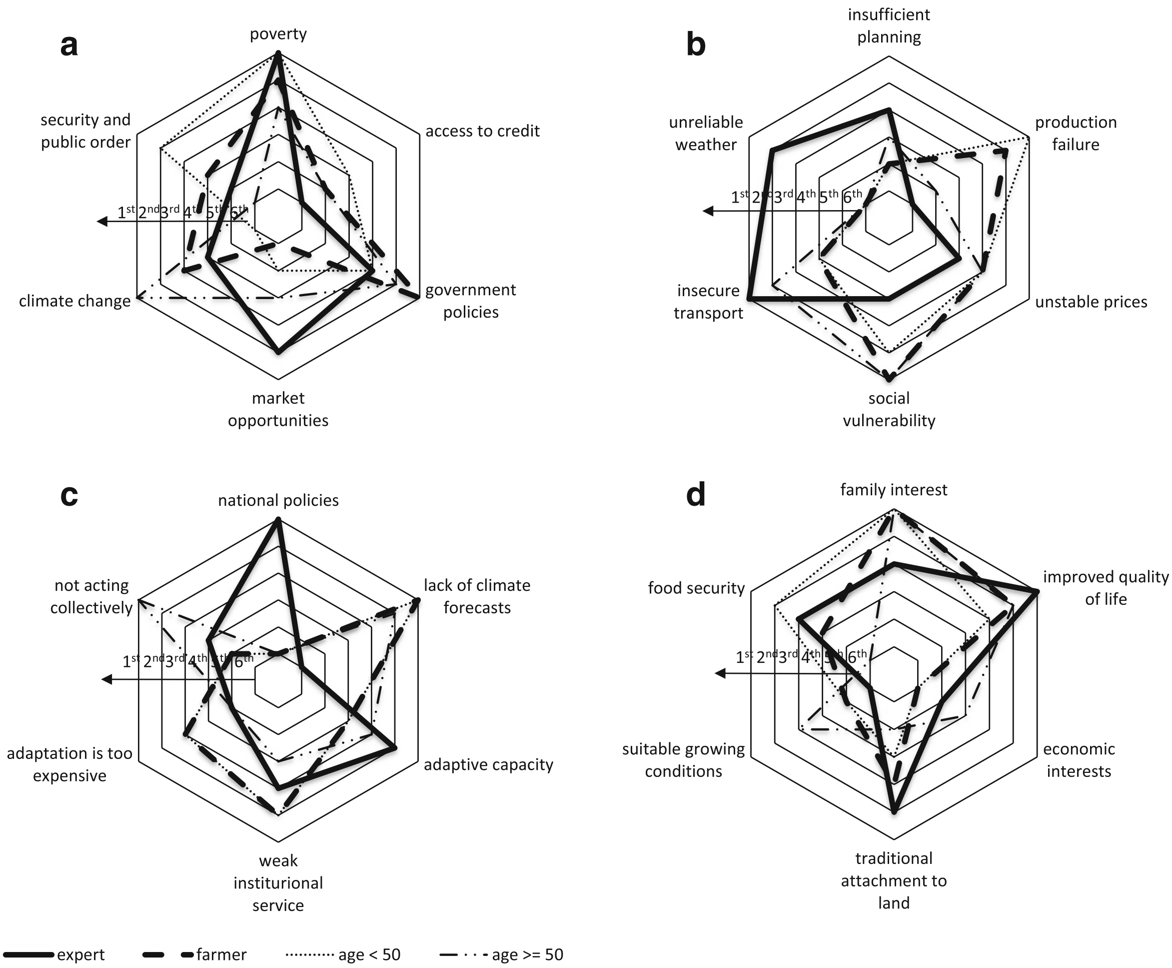

Fig. 4 Differences in experts' (solid thick line) and farmers' (dashed thick line) rankings of farmers' **a** worries, **b** risks, **c** barriers to adaptation, and **d** enablers for adaptation. Rankings of farmers with age below 50 (dotted narrow line) and farmers with age above 50 (dashed-doubled-dotted narrow line)

The main differences in the rankings between experts and farmers were related to risks (Fig. 3b). For farmers, the highest perceived risks were a failure in crop production and social vulnerability (lack of access to health and educational services). Experts, in contrast, perceived insecurity (theft of products from plots or during transportation) and the unreliable weather to be the highest risks for farmers. From a gender perspective, results showed that women and men disagreed in rankings with experts for few themes. Whereas women agreed with experts that insufficient planning is a major risk (even ranking it higher than experts), men agreed with experts that insecurity is a high risk (for women, this was among the lowest risks). The risk rankings showed clearly that farmers see the symptoms of social inequality (first rank of social vulnerability), agricultural production, and market risks such as unstable prices or production failure. Farmers ranked insufficient planning lower and unreliable weather very low compared to experts. These results showed that experts rather ranked risks from climate higher than farmers did. Experts would rather expect a higher planning activity of the farmers for adaptation to climate risks. Contrastingly, farmers believed that they were doing already as much as they could.

Experts and farmers also ranked barriers to adaptation differently (Fig. 3c). Experts perceived both external factors such as the national policy and internal factors such as the adaptive capacity of farmers to be the main barriers for deciding to take action and to adapt to change. Farmers, in contrast, ranked the lack of information about weather and climate, especially seasonal weather forecasts, as their main barrier to act by adapting to change. Farmers with age above 50 ranked not acting collectively the highest among the barriers for adaptation. The ranking of barriers showed that especially younger farmers felt financially unable (they ranked *adaptation is too expensive* high) to adapt to production risks from climate change (Fig. 4c). The fact that they ranked adaptive capacity low as barrier showed that they felt prepared to adapt to change but missed access to reliable weather information for planning (ranked high as a barrier). The experts rather saw the necessity for more activity in adaptation (high ranking of adaptive capacity as a barrier) and the rigid national policies impeding farmers' adaptation. Experts did not share farmers' perception about the relevance of improved weather information.

The agreement between experts and farmers was mostly on farmers' motivations (enablers to adaptation), which were family interests, increased quality of life, and traditional attachment to land (Fig. 3d). Regarding the motivations, one expert mentioned during the interview that: "Farmers in Cauca do have a strong connection to their roots. Territories and family unity are very important" (expert's interview, translated from Spanish, Colombia, August 2014). Within these motivations, however, men and women placed different emphases. While women ranked food security and traditional attachment to land higher than men, men ranked economic interests and improved quality of life higher than women.

3.3 Farmer typologies of risk perception

The cluster analysis of farmers' first ranked answer to each question yielded four typologies of farmers based on the farmers' perception of concerns, risks, barriers to adaptation, and enablers for adaptation:

i) Cluster 1—Higher-educated women–dominated farmers that are attributing risks to external factors: farmers belonging to this group are worried about ending up in poverty and fear that they will not be supported by the government. They consider insufficient planning of their farming activities as well as a lack of access to social services (social vulnerability) as key risks for their future. In the view of this group, farmers are dependent on weather forecasts which they consider necessary to adapt to risks in agricultural production; they perceive that not cooperating as a community is a barrier for taking action. Their adaptive capacity could potentially be triggered if they perceived that the quality of life for them and their families would increase from implementing adaptation measures. The group of farmers in cluster 1 consists of 62.5% women and 37.5% men with an average age of 44 years; 50% of the farmers reached the primary education level only, and 38% have obtained a legal land title (50% have started a legal process). The average farm size is 4 ha.
ii) Cluster 2—Lower-educated production–focused farmers with the land title: farmers belonging to this group are worried about a lack of access to credit or money to adapt agricultural production to change, and they are concerned about the government policies for rural development. These farmers perceive production failure due to uncontrollable factors (pest and diseases, climate events) and volatile selling prices for their products as the highest risks. The main barrier to adapt to change is a combination of low adaptive capacity and missing support from institutions. Similar to the first group, production-focused farmers are motivated to adapt to changes if their own and their families' quality of life would increase. The group of farmers in cluster 2 consists of 43% women and 57% men with an average age of 44 years; 64% of farmers reached the primary education level

only, and 57% have obtained a legal land title (29% have started a legal process). The average farm size is 2 ha.

iii) Cluster 3—Vulnerable, less-educated farmers with lower access to land: farmers belonging to this group are worried about unstable markets for selling their products and the associated poverty risk. Compared to the others, their perceived risk is based not only on production but also on insecurity issues on their farms and during the transport of their products to the market. The main barriers for this group of farmers are high costs for implementing adaptation measures to cope with risks and the missing support from institutions. Members of this group share motivation for adapting to change due to being traditionally attached to their land and region. They want to improve the quality of life for themselves and their families. The group of farmers in cluster 3 consists of 47% women and 53% men with an average age of 46 years; 67% of farmers reached the primary education level only, and 27% have obtained a legal land title (47% have started a legal process). The average farm size is 2 ha.

iv) Cluster 4—Risk-aware male–dominated elderly farmers with the land title: farmers of this group are worried about the government, risks from climate change, and the overall security in their region. The risks perceived as the highest by these farmers are social vulnerability such as the lacking access to social services and the risks associated with regional insecurity. The main barriers to adaptation lack weather forecasts and a low adaptive capacity on their farms. Like cluster 3 farmers, they feel traditionally attached to their land and also believe that their land is highly suitable for agricultural activities. The group of farmers in cluster 4 consists of 38% women and 62% men with an average age of 57 years; 69% of farmers reached the primary education level only, and 62% have obtained a legal land title (38% have started a legal process). The average farm size is 3 ha.

Detailed results of all comparisons, gender differences, and the hierarchical clustering of farmers' rankings are presented in Online Resource 4.

4 Discussion

This paper presented an integrative approach to understanding how climate risks are integrated into the context of other risks in the farmers' decision-making process. We compared the experts' with the farmers' view and differentiated between concerns, risks, and barriers for adaptation, and enablers to adaptation. Two explanations in the literature stress why this type of integrated analysis of farmers' risk is more suitable than an isolated analysis of climate change risks: (i) farming systems of smallholders in the developing world are complex systems of location-specific characteristics integrating agricultural and nonagricultural livelihood strategies, which are vulnerable to a range of climate-related and other stressors (Morton 2007; Feola et al. 2015), and (ii) farmers' long-term memory of climate events tends to decrease significantly after a few years; therefore, the importance of climate risks in farmers' perceptions may equally decline very quickly after disturbing climate events (Brondizio and Moran 2008).

In the case of Cauca, the interviews were conducted in 2014, a year with ENSO neutral conditions, the same as the two previous years. Farmers ranked climate risks low among their perceived risks in agricultural production, a perception that might change if the interviews would have taken place in a year affected by ENSO conditions (e.g., with a prolonged drought and high temperatures).

4.1 Reasons for potential maladaptation

Our findings showed that in Cauca, differences in experts' and farmers' perception and related farmers' concerns, risks, and barriers and enablers for adaptation existed and could lead to miscommunication and, consequently, to a maladaptation to climate change. This was partly explained by the finding that experts agreed with farmers about main concerns for farmers but disagreed about risks and barriers for adaptation, thus suggesting that the same view on a problem might not necessarily lead to similar action propositions. Our study contributes to a growing literature on how perception influences farmers' decision-making for adaptation and adaptation behavior. We especially analyze how climate risks relate to and interact with other risks and concerns in the farmers' decision-making process. This is important because smallholder farmers in countries like Colombia are subject to multiple interdependent stressors and deeply rooted social vulnerability. This interdependency requires a systemic perspective in farmers' risks. Some other studies simply compare meteorological data with people's memories of historical climate events (Boissiere et al. 2013); they attempt to link farmers' perceptions about climate change and related risks to adaptive behavior (Jacobi et al. 2013; Quiroga et al. 2014; Barrucand et al. 2016). Our integrated view on farmers' perceptions and decision-making might better capture the multitude of stressors for farmers and showed a lower perceived relevance of climate risks than other studies focusing on farmers' perception of climate risks. Especially for countries like Colombia, where multiple stressors and rooted causes of social vulnerability act simultaneously on farmers' decision-making, the adaptive capacity to climate risks is constraint (Reid and Vogel 2006; Feola et al. 2015). Our findings show that farmers see the symptoms of social inequality but not their low adaptive capacity to cope with risks from climate change. The farmers' low ranking of insufficient planning and unpredictable weather as risk equally underlined their lack of perception of climate risks, which was not perceived in the same way by experts. Contrastingly, the experts rather looked first at climate risks and insecurity for transport, but instead did not perceive production failure, unstable prices, or roots of social vulnerability as high risks.

4.2 What can we learn about climate risk communication?

While experts focus on communicating climate change risks, in cases such as we found in Cauca, farmers do not see such information as practical since their highest perceived risk is the poverty trap (social vulnerability) and the sum of risks related to the agricultural production of which climate risks are merely a part. In their article, Reid and Vogel (2006) pointed to this fact by stating that farmer's associate crop losses sometimes with climate events which are, however, not always seen as extraordinary and farmers are accustomed to coping with them. This is also supported by our findings. Farmers in Cauca do not rank climate risks high among their perceived risks, but they rank the lack of weather forecast and weak institutional services as the most important barriers for adaptation to agricultural production risks. Differences between experts' and farmers' views related to the weather forecast, seasonal forecast, and climate change projections of long-term changes and inter-annual climate variability are relevant issues in climate risk communication (Weber 2010). In the case of Cauca, experts do not perceive that there is a lack of climate information for farmers. Thus, we recommend that experts should provide context-based–climate-related information in such a way that it becomes tangible and usable for farmers in their everyday and long-term decision-making, for example daily and seasonal weather information associated with agro-advisory services on varieties, planting dates, and water management.

4.3 A need for a more holistic perspective on adaptation

Our findings show that farmers in Colombia do not perceive climate risks separately; they are embedded in their mental models of agricultural livelihood risks. Other scholars have shown that in Colombia, climate change, trade liberalization, and violent conflicts act simultaneously on farmers' livelihoods, but policies address them separately (Feola et al. 2015). If the implementation of policy actions is not coordinated, they might hinder each other or lead to failure. Understanding differences between experts' and farmers' mental models about risks is the first step to better design adequate policy actions for adaptation. Additionally, our results show that farmers in Cauca hardly trust national policies as mentioned by some experts as well as by farmers during the interviews. Farmers in Cauca are overall concerned about national policies. Llorente (2015) asserts that this is a result of the violent conflict which, in rural areas like Cauca, has led to profound mistrust in the state. Feola et al. (2015) argue that the institutional integration between different levels of government has been historically difficult in Colombia. Agricultural policies are often not based on the realities of smallholders. However, before designing adaptation strategies for farmers, the deeply rooted social vulnerability and inequality must be addressed and brought to the focus of experts. Ideally, this should be done together with farmers as a social learning process.

"Adaptation is a dynamic social process" (Adger 2003, p. 387), including many different actors. We agree with Vogel and Henstra (2015) to involve local actors in the development process of adaptation plans instead of operationalizing top-down adaptation measures. We suggest starting this process by developing a Local Adaptation Plan of Action (LAPA) in Cauca, aiming at initiating a bottom-up process of adaptation planning, which takes into account the community and individual levels (Jones and Boyd 2011; Regmi et al. 2014). The uptake of adaptation strategies depends on barriers and the adaptive capacity of both the community and the individual farmer.

Effective adaptation at the community level would require a mix of top-down structural measures, often provided by institutions, including national adaptation plans, financial services, economic incentives, and nonstructural measures developed by the community itself as a collective action (Girard et al. 2015).

Finally, transformative adaptation instead of targeting climate change by individual technological solutions would be a better approach for Colombian smallholders because it focuses on the root of vulnerability rather than on the adaptation of production systems only (Feola 2013). Such an approach would bring a more central role to farmers in developing adaptation options together with experts and would stimulate a social learning process in which science engages with lay knowledge and contributes with its transformative role to society (Feola 2013; Mauser et al. 2013). Climate change in the context of Latin America is characterized by complex lay and expert knowledge systems, social coping mechanisms, and ancient resilience mechanisms to adapt to perturbations (Sietz and Feola 2016). Several scholars support the need for an integrated approach to address critical dynamics of vulnerabilities and constraints for adaptation around climate change more integrated into cultural and socioeconomic realities (De los Ríos Cardona and Almeida 2011; Ulloa 2011). Other authors call for identification of causes of vulnerability and transformative solutions to cope with risks from climate change

(Ribot 2014). Anyway, the state and its institutions are also important to provide a policy framework for adaptation, to intervene when resources are required, and to enable needed policies (Ramirez-Villegas and Khoury 2013). Finally, cooperatives could play a crucial role and become vehicles for rural development, opposite to previous top-down approaches that have failed in Colombia (Gutiérrez 2014).

For further research, we recommend to study the dynamics in the farmers' complex livelihood system, to analyze the actor's network of farmers, and to identify adaptation pathways for farmers to cope with climate change in Cauca, Colombia.

5 Conclusions

Since the 2015 Paris Agreement (COP 21), the political commitment to take action on climate change increased. Even in developing countries, policymakers have started working more specifically towards policies for achieving climate resilience, especially in the agricultural sector. Agriculture, both contributing to climate change and being affected by climate change, needs a transformation to become more sustainable and climate resilient by improving farmers' livelihood system and farm productivity while reducing emissions from agriculture. Especially, transforming smallholders' agriculture in developing countries such as Colombia requires greater attention to human livelihoods and related concerns, risks, barriers to decision-making, and the adoption of adaptation strategies.

This study applied a mental model approach to understand better climate risks in the context of farmers' decision-making process. It showed that climate risks need to be seen in the overall context of farmers' livelihood risks. Climate change adaptation strategies and policies can be more successful if they (i) address specific climate risks, (ii) simultaneously address other risks of major importance for farmers, and (iii) target more climate risk–sensitive groups of farmers. Our research demonstrates that understanding differences in experts' and farmers' perception of farmers' livelihood risks could avoid maladaptation and improve climate risk communication from experts to farmers. Therefore, we recommend to study the dynamics in the farmers' complex livelihood system, to analyze the actor's network of farmers, and to identify adaptation pathways for farmers to cope with climate change in Cauca, Colombia.

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Understanding farmers' livelihood system and actors for effective climate change adaptation

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Abstract

Threats from climate change are becoming more frequent and the impact on agriculture and food security is evident. Given that climate risks are not the only risk that farmers face in their rural livelihoods system, it is important to understand multiple risks and feedback loops of livelihood dynamics and to identify important actors for a successful climate change adaptation. Therefore, it is necessary to understand how beneficial knowledge on climate change adaptation reaches farmers and influences their decision-making. In this study, we (i) analyze the farmers' actors network as a major element of social capital for adaptation, and (ii) elicit feedback loops between livelihood capitals that enable decision making and action. We found that farmers perceived local community actors to be closer to them than actors from the agricultural value chain and they perceived governmental actors as being most distant from them; experts perceived actors from the agricultural value chain and from governmental institutions closer to farmers. Thus, local community actors should be involved in the design and implementation of climate change adaptation plans. Further, we found complex feedback loops in the farmers' livelihood system that might hinder farmers to perceive risks from climate change. Thus, we recommend that effective climate change policies and communication should show and address the interlinked multiple risks that farmers face in their livelihoods system, including climate risks.

Keywords:

Climate change

Adaptation

Sustainable livelihood framework

Network analysis

Systems dynamics

Causal-loop diagram

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1. Introduction

Threats from climate change are growing and are becoming evident around the world (Hansen and Cramer 2015). While public concern and climate change awareness have gained more weight (Lee et al. 2015; Knight 2016), implementation of policies to reduce greenhouse gases (GHG) and mitigate threats coming from climate change is still slow (Beddington et al. 2012; Heffernan 2016). Agriculture plays a double role: on the one hand, it is one of the main contributors to global GHG emissions (Roman-Cuesta et al. 2016); on the other hand risks from weather fluctuations and seasonal anomalies already affect agricultural yields and food security in many regions of the world (Lobell et al. 2011). Furthermore, impacts from climate change on agriculture are expected to hit economic livelihoods in poor countries hardest (Fischer et al. 2005; Hertel et al. 2010).

Over the last two decades, adaptation has become an important framework in agriculture to deal with impacts from climate change (Eriksen et al. 2015). Unlike mitigation, which often starts on a national level through policies, adaptation often arises from concrete needs for local activities to limit impact (Biagini et al. 2014). Depending on the impact gradient, it consists of coping strategies for existing agricultural systems, systemic changes, and transformation when incremental adaptations are insufficient (Kates et al. 2012; Ramirez-Villegas and Khoury 2013). In developing countries, farmers' livelihood system capacity to adapt to changes is lower than in developed countries and farmers are often exposed to multiple risks, including climate risks (Mubaya et al. 2012; Eakin et al. 2014; Feola et al. 2015). Moreover, livelihood systems of smallholders in these countries are difficult to understand because they rely on agricultural and non-agricultural livelihood strategies. For all these reasons, it is important to understand the farmers' livelihood system and its related risks when starting to design and implement adaptation strategies at the local scale.

The sustainable livelihood framework (SLF) has been widely used as a common approach to study farmers' livelihood systems (Reid and Vogel 2006; Simane et al. 2014). The livelihood approach helps to understand the diversification of rural livelihoods as part of a coping strategy regarding hazards from climate shocks (Berman et al. 2014), and it can be useful to identify the farmers' vulnerability to climate change (Baca et al. 2014). The SLF provides an analytical approach to structure farmers' livelihood resources as capitals, which, in combination, form livelihood strategies. In the SLF, livelihood resources can be differentiated as farmers' human, natural, social, physical and financial capital (Scoones 1998). The SLF usually takes a rather static and linear perspective, whereas farmers are confronted with interactions and dynamics between the different livelihood capitals in their decision-making process (Binder and Schöll 2010).

Several scholars have used a system dynamics (SD) approach to better understand these dynamics between livelihood capitals in agricultural systems (Bontkes and Van Keulen 2003; Tittonell 2014). The causalities elicited in, e.g., semi-structured interviews and mental models (Sterman 2000; Schoell and Binder 2009; Binder and Schöll 2010) are represented with causal-loop diagrams (CLD); (Sarriot et al. 2015). Given the complex decision-making situation of farmers, we consider that the identified causal structure from such diagrams could inform us on how farmers evaluate dynamics in their livelihood systems and how they include climate risks in their evaluation.

Finally, it has to be noted that social capital is an integral part of successful adaptation to climate change because it facilitates cooperation and trust (Paul et al. 2016). Social capital is nourished by networks, relations, associations, and other social resources upon which people draw to coordinate action (Scoones 1998). The adaptation process is a social process as it often involves networking of agents through their relationships and with the institutions they depend on (Adger 2003; Eriksen et al. 2015). To be effective, adaptation processes should link top-down policies with bottom-up community approaches. While top-down strategies are often impact-based, bottom-up approaches focus on social domains like vulnerability, adaptive capacity or community needs (Regmi et al. 2014; Girard et al. 2015). For successful adaptation, it is crucial that farmers trust actors who are involved in the design and implementation of adaptation strategies.

The goals of this study are (i) to explore farmers' social capital by analyzing farmers' networks of actors; (ii) to compare the experts' external view of the actors' network with the farmers' internal view, (iii) to analyze the dynamics and interactions between livelihood capitals; and (iv) and to identify feedback loops in the farmers' livelihood system.

This paper presents results from the Cauca department in Colombia. We combined the SLF with CLD and compared the experts' external view with the farmers' internal view of the livelihood system using a mental models approach. It is part of a study looking at differences between farmers' and experts' risk perception and consequences for decision-making in climate change adaptation. In a complementary paper, we address the differences in perception between experts and farmers on climate change risks in relation to other livelihood risks.

2. Material and methods

2.1. Study area, sampling and data collection

This study was carried out in the Cauca department in Colombia. Five villages from a rural community of the municipality of Popayan were selected for this study. The major crops grown by smallholders in the study area are coffee, sugarcane, cassava, maize, plantain and common beans. For several decades, farmers in Cauca among other regions in Colombia suffered under the armed conflict; hence, the region is lacking behind in infrastructure development. These circumstances prevented especially rural smallholder farmers from improving their livelihood systems in the past. We employed semi-structured interviews with 13 national and local experts and with 58 farmers from the selected villages, which amounted to more than 10% of the total number of farm households in the study region. The interviews sought to understand the differences of the experts' external view and the farmers' internal view on dynamics in the farmers' livelihoods system and the farmers' actors' network representing the social capital. We chose a quota sampling method that requires representative individuals out of subgroups, we gathered 10 to 12 farmers from different villages, from age groups between 20 and 60 and equal representation of men and women. In Cauca, farmers have similar beliefs and we rely on a small sample to be reasonable according to Morgan et al. (2002)

2.2. Approaches for understanding interactions in the farmers' livelihood system

Following the Structured Mental Model Approach of Binder and Schöll (2010), we analyzed and compared interactions of livelihood capitals between farmers and experts to understand dynamics that influence their decision making. The underlying conceptual framework hypothesizes that farmers' perception of climate change is shaped by intangible characteristics like their beliefs, existing social norms and values, as well as existing knowledge and previous experiences from climate shocks. The differences of experts' and farmers' perception of climate risks in Cauca using a mental models approach are described in first part of our research. Here, in the second part of our research in Cauca, we focus on farmers' livelihood system using the SLF and CLD from systems dynamics (Fig. 1). In applying our approach, we captured experts' external views and compared them to the farmers' internal views about interactions between livelihood capitals embedded in the farmers' livelihood system.

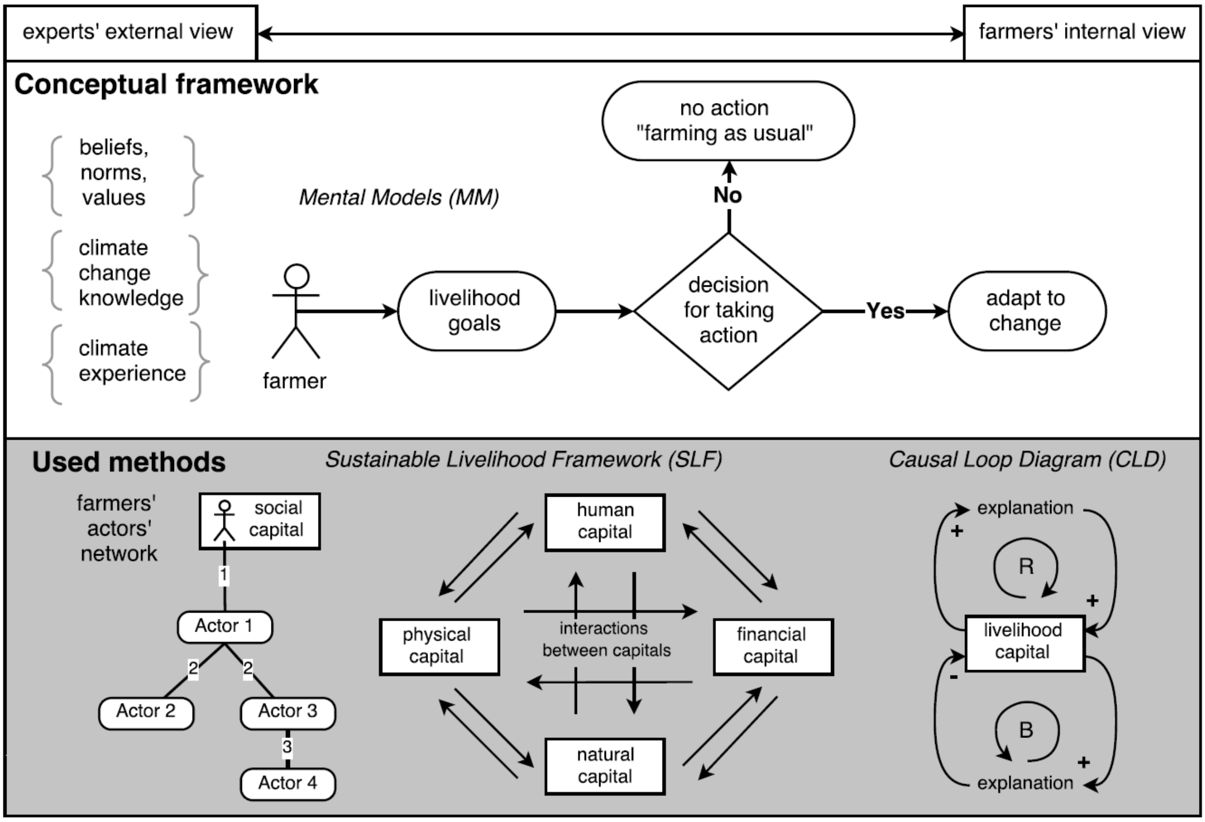

Fig. 1 Approaches used for understanding interactions of livelihood capitals in the farmers' livelihood system; mental models (MM), network Analysis, the sustainable livelihood framework (SLF) and causal loop diagrams (CLD).

Our conceptual framework is based on mental models (MM) to elicit farmers' perceptions and underlying views on livelihood risks. Using a MM technique in interviews provides better insights in perceptions and priority settings of farmers (Morgan et al. 2002) and it can help to understand how individuals construct representations of risk (Schoell and Binder 2009). For the farmers interview we used pictures of the livelihood capital elements and cards with names and logos of actors to develop the actors' network.

The concept of SLF by Scoones (1998) postulates that sustainable rural livelihood strategies depend on livelihood resources consisting of different types of capitals. We used this concept to gain insights into experts' and farmers' views of the farmers' livelihood system. First, we analyzed the social capital by elaborating, visualizing and comparing a farmers' actor network of both experts and farmers. Second, we analyzed the views of experts regarding the interactions between the other four livelihood capitals, i.e., natural, human, physical and financial capital. Based on the experts' explanation of interactions between the different livelihood capitals, we developed specific questions for the farmer interviews to understand their view on interactions and feedback loops within their livelihood system. Analyzing the explanations of interactions between livelihood capitals by farmers and experts, we developed a CLD (Sterman 2000) in which we focused on understanding feedback loops and decision-making within the context of the farmers' livelihood system.

2.2.1. Depicting the farmers’ social capital through a network of actors

We depicted experts’ and farmers’ views of the farmers’ social capital by developing a network of actors for the farmers. We then calculated the distance of each actor to all individual farmers. In the expert interviews, we first identified the relevant actors and designed a network of actors from the experts’ point of view. We formed groups of actors, i.e., (i) actors from farmers’ social community network such as family, neighbors, churches, and community leaders, among others, (ii) governmental actors, including the local government, the ministry of agriculture, and state banks, and (iii) actors in farmers’ agricultural value chain, comprised of producer organizations, intermediaries, input sellers, and extension services. Subsequently, we calculated the distance of each actor and of each actor group to farmers as perceived by experts. We assigned a value of one to actors directly connected to farmers; we assigned a two to actors connected via a different actor; more distant actors were assigned a three (see *farmers’ actors’ network* in Fig. 1 (left)).

After developing the experts’ version of the farmers’ network of actors, we prepared cards with the names or institutional logos of the actors named by the experts. We showed the full set of cards to each farmer during the interview and asked each farmer to build his/her own actors’ network. As for experts, we calculated the average distance of actors assigned by farmers. Finally, we determined the average difference between the arithmetic mean distance assigned by experts and the mean distance assigned by farmers for each actor and for each group of actors.

2.2.2. Understanding interactions between natural, human, physical and financial capitals

To understand the farmers’ livelihood system, we first identified important interactions between human-, natural-, financial-, and physical capital from the experts’ view. In the interviews, we started by introducing the concept of the SLF to stimulate ideas. Subsequently, experts listed individual capital elements they thought to be important for the farmers and gave explanations for each. We kept this part of the interview open in order to capture experts’ explanations of livelihood capital elements in farmers’ livelihood system. Experts sorted each of the elements into one of the four individual capitals mentioned previously.

Following the identification and sorting of capital elements, we asked experts about their opinion on how the different capitals interact with each other. We prepared templates (see *interactions between capitals* in Fig. 1) on which experts drew and illustrated their explanations of potential influences such as positive (reinforcing) feedback loops (R) or negative (balancing) feedback loops (B) between individual capitals. In one example, we asked experts how the natural capital would change if the human capital increased, and how the natural capital would change if the human capital decreased. We then counted experts’ responses about positive and negative feedback loops between livelihood capitals and developed structured questions for farmers building on the experts’ discussions and explanations of the feedback loops between capitals. Similarly, we explained to farmers the concept of individual livelihood capitals and showed them pictures of the capital elements which were selected after the expert interviews. After this explanation, we asked farmers structured questions which were prepared based on explanations of expert interviews. For example, experts mentioned the human capital and its positive feedback on the financial capital through the existence of family labor. To understand farmers’ perception about family labor we asked the following questions: Who is helping on your farm? Will the young generation continue farming? Experts’ and farmers’ allocation of elements to each livelihood capital and structured questions for the farmers’ interview can be found in Online Resource 1.

2.2.3. Developing a causal loop diagram of farmers' livelihood system

As a final step, we developed a CLD from farmers' explanations of interactions between livelihood capitals to obtain an integrative perspective of farmers' livelihood system. Within the CLD, we identified critical feedback loops to understand the dynamics in the farmers' livelihood system. The identified causal structure and interactions between variables in the farmers' complex livelihood system inform us on how farmers relate variables to each other and how they include climate risks in their evaluation. To visualize the CLD, we used the program Vensim (Ventana Systems Inc. 2006).

Starting from the four livelihood capitals and using variables derived from farmers' answers to open questions about livelihood capital dynamics, we linked the causal influences among variables by arrows. We indicated the polarity (+/-) of arrows showing how the change in one variable affects the subsequent variable. We included loop identifiers showing positive (reinforcing) and negative (balancing) feedback loops (see template for CLD in Fig. 1). An example for a reinforcing feedback loop is that if farmers are worried about poverty, they will increasingly look for off-farm work, which in turn causes reduction of labor opportunities in the region and increases worries about poverty among farmers.

In choosing variable names, we referred to terms that closely corresponded to the wording of answers from farmer interviews and derived polarities from farmers' explanations about dynamics. For example, farmers ranked the risk of production failure high due to the following reasoning: change to commercial coffee seeds resulted in increased need for inputs (+) and increased production costs (+); pest and diseases are uncontrollable external factors that can lead to production failure.

3. Results

3.1. Farmers' network of actors

In general, farmers perceived actors from their own social community network as being closer to themselves than actors from governmental institutions and actors from the agricultural value chain (Fig. 2). Experts agreed with the view that actors from farmers' social community network were closest to farmers. However, they perceived actors from the agricultural value chain and from governmental institutions closer to farmers than farmers themselves.

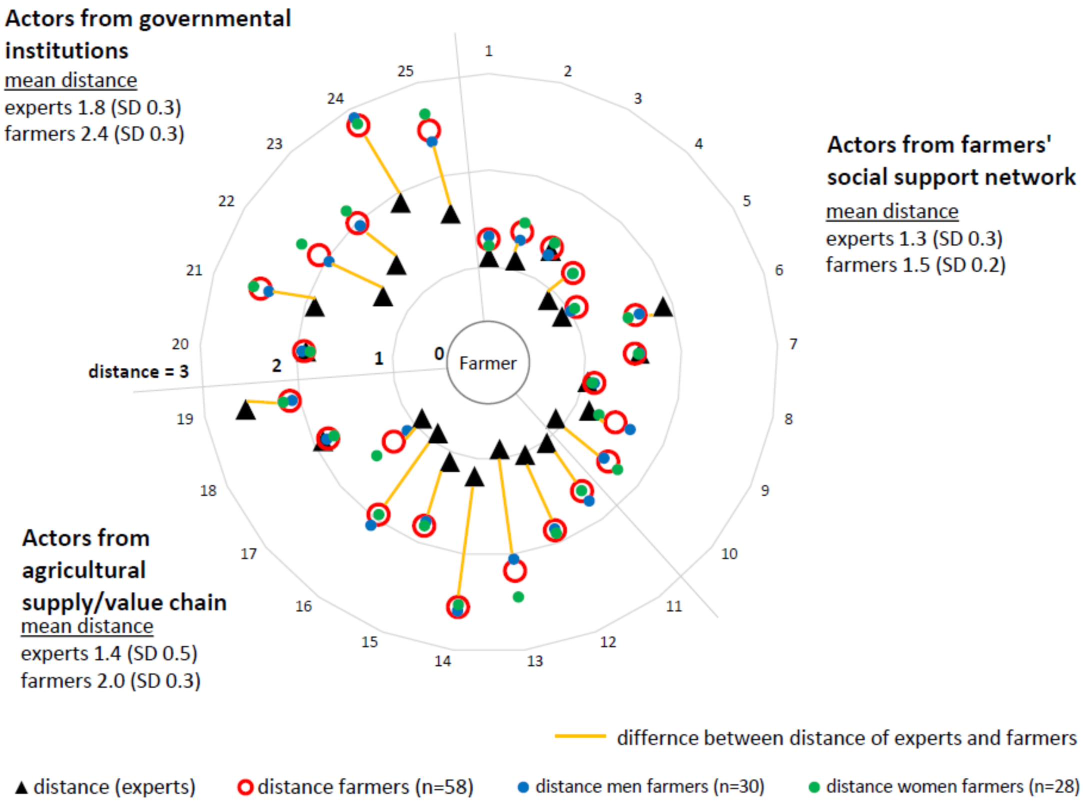

Fig. 2 Farmers' actors network; the calculated distance of farmers to their network actors perceived by 13 experts (black triangles) and 58 farmers (circles (all farmers) and points (gender specific)) on a scale from 1 (close to farmers) to 3 (distant to farmers). Parents' association (1), single mothers association (2), board of community leaders (3), village busdriver (4), family and relatives (5), families in action groups (6), local health service (7), neighbors (8), church and other religious groups (9), sports and culture groups (10), coffee producer association (11), sugarcane producer association (12), market intermediary (13), pesticide & input seller (14), extensionists and technical assistance (15), stores in municipalities (16), workers (17), coffee federation (18), sugarcane federation (19), state bank institute (20), national agriculture institutions (ICA, Corpoica) (21), ministry of agriculture (22), police / security groups / soldiers (23), representatives from the local government (24) and representatives from the municipality (25).

Experts perceived that actors from the value chain were equally close to farmers as actors from the social community network (mean distance 1.4), while farmers perceived value chain actors as more distant (mean distance 2.0); the largest distances were identified by farmers for pesticide and input sellers, intermediaries at the local market, and input stores in the municipality (numbers 14, 13, and 16 in Fig. 2). The only actors from the farmers' value chain which were indeed perceived as close to farmers also by the farmers themselves is the national coffee federation Fedecafé (18) (farmers' mean distance 1.9; experts' mean distance 2.0) and the coffee producer association working inside the community. Farmers perceived governmental actors as being most distant from them (farmers' mean distance 2.4). This is true for the representatives of the local government, from the municipality (24 and 25 in Fig. 2), as well as the national actors (22, ministry of agriculture). Experts' perceived government actors as being closer to farmers than the farmers themselves did, but still more distant than actors from the value chain and the social network (mean distance 1.8). Overall, women and men perceived most actors as comparably distant to themselves (red and blue dots in Fig. 2). A list of actors and distances to farmers perceived by experts and farmers can be found in Online Resource 2.

3.2. Interactions between livelihood capitals: the experts' view

During the expert interviews, we identified interactions between farmers' livelihood capitals as explained by experts (Table 1). Experts claimed that financial capital will increase if the human capital increases (11 of 13 experts), and vice versa, the human capital increases if the financial capital increases, and that this is a reinforcing loop (+ sign). The same view can be observed between human- and physical capital (12 and 7 experts) and between financial- and physical capital (all 13 experts). Between the natural and the financial capital, experts perceived differing effects stating that the financial capital will increase if the natural capital increases (11 experts), whereas the natural capital will decrease if the financial capital increases (9 experts), which lead to a balancing loop (- sign).

Table 1 Interactions between livelihood capitals based on experts' interviews; numbers are the number of experts identifying positive/negative interactions between capitals; bold numbers show that more than 50% of experts agreed on the respective interaction.

	Human		**Natural**		**Financial**		**Physical**	
Feedback loops	(+)	(-)	(+)	(-)	(+)	(-)	(+)	(-)
Human			6	2	**10**	2	**7**	3
Natural	5	7			3	**9**	3	**7**
Financial	**11**	1	**11**	2			**13**	0
Physical	**12**	0	5	2	**13**	0		

3.3. Interactions between livelihood capitals: the farmers' view

We found six reinforcing and two balancing feedback loops derived from farmers' responses to the structured questions about interactions between livelihood capitals (Fig. 3). We found three main reinforcing feedback loops that were explained by farmers as interactions between human, financial, and physical capital. However, farmers did not see relevant interactions of the natural capital with the other livelihood capitals.

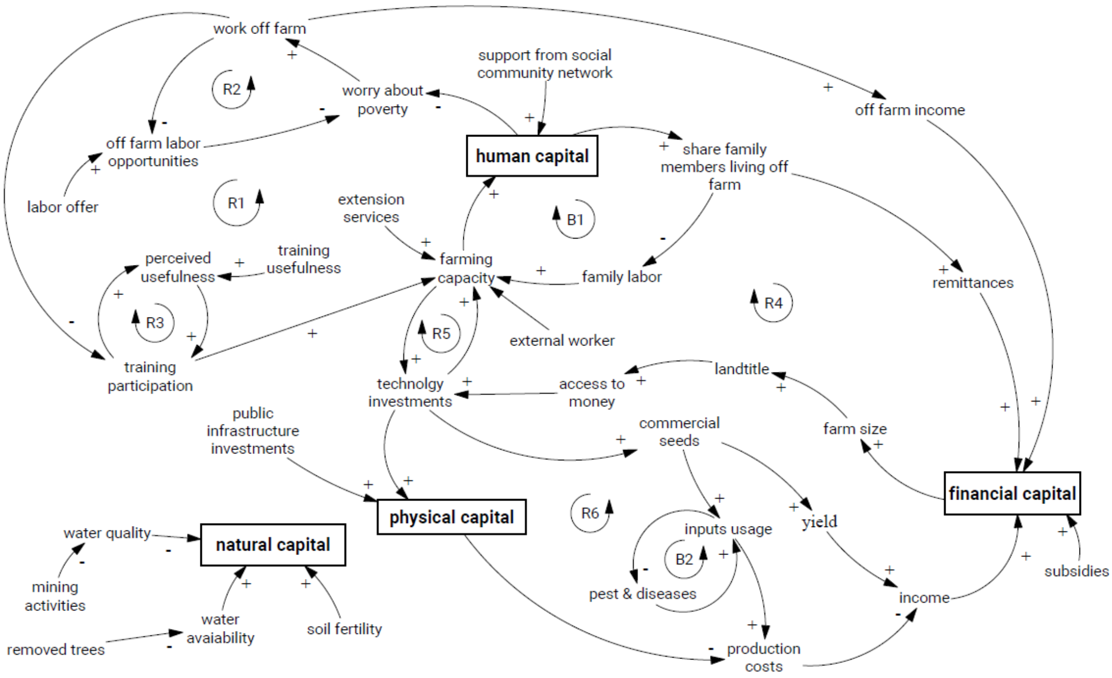

Fig. 3 Farmers' perception of livelihood dynamics, risks and feedback loops depicted as causal-loop diagram. Balancing feedback loops are marked as B, and reinforcing feedback loops are marked as R.

The reinforcing feedback loop *poverty trap* (R1) alludes to the problem of the perpetuating poverty loop. It is composed of the *off-farm labor* (R2) and *training assistance* (R3) loops. Farmers' concerns about poverty force them to increase their share in off-farm work. An increased share in off-farm work increases their financial capital, but, in turn, decreases their training participation, which is increasingly fostered by the low perceived usefulness of the latter. The lack of additional training leads to a stagnation in their knowledge about farming (farming capacity) and thus affects their human capital. This, in turn, fosters their concerns about poverty, leading to the positive reinforcing loop.

The *financial asset* (R4) feedback loop between human and financial capital is a moderated reinforcing loop, composed of the reinforcing feedback loop *technological investment* (R5) and the balancing feedback loop *family labor* (B1). In this loop, an increase in human capital leads to an increase in the share of family members living off-farm. This has two consequences: on the one hand, it decreases a family's labor capacity, thus, farmers need more paid external workers to do the farm work (B2). On the other hand, off-farm family members contribute to the financial capital through payments of remittance. This, in turn, opens the opportunity for farmers to increase their farm size and to get access to money by credits for technology investments which leads to more income from production (R4).

The reinforcing *production loop* (R6) combines financial and physical capital. From a farmers' perspective, increased financial assets lead to more land, technological investment, and income. The more comprehensive *production loop* R6 is balanced by the *production risk control* (B2) loop which the farmers explained by the steadily increasing need for fertilizer and chemical input for pest control and by the change to commercial seeds. Many farmers mentioned that public infrastructure investments such as improved road networks, which reduced their transport costs, improved the physical capital and reduced their production costs.

Farmers' explanations of interactions between the natural capital with the other capitals were limited. Some farmers explained that, by removing trees throughout the last decades, water availability had decreased, soils have become less fertile, and water quality deteriorated as a result of an increase in recent, mostly illegal mining activities.

4. Discussion

Our findings show that farmers in Cauca perceive actors from their own social community network as being closer to themselves than actors from governmental institutions and from the agricultural value chain. Experts partly agreed with farmers on the distance of actors; they perceived that actors from the agricultural value chain and governmental actors would be closer to farmers. From the causal-loop diagram that we developed from the interviews with experts and farmers, we found that farmers hardly see any relationship between climate change risks and their livelihoods system. We discuss three major aspects: First, the importance of local actors for implementing adaptation strategies; second, smallholders' capacity to adapt to climate change; and third, next steps and recommendations for future research.

4.1. The importance of local actors for implementing adaptation strategies

We showed for the Cauca department in Colombia as a region dominated by small—scale farmers in a developing country, which actors to assess for more likely success of developing and implementing adaptation strategies. Farmers perceived actors from their social community network as the only group to be close to themselves, whereas the experts thought that actors from the agricultural value chain and governmental actors would be closer to farmers. A study by Schoell and Binder (2009) showed that a reason for this perception of farmers was the lack in trust in the governmental institutions. In their analyses, farmers stated that representatives from governmental institutions were likely not to keep their word, not to provide the things they promised and that led to low trust in the government over time. Similarly, Baudoin et al. (2013) argue that local actors are often more trusted by farmers. Thus, for the implementation of adaptation strategies trusted and local actors should be considered.

Furthermore, we support the argument of Vogel and Henstra (2015) to involve local actors in the development process of adaptation plans instead of implementing them top-down. Government actors, once again, would not be successful in communicating adaptation strategies to farmers. The low success rate of beneficial outcomes for smallholders from top-down policies has also been supported by other studies that show that past approaches of rural development in Colombia failed. For example, the agrarian reform by the government starting in the 1960s and the recent hands-off approach, in which the government focused on enabling financial services without major involvement in the implementation, have failed to improve smallholders' livelihood system (Gutiérrez 2014).

We suggest based on our results from Cauca that local climate change adaptation plans should designed using participatory bottom-up approaches to enhance the adaptive capacity of smallholders and they should be linked to top-down policies without having dominating government agency representatives and other experts in the process (Lee et al. 2014; Regmi et al. 2014). In particular, our findings suggest that actors from the social community network such as the members of the board of community leaders are the key actors within the farmers' actors' network and should be included when developing adaptation strategies. However, other authors stated that while community opinion leaders are critical for mobilizing adaptive capacity, they are often not strategically connected with outside networks and not well-informed about projected impacts of climatic change (Keys et al. 2014). Considering this, we stress that experts from outside the community are important for awareness building and to support local leaders during the adaptation process with relevant information and practical knowledge about adaptation practices. Finally, we underline the fact that community-based bottom-up approaches are often more likely to be successful in the first phase of implementing adaptation strategies, but they need to be linked to policy-making and institutions in order to be scaled up (Regmi et al. 2014).

Several authors frame adaptation as a social process (Jones and Boyd 2011; Pidgeon and Fischhoff 2011; Adger 2016) which leads to the fact that more attention must be brought to the social capital. The social capital represents the value of relationships that facilitate cooperation and collective action through trust (Paul et al. 2016). Farmer-to-farmer extension (FFE) as a paradigm shift away from top-down strategies is becoming more and more important and is playing a complementary role to formal extension services (Kiptot and Franzel 2015). It requires observation, joint learning, reflection and feedback. Our findings support the above statements and, as a consequence, highlight the role of local actors from the social community network. The role of the government in the adaptation process must be to support ongoing local dynamics of farmers in their social community network and to scale successful adaptation. This further implies that government-related organizations have to build trust with farmers by considering their vulnerability and needs for adaptation.

4.2. Smallholders' livelihood system and the capacity to adapt to climate change

National and local adaptation plans should address interlinked livelihood risks. This is important because complex feedback loops in the farmers' livelihood system might hinder farmers to perceive risks from climate change.

Smallholders' livelihood systems are complex and they are characterized by interactions between livelihood capitals that often lead to unexpected feedback loops for farmers. In our causal-loop diagram of farmers' livelihood system in Cauca we showed these interactions as reinforcing and balancing feedback loops from experts and farmers explanations. Especially in the farmers' view of capital interactions, climate risks were not important. However, climatic change and increased climatic variability are very likely to be exacerbated in the coming decades in Colombia and expected impacts on agriculture are most likely negative (Jarvis et al. 2011; Ramirez-Villegas et al. 2012). These impacts from climate change and variability act besides other stressors on smallholders' livelihood systems. Other stressors in Cauca are particularly trade liberalization and the legacy of violent conflict and post-conflict resolutions (Feola et al. 2015). Multiple stressors acting on the farmers' livelihood system enhance the vulnerability and constrain the adaptive capacity to climatic change and variability (Reid and Vogel 2006).

4.3. Next steps and recommendations for future research

Although the benefits of using a holistic approach, including interviews, network analysis and analyzing systems dynamics, are considerable, they provide a significant avenue for further research. First, the cause of different perceptions of the farmers' network of actors between experts and farmers needs to be analyzed. Second, the causal-loop diagrams should be validated again with farmers and experts separately to support the development of a common system understanding. Thus, we propose that future research should focus on two things: First, analyze the causes for the difference in perceptions of the farmers' network of actors in workshop and in depth-interviews. Second, based on the basic causal-loop diagram of the farmers' livelihood system, we could develop an agent-based model to simulate effects and parameters that stabilize or destabilize the farmers' livelihood system. Independent variables in the model could be farm size, ownership, and access to financial services among others.

5. Conclusions

Threats and damage from climate change are becoming more frequent and the impact on agriculture and food security is now evident. While the implementation of policies is still slow,

the public awareness of the need for adaptation has increased. Developed adaptation strategies should be implemented now in coordination with community-based bottom-up approaches.
In this paper, we explored the experts' and farmers' views on the role of different actors in the farmers' network. Subsequently, we applied concepts from the sustainable livelihood framework and causal-loop diagrams to understand interactions in the farmers' system of livelihood capitals. We found (i) that farmers perceive actors from their social community networks to be closer to them than actors from outside the community, (ii) that farmers' livelihood systems are characterized by interactions between livelihood capitals that might lead to unexpected feedback loops for farmers, and (iii) that climate risks are not perceived as being problematic in their livelihoods systems.
As a consequence of our findings, successful top-down policies and adaptation plans need to fit into the local context of farmers' livelihoods system and risks farmers are exposed to. Moreover, the implementation process of adaptation strategies in agriculture needs to be co-designed with farmers and other local key actors.

Online Resources

Online Resource 1 Elements to stimulate mental models about dynamics in livelihood systems
Online Resource 2 Experts' and farmers' view on distances of actors to farmers

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Original papers

GeoFarmer: A monitoring and feedback system for agricultural development projects

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ABSTRACT

Farmers can manage their crops and farms better if they can communicate their experiences, both positive and negative, with each other and with experts. Digital agriculture using internet communication technology (ICT) may facilitate the sharing of experiences between farmers themselves and with experts and others interested in agriculture. ICT approaches in agriculture are, however, still out of the reach of many farmers. The reasons are lack of connectivity, missing capacity building and poor usability of ICT applications. We decided to tackle this problem through cost-effective, easy to use ICT approaches, based on infrastructure and services currently available to small-scale producers in developing areas. Working through a participatory design approach, we developed and tested a novel technology. GeoFarmer provides near real-time, two-way data flows that support processes of co-innovation in agricultural development projects. It can be used as a cost-effective ICT-based platform to monitor agricultural production systems with interactive feedback between the users, within pre-defined geographical domains. We tested GeoFarmer in four geographic domains associated with ongoing agricultural development projects in East and West Africa and Latin America. We demonstrate that GeoFarmer is a cost-effective means of providing and sharing opportune indicators of on-farm performance. It is a potentially useful tool that farmers and agricultural practitioners can use to manage their crops and farms better, reduce risk, increase productivity and improve their livelihoods.

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1. Introduction

The agriculture paradigm is changing, with the collection and use of data for decision making becoming increasingly important (Pham and Stack, 2018). The strategic application of information and communication technologies (ICT) in order to improve information sharing has been used as one means to achieve economic growth and increase welfare in developing countries (Yonazi and Kelly, 2012 quoted by Baumüller, 2017). Smart farming (Griffith et al., 2013) using ICT components has been promoted by many national and international initiatives for inclusion in development initiatives (ARD, 2011). For scientists and agricultural practitioners, digital skills, including data collection methods, analytical techniques, and communication technologies, offer opportunities to understand complex farming ecosystems and to tackle the challenges of agriculture (Kamilaris et al., 2017). ICTs can provide farmers with better access to information and improve their ability to share knowledge amongst themselves and with others.

However, the use of ICT in agriculture does not always lead automatically to higher yields and profits for farmers. Even though ICT access and use are emerging fast in developing countries, barriers to accessing mobile-phone based agricultural services still exist (Aker and Mbiti, 2010; ARD, 2011). Though progress has been made through digitalization initiatives that lead to improvements for smallholder agriculture (Baumüller, 2015; Courtois and Subervie, 2014; Tata and McNamara, 2018), they still do not reach many farmers in developing countries. Lack of connectivity, missing digital capability and poor usability of ICT applications are some of the impediments that slow implementation of digital agriculture in the rural context (Baumüller, 2017; Salemink et al., 2015). If new solutions for digital agriculture do not address these shortcomings, farmers may face new digital poverty (May, 2012). ICT initiatives should recognize the local context of connectivity, users capacities, and the cultural background to avoid a digital divide with marginal groups of smallholders driven into digital poverty (Aker et al., 2016; May and Diga, 2015).

Despite the many barriers that still exist for employing ICT for agriculture, especially with marginalized communities in rural areas, mobile phone-based technologies are becoming increasingly important to close the last mile of communication. ICTs can ameliorate the lack of technical assistance and extension staff, and provide information to marginalized areas (Babu et al., 2015; Kiptot and Franzel, 2015). In recent years, ICT extension services, based on mobile phone services referred to as m-services, with the private and public sector working together often with limited personnel, have gained much attention. However, they often struggle to reach a level of sustainability and often do not fulfill their promised potential (Hatt et al., 2013; Wyche and Steinfield, 2016). Most information services focus on delivering information on prices, farming practices and weather (Aker, 2011; Tadesse and Bahiigwa, 2015). Few m-services offer training and extension services to farmers (Baumüller, 2017) and even fewer opportunities for farmers to share their experiences amongst themselves and with others.

Sharing experiences and information is crucial as farmers prefer to make their decisions based on discussions and their own experiences, rather than accept top-down generalized recommendations (Ingram, 2008; Wellard et al., 2013). Farmers' preference for participating in the decision-making process changes the role of the extension agents: the extension technicians become catalysts, facilitators, and promoters of knowledge generation and exchange. These pluralistic extension systems are a key element of the shift toward Farmer-to-Farmer Extension (FFE). Their relevance is increasing, and they now complement traditional extension services (Kiptot and Franzel, 2015; Rao, 2007). ICTs can enhance dialogue and knowledge-sharing by farmers. Furthermore, ICTs can bring to scale these extension approaches based on local expert facilitators (LEF) and volunteer farmer trainers (VFT). Within this framework, younger members of the community who are more familiar with ICTs can play a major role in helping farmers access information through ICT (Muktar et al., 2015).

ICTs are not only important to improve extension services, but also to scientists who can use ICTs that facilitate interactions between them, experts and farmers. Farmers have the potential to provide massive amounts of useful data on their activities and experiences. ICT-based approaches are more cost-effective for data collection, monitoring and evaluation of agriculture development projects than traditional methods (Hammond et al., 2016; Jarvis et al., 2015). Thus, ICT-based solutions can play a major role in efficient data collection which can, in turn, be the basis for better decisions by farmers and policymakers (Delerce et al., 2016).

The advantages of digital agriculture are clear. However, to implement digital agriculture in the context of small farmers, we cannot simply throw ICT solutions at farmers: we need to design the solutions and development in partnership with farmers and facilitators in participatory projects.

In this paper, we first describe the design and development process of a modular ICT application system called GeoFarmer. Geofarmer was designed to provide a means by which farmers can communicate their experiences, both positive and negative, with each other and with experts and consequently better manage their crops and farms. We designed GeoFarmer in a collaborative, incremental and iterative process in which user needs and preferences were paramount. The aim was to get a customizable system for near real-time data flows between system users, i.e., experts to farmers, which could support processes of co-innovation and usage of GeoFarmer for citizen (farmer) science projects. We describe the iterative development process based on our experiences with GeoFarmer in five projects within four geographical domains in Tanzania, Uganda, Colombia, and Ghana. We present and discuss the results of the lessons learned from the five projects and indicate how GeoFarmer can be further developed and used to facilitate information and knowledge sharing amongst farmers and between farmers and scientists. Increased knowledge sharing can reduce the risk of failure through informed decision-making and improve the livelihoods of the small farmers.

2. Methods

The rationale of the GeoFarmer design process followed the Principles for Digital Development (Waugaman, 2016). Following these principles, the specifications for the design of GeoFarmer were defined as follows: i) employ a systems approach to design GeoFarmer and make it replicable and customizable in other countries and contexts; ii) develop a modular design, with a system that is interoperable with a well-documented Application Programming Interfaces (API); iii) use/modify/extend existing tools and follow open standards; iv) design and develop GeoFarmer in a collaborative, incremental and iterative process with inputs from diverse disciplines and constant reference to user needs v) document the design process, results and lessons learned throughout the development of GeoFarmer.

2.1. GeoFarmer design as a geospatial cloud-based system

GeoFarmer uses a multilayer architecture with a system of modular components (functionalities and interfaces) that communicate with a central cloud application, which includes the central database where all information is compiled (see Fig. 1). The cloud applications' backend also communicates with external components and services. The modular structure and multilayer architecture simplifies the development of single components for a specific usability context, like a simple user interface for standard users and a more complex interface for expert users.

We evaluated existing tools, platforms and frameworks to reuse existing approaches instead of developing new ones. These tools included several that have been developed and used for agricultural development projects. For example, the Open Data Kit (ODK) is widely

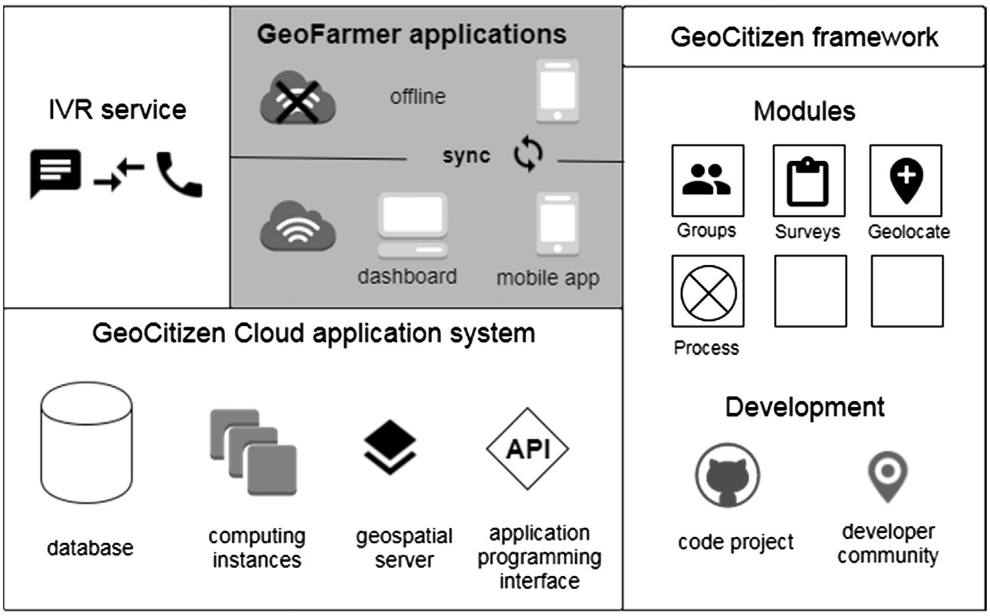

Fig. 1. Overview of GeoFarmer application systems' architecture, developed as a subsystem of the GeoCitizen framework.

used in development work in Africa, and others have integrated ODK into new applications. The Rural Household Multi-Indicator Survey (RHoMIS) uses ODK as survey module for a standardized and rapid characterization of households (Hammond et al., 2016). We considered incorporating ODK as a survey module in the early design process of GeoFarmer but found it challenging to integrate ODK in our system or interoperate between ODK and our database. Furthermore, it does not include two-way communication functionalities; hence we decided not to use ODK for the survey module.

From the evaluation process, we chose to develop GeoFarmer as a subsystem of GeoCitizen (Atzmanstorfer et al., 2014). The GeoCitizen framework provides several modules such as georeferenced surveys, geolocation of context-relevant information and structured and transparent discussion and feedback loops that fitted well with our aim of developing a system with near real-time, two-way data flows that support processes of co-innovation. Atzmanstorfer et al. (2014) developed the GeoCitizen framework to provide citizen participation in a structured manner with geospatial data collected from many sites, over time, by many participants, collated in a central database, and then interpreted by individuals and groups of citizens to meet their needs. The GeoCitizen platform has been applied for development projects in a long-term study in Ecuador, where it has been used in a participatory land-zoning process. Furthermore, GeoCitizen was subjected to a Human-Computer Interaction (HCI) evaluation study, carried out for the GeoCitizen-reporting application amongst members of marginalized communities in Cali, Colombia (Atzmanstorfer et al., 2016).

The backend of GeoCitizen provides application program interfaces (API) of functionalities that we used for user interfaces and applications. Features of GeoFarmer include data requests from the database and returning data for processing and storing. We used open-source component-based development frameworks for the cloud backend, web applications, and mobile application.

Existing modules and ICT components of GeoCitizen were adapted and modified for GeoFarmer to handle data and information in the context of agricultural development. We also added new complementary modules for GeoFarmer to the GeoCitizen application framework. We developed new user interfaces for GeoFarmer, which includes a smartphone application and a web-dashboard.

In recognition of low levels of ICT literacy frequently found in rural communities, where small farms are the norm, we emphasized simple, easy to learn functionalities. We developed a three-tier approach for farmers' means of interaction with GeoFarmer to take into account the limited capacity for direct use by small farmers in some cases. First, user-direct second facilitated and third indirect.

2.2. *Design as an iterative process to improve usability*

The design and development team worked closely with scientists from various disciplines including computer science, geography, agriculture, and environmental change. The design and functionalities were improved in an iterative process from lessons learned in several pilot projects.

2.2.1. *GeoFarmer for evaluating agricultural best-practices in Tanzania*

In a first pilot in 2014 and 2015, we examined the capacity of the GeoFarmer application system to support an ongoing citizen science project. Farmers in Lushoto, located in the Usambara Mountains in Northeastern Tanzania, co-managed demonstration plots with scientists and tested the effectiveness of climate-smart agricultural practices. GeoFamer was used to collect data and monitor the farmers' uptake of and the effectiveness of management practices.

2.2.2. *Transect walks and repeating training with local youth facilitators*

During the first pilot, future facilitators learned how to use the smartphone application of GeoFarmer. We trained three youth agricultural extension officers from Lushoto in two training sessions (Fig. 2). The objective of the first training session was to familiarise the facilitators with the basic functionalities of the system. The training focused on: i) registering farmers, ii) collecting face-to-face surveys with farmers and iii) collecting field points using the map functionalities.

We carried out transect walks with local experts, researchers and youth facilitators to gain experience on the use of GeoFarmer in the field. We collected observations on farming constraints, the crops farmers grow, topography, potential sites for demonstration sessions, and infrastructure such as schools for carrying out workshops with farmers. Observations from the training and transect walk on functionality and usability, i.e. youth facilitators requested translations of buttons and filters for registered farmers, were documented and used to improve the new versions of the application. At the end of the first training session, the youth facilitators used the application for several weeks, gaining experience that would provide feedback for the second

Fig. 2. Youth facilitators from Lushoto during the training (a), a farmer responding to a survey carried out by a local facilitator (b) and (c), a farmer responding to a phone survey while being on the way to her field. Photo credit: Manon Koningstein (a,b) & Georgina Smith (c) / CIAT.

training session.

In the second training, experiences with GeoFarmer were shared to provide insights on how it could be improved, i.e. participants mentioned the need for a offline functionality, and participants learned how to deal with more complex tasks, such as starting a discussion by publishing farmers' observations and receiving comments from experts or other farmers on the map viewer.

2.3. The 5Q approach to monitoring progress through feedback

To set up an effective feedback mechanism between farmers and researchers related to project activities in the study area, we used the 5Q approach (Jarvis et al., 2015). The approach uses low-cost ICT tools to ask sets of five *smar*t questions to all stakeholders at regular intervals throughout the project cycle. "5Q approach moves from simply collecting data to using data from multiple sources to give a clearer idea of knowledge, attitudes, and skills" (Jarvis et al., 2015, p. 3) for a specific practice or technology to be evaluated for a specific geographical site. It uses *feedback rounds* as a new approach to monitoring the progress, and it uses different ICT components to collect information, i.e., it suggests using interactive voice response (IVR) surveys were possible and face-to-face surveys using ICT tools and the help of youth facilitators to complement the data gaps, and where the feasibility of phone surveys is restricted.

In our first pilot in Tanzania, we experimented and compared the performance of 5Q IVR surveys and 5Q face-to-face surveys using the GeoFarmer smartphone-application by running them in parallel. We did this experiment after the second training session with youth facilitators. We ran feedback surveys with both, IVR calls and face-to-face surveys with registered farmers to monitor the uptake of climate-smart agriculture (Lipper et al., 2014) practices, i.e., farmers' uptake of manure composting after demonstrations on farmer managed demonstration plots that have been operated throughout several months. We selected farmers for the IVR surveys based on the criteria of having own cell phones, which they do not share with others, and selected another group of farmers who did not have cell phones for the face-to-face surveys using the GeoFarmer smartphone-application. The question about having own cellphones was asked during the registration of farmers in GeoFarmer. We carried out two rounds of surveys with farmers in Lushoto with four months between the first and the second round of surveys. We designed surveys with questions trees (see an example for the first round in Fig. 3) using simple yes/no or single-choice questions.

In the first round, youth facilitators did face-to-face 5Q surveys with farmers using the smartphone application, and in parallel, we ran 5Q IVR call surveys on an external platform for mobile phone services (previously votomobile, now viamo). After finishing the first 5Q round, either on IVR or face-to-face surveys, farmers were grouped into typologies based on their answers. In the second round of surveys, we used distinct surveys for grouped farmers based on typologies from the first round.

2.4. Evolution of GeoFarmer through pilots in Uganda and Colombia

After experiences from the first pilot, we improved and tested GeoFarmer in pilot schemes in distinct geographic domains in Uganda, Colombia, and Ghana.

A pilot scheme was established in Nwoya, in the southern part of the Acholi sub-region in Northern Uganda in 2016 (Mwongera et al., 2016). Farmers participated in demonstration sessions on climate-smart agriculture practices similar to those in Lushoto. Our primary focus was to test the system in a different context, characterized by lower ICT literacy of the farming community and low availability of mobile data network coverage (internet access). A significant challenge to the functionality of GeoFarmer was the lack of mobile data network access. This difficulty was overcome by the development of an offline operating mode for GeoFarmer.

In 2016, we carried out a third pilot in Colombia. In this pilot, we focused on scaling the IVR calls and 5Q approach to 1240 farmers across the Province of Cauca, southwestern Colombia. We used IVR calls for collecting farmers' perceptions of climate risks in the context of other risks that farmers face in agricultural activities. We used an existing database of farmers from Agronet (MinAgricultura, 2017) to carry out the 5Q IVR surveys.

2.5. Further development of GeoFarmer towards a SmartMonitoring system

In 2017, the CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS) started using GeoFarmer to monitor and evaluate outcomes on its Climate-Smart Village (CSV) agricultural research for development (AR4D) approach, where CCAFS is testing since 2011 climate-smart agriculture practices with farmers, local experts from the national extension service and researchers alike. Together with the CCAFS team, we designed a set of indicators, related questions and survey blocks as modules that we tested in two additional pilots during 2017, in Colombia and Ghana.

We upgraded the development frameworks for the GeoFarmer mobile application and dashboard, using the latest backend for the GeoCitizen framework. Besides the latest technology, the main advantage of using the new framework was improved sync and on/offline functionality.

In Colombia, we examined the new GeoFarmer improvements in the CSV Cauca. We repeated training with facilitators before starting the survey data collection and carried out a small pilot of 60 farmers testing the new system. We used more extensive surveys with the focus on collecting data for tracking performance-based indicators on food security, climate services, practice adoption and among others. We faced the challenge of low mobile phone network coverage. The IVR calls did not work in this specific area of the Cauca department, and we had to do most surveys through facilitators.

Based on the experiences from Colombia, we decided to use the GeoFarmer smartphone application in offline mode and not the IVR calls for the next pilot in Ghana. Another reason for doing this, however, was the fact that our surveys covering indicators for CSVs were

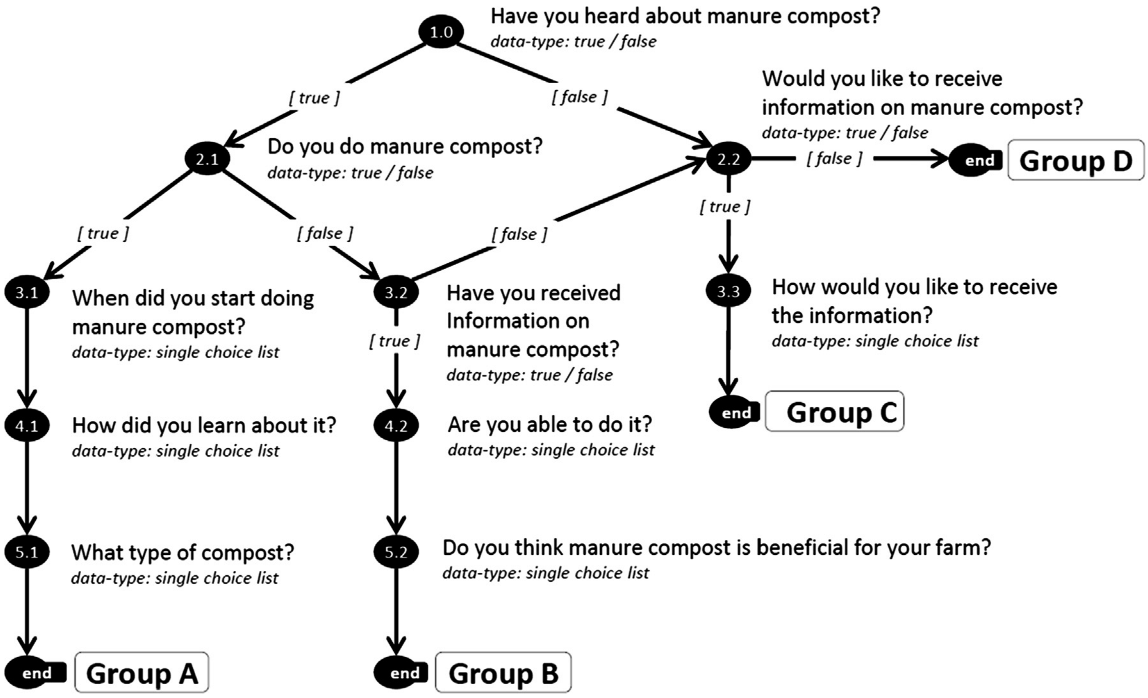

Fig. 3. Question tree of the first round. In the end, farmers are grouped based on their responses.

lengthy, complicated, and difficult to ask in IVR calls. For this reason, we combined registration, demographic baseline and several survey modules in one farm visit through local facilitators. The CSV in Northern Ghana, called Jirapa-Lawra, is situated in a landscape of Guinea Savannah woodland with low land productivity and distinct food security and agricultural adaptation strategies (Douxchamps et al., 2016). In this last pilot, we tested the system capacity of GeoFarmer and the new on/offline functionalities in a productive environment.

3. Results

We successfully designed and developed a prototype of an ICT applications system with near real-time, two-way data flows and the capacity to monitor processes of co-innovation in agricultural development projects. The design is a multilayers architecture with a system of modular components (functionalities and interfaces) that communicate with a central cloud application and can interoperate with external services, i.e., interactive voice response (IVR) services.

3.1. Specification of GeoFarmer

GeoFarmer was designed to house geospatial information and allows efficient feedback from and monitoring of farmers' implementation of agricultural practices and technologies. Inputs to the system can be both directly online or via a specially developed smartphone application and alternatively through an interactive voice response (IVR) service.

For each geographical region or domain, GeoFarmer is modified to meet the specific requirements of that geographic domain, such as language, categories for data collection (crop species, production systems, used practices, and among others), predefined survey modules and map layers. Map layers are integrated as open standards such as Web-Map-Services (WMS). The geographical domains, wherever possible follow the idea of recommendation domains, which consist of farmers within an agroclimatic zone whose farms are similar and who use the same practices (Harrington and Tripp, 1984). Farmers and experts can add new content as georeferenced observation in the map viewer, including text descriptions, photos, and recordings. Moreover, they can add comments to existing observations of another user. In the following, we show a use case diagram and specify the functionality of different means of interaction.

3.1.1. Use case diagram

The use-case diagram in Fig. 4 provides an overview of the functionality of the GeoFarmer application system. The principal means of accessing the GeoFarmer application are (i) web dashboard, (ii) smartphone application, (iii) IVR calls and (iv) database. The GeoFarmer assigns distinct roles to four categories of users, (i) moderator, (ii) facilitator, (iii), expert and (iv) farmer. As many farmers either do not or cannot interact directly with modern ICT devices, facilitators act as catalysts either inputting data directly or helping farmers introduce data and information to GeoFarmer. The farmers, either on their own or with the facilitators, interact with the system through the smartphone application. The first step for farmers is to register. They can do this themselves or with the help of the facilitators. Once registered, the smartphone-application is used to collect point information and to participate in discussion processes with other farmers, facilitators, and experts. On the smartphone application, only the facilitators are authorized, through the system, to collect surveys with multiple farmers. Farmers and experts using the smartphone application can only view their information. All can participate in discussions. A moderator uses a web-dashboard to manage the system for a geographic domain and to organize surveys. The expert's role is to provide inputs to the discussion and answers to questions that have been uploaded by farmers or facilitators. Farmers can also interact and provide feedback through interactive voice response (IVR) services, which use automated phone calls to respond to surveys or to receive text and voice messages.

Following Atzmanstorfer et al. (2014), the system is based on processes. A single process consists of a discussion where the user can submit an observation or question. Other users (facilitators, experts, and farmers) can react to the observation and provide answers or vote for existing responses from other users. The system highlights best-voted responses as best practices and platform users can access the relevant information regarding this process. The conceptual idea comprises a social geoweb platform for sharing observations, discussing ideas, solving problems, and monitoring what farmers are doing. For

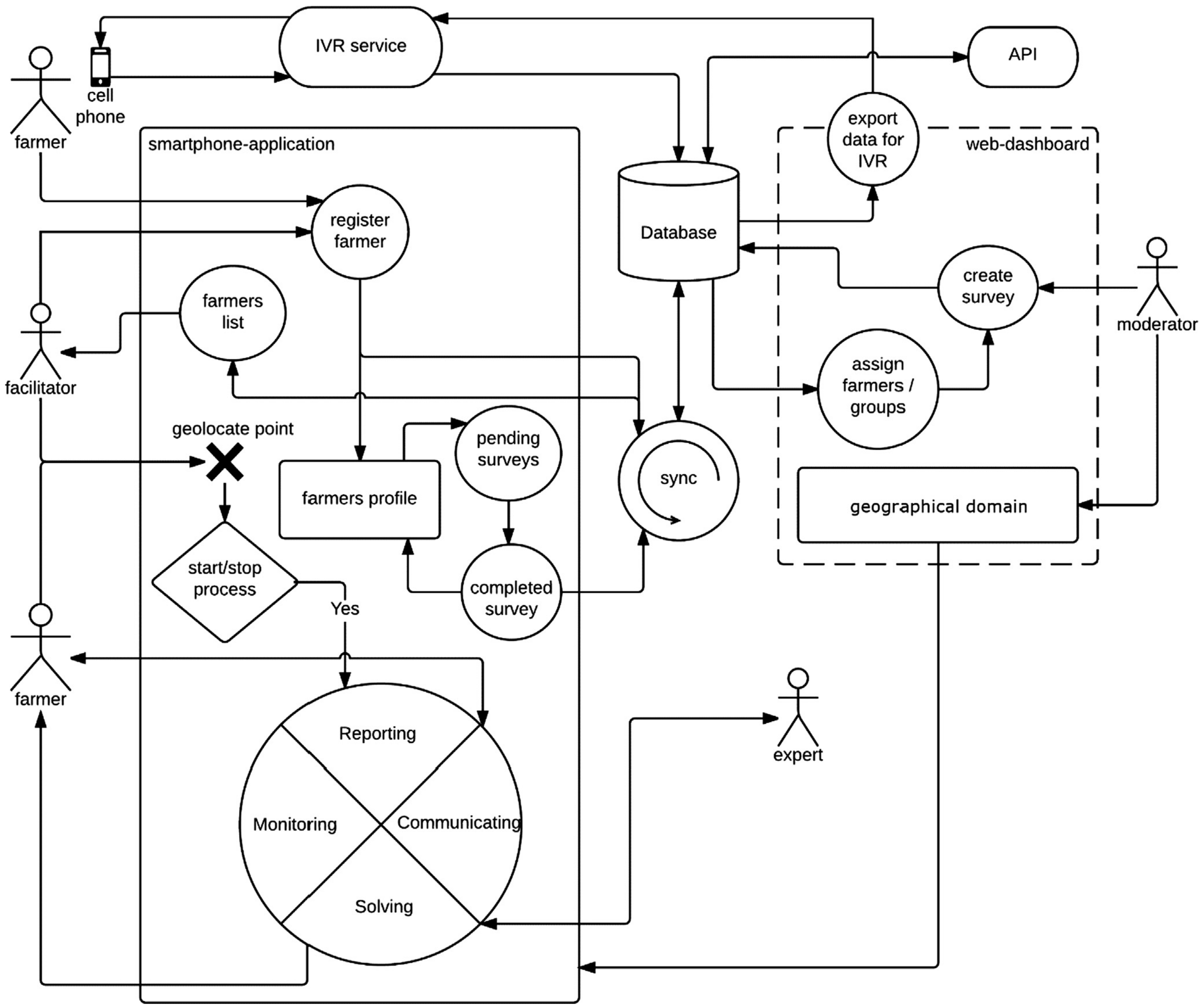

Fig. 4. Use case diagram of GeoFarmer application systems, based on the GeoCitizen framework for citizen participation.

the first version of GeoFarmer, we reduced the process functionalities to a simple *comment* function for users to make observations or comments. However, the GeoCitizen framework provides a more detailed process module, which includes discussion, voting, and rating mechanism to determine best practice solutions (see Fig. 4).

3.1.2. Review of functionality

GeoFarmer systems functionalities allow users to interact with the system and carry out different tasks. Users with moderator role, i.e., local implementers of projects, use functionalities of overall project management mainly on the web dashboard. Users with facilitator role, i.e., project facilitators, support farmers in participating on two-way communication, and farmers as a user interacting by themselves with Geofarmer. Finally, users with expert role, i.e., agricultural scientists and extension technicians, use the smartphone application and web dashboard to contribute to knowledge sharing.

Table 1 summarises the systems functionalities, its objectives, user roles and means of interaction.

In the following sections, we explain the four means of interaction in more detail.

3.1.3. Web dashboard

The GeoFarmer dashboard is a management tool and integration platform for collecting data in the field. It is the central tool for managing GeoFarmer geographical domains and data. Only registered users with moderator role can log in to the dashboard and access their geographic domains (projects). The moderator creates new surveys and questions, and he approves facilitators that requested a facilitator role through the smartphone application. Collected survey data and results are accessible on the dashboard; the moderator can create public links of results and share them on the internet. The moderators manage the discussion process of smartphone-application users, i.e., set parameters or control user access to the discussion process thus ensuring a free exchange of information between users. Although the facilitators, experts, and farmers do not use the dashboard, their ability to communicate depends on it being well managed.

3.1.4. Smartphone application

Facilitators and experts use the smartphone application during fieldwork activities while interacting with farmers. Farmers can also use it as an individual user. It is the central data-collection tool (Fig. 5). The smartphone application is simple and optimized for fieldwork usage. After user registration and login, the user can send a request to be a facilitator in a specific geographic domain, which requires approval from the moderator in the web-dashboard, or he logs in as an individual user (farmer).

Table 1
The chart shows systems functionalities.

Systems functionality	Objective	Systems user and roles	Means of interaction
- User registration - Create geographical domain - Edit geographical domain	- Create a new user account - Create a new geographic domain, define the geographic extent, assign moderators - Edit domain parameters, define point categories, add map-layers, manage participants	Moderator *(System Administrator)*[*]	Web dashboard
- Approve user roles - New surveys - See/share survey results - Edit process parameters	- Approval of users as a facilitator/expert - Create surveys and assign surveys to farmer groups; create and add questions, edit survey parameters - Access and share survey results as a public link - Edit process parameters for the discussion process	Moderator	Web dashboard
- User registration - Register farmer	- Create a new user account - Register a farmer in the system	Farmer, Facilitator, Expert Facilitator	Smartphone-application
- Self-registration - List of farmers	- Self-registration of a farmer (profile) - Query/sort/filter list of registered farmers	Farmer Facilitator	Smartphone-application
- Edit Farmers (profile)	- Edit all farmers' profile page - Edit own profile page	Facilitator Farmer	Smartphone-application
- Monitoring (surveys)	- Fill surveys assigned to multiple farmers - Fill surveys assigned to own profile	Facilitator Farmer	Smartphone-application
- Set a point-observation on the map - Communicating	- Geolocation of points on the map viewer - Start a participatory process on a point	Facilitator, Farmer	Smartphone-application
- Solving	- Comment, discuss, ask questions, provide answers - Users can vote (support) for answers	Experts, Farmer, Facilitators	Smartphone-application
- Monitoring (IVR)	- Run survey on IVR service portal - Respond to an IVR call of survey questions	*(System Administrator)* Farmer	IVR call
- Export data (for IVR calls) - Import data (from IVR calls)	- Export farmer lists, survey questions from the database - Import results from IVR service into the database	*(System Administrator)*	Database

* The system administrator is the platform operator.

The facilitator can access the farmer's list and manage all registered farmers for the geographic domain. In an individual farmers' profile, he can assign surveys that are available for the geographical domain to them. He registers new farmers in the menu *Farmers* by filling the farmers' profile. The registration process includes a project-specific electronic consent statement in the farmers' local language, which the facilitator must read to the farmer before finalizing the registration with the new farmer; the farmer must provide the electronic consent if he is to be part of the overall system. By clicking on the menu item *Surveys*, facilitators can access the list of available surveys for a geographic domain and search for farmers with pending surveys. Farmers logged in to the smartphone application can only access their surveys pending to be filled.

The user (facilitator, farmer, and expert) can collect spatial observations on the *Map viewer* page. The map viewer consists of simple GIS functionality for navigating (pan, zoom, GPS location) on a base map or geographical domain specific map layers, (which are added by the moderator in the web-dashboard). After setting a point on the map, the user can provide related information as text or media files and start a process assigned to the new location. When the smartphone is online,

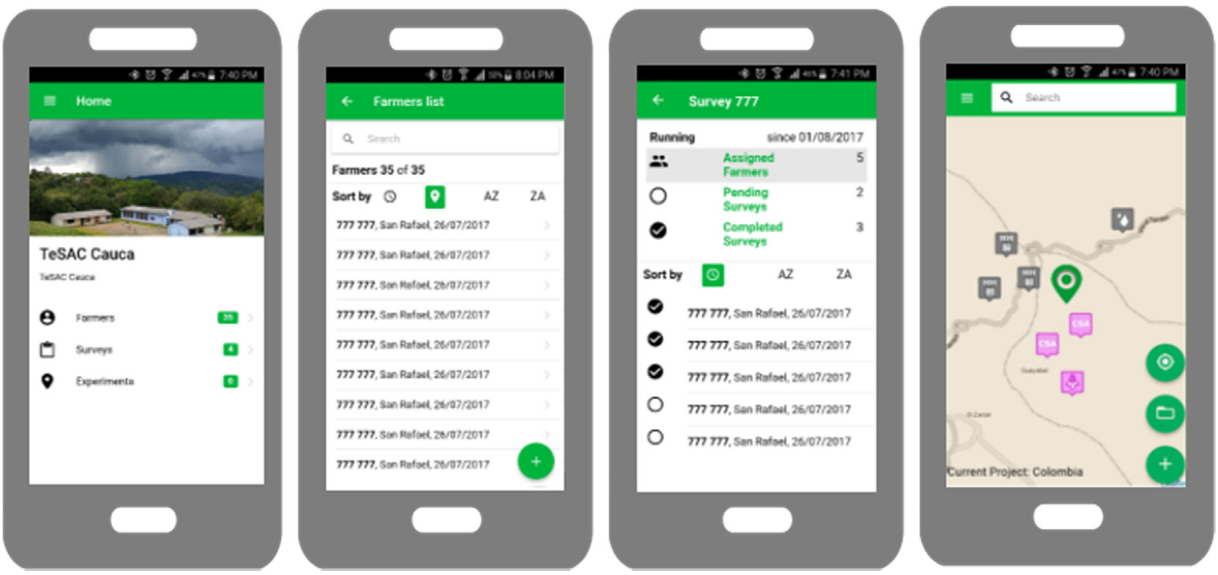

Fig. 5. Selected screenshots of the smartphone application show the start page, the list of farmers' page, a list of pending and completed surveys and the map viewer with observation points set by users.

the server database and the local phone storage are synchronized. Once synchronized the smartphone application can be used offline. However, new data from other users up to the last time when smartphones were connected to the internet and synced with the central database, are not available while the application is in offline modus.

3.1.5. IVR calls

Some of the farmers' barriers to access to ICT technology in the developing world, like lack of smartphones, low ICT literacy and pluralism of local languages can be partly overcome by using voice-based channels of communication, such as call centers, voicemail or Interactive Voice Response (IVR) systems (Islam and Grönlund, 2010; Vashistha and Thies, 2012). IVR calls are a cost-effective alternative to collecting data compared to face-to-face surveys carried out by facilitators during fieldwork, and they are simpler to use by farmers than smartphone applications (Jarvis et al., 2015). We combined IVR calls with the existing survey modules adapted from the GeoCitizen framework to provide broader access to the GeoFarmer system. Currently, the IVR calls are not yet fully integrated into GeoFarmer. A third party platform (previously votomobile, now viamo) was used for IVR call surveys. The results of the IVR calls were imported to the GeoFarmer database.

3.1.6. Database and backend functionalities

Database and backend functionalities are part of the GeoCitizen cloud-platform. Import/Export of data from the database requires a *systems administrator* role for the database and is carried out in this version of GeoFarmer through Standard Query Language (SQL) statements. In the next version, data import/export is planned to be integrated into the web-dashboard. The access to backend functionalities for the development of the GeoFarmer smartphone application is provided through an API and can be accessed by members of the GeoCitizen developer-community (see Fig. 1). Further developing the API of future versions of GeoFarmer could allow other applications to interoperate with the GeoFarmer database. Interoperability between ICT systems in agriculture is a crucial requirement for improving the sustainability of these systems.

3.2. Results and lessons learned from five pilots in four geographic domains

We tested GeoFarmer in four geographic domains associated with ongoing agricultural development projects in East and West Africa and Latin America. Our results demonstrate that GeoFarmer is a cost-effective means for data collection and potentially a useful tool that farmers and agricultural practitioners can use to manage their crops and farms better, reduce risk, increase productivity and improve their livelihoods.

3.2.1. Experiences from testing the GeoFarmer and IVR surveys in Tanzania

Before we could start using the system in Lushoto, the moderator had to establish a geographical domain for Lushoto in the web dashboard. We also defined and configured categories for point-data collection. We used categories for crop cultivation, climate-smart agriculture practice, farm household, plant disease and point of interest among others. We added thematic map layers from existing map-services for the region to improve the cartography for the map-viewer. We included map layers of land-use classification, road network and main villages for the fieldwork. The moderator created the surveys on the web dashboard.

We used the smartphone application in transect walks with local experts, researchers and youth facilitators. The *map viewer* was opened in the menu option, and then the phones' GPS signal provided the exact location on the map. Once the application received the position, the *collect* button was activated, and the location-specific information was entered. The entry consisted of a form to be filled in and the additions of photos taken by the smartphone camera and short descriptive text.

After the transect walks, the youth facilitators continued using the system between the first and second training. Over the six months from the first to the second training session, two local facilitators registered more than a thousand farmers from nearby villages and collected a baseline survey of demographic information with 91% of the farmers contacted. In total, facilitators registered 956 farmers with completed demographic surveys in GeoFarmer. Additionally, the two volunteers geo-referenced more than 670 field observations using the defined categories and provided data of cultivated crop species, farm locations and details of farmers' field plots.

During the second training and transect walks we observed that the purpose of the more complex tasks of starting a process by commenting on others point-observations was difficult for local experts to practice. We noticed that it was necessary to repeat the basic tasks from the first training to improve local experts' familiarity in using GeoFarmer. As a lesson learned from the second training, we concluded that more complex tasks need to be simplified and divided into simpler tasks and guided steps, with a focus on improved user experience and applications' usability to carry them out.

After the second training with facilitators, however, we piloted Geofarmer testing the more complex tasks, such as publishing farmers' observations, submit activity reports on demonstration plots and post questions of farmers. During the following weeks, facilitators published information from several demonstration plots by using the Geofarmer smartphone application (Fig. 6). The number of interactions with the system was still low in this first project phase, and it shows that facilitators had difficulties using GeoFarmer for information and knowledge sharing.

After the training, transect walks and registration of farmers in GeoFarmer, we started experimenting with using structured survey trees, following the 5Q approach, to obtain feedback from farmers on information provided to them on climate-smart agriculture practices. We compared the differences in cost-effectiveness, response rates and farmers preferences between face-to-face surveys through facilitators using the GeoFarmer smartphone application with that from the IVR calls.

Farmer's adoption and awareness of manure composting were used to evaluate the effectiveness of the surveys. A series of surveys were initiated after the initial demonstration of manure composting to farmers in Lushoto. The surveys were carried out in six villages, surrounding the sites where the demonstration training was held, and where we registered farmers in GeoFarmer. The second round of the survey was carried out four months later, and it shows changes in farmers' knowledge, attitudes, and skills about the climate-smart agriculture practice manure composting in Lushoto. We used a Sankey diagram to visualize the flow of information and awareness of the manure composting practices (Fig. 7). The chart shows registered farmers and timeline of surveys (blue bars) in the study area who were aware of the smart-practice manure composting (light blue bar), not aware (orange bar) and unsuccessful calls (light-orange bar). As a subset of aware farmers, it shows farmers practicing manure composting on their farm (dark green), farmers who know how to manure compost (red), and farmers who are interested in receiving more information on the practice (light green). The diagram shows the changes in farmers responses between the first (bar two and three) and second (bar four and five) survey. Between the two survey rounds, some farmers changed from doing manure composting to not doing it, some of them started manure composting and others maintained the same status as in the first survey.

We characterized respondents and non-respondents based on the demographic baseline that we collected when registering all farmers through the smartphone application. Fig. 8 shows the different demographic characteristics of age, household size, household position and gender of respondents (RSP) and non-respondents (Non-RSP) of both means of interaction. It shows that men are more likely to respond to both means of interaction than women are, and the heads of household

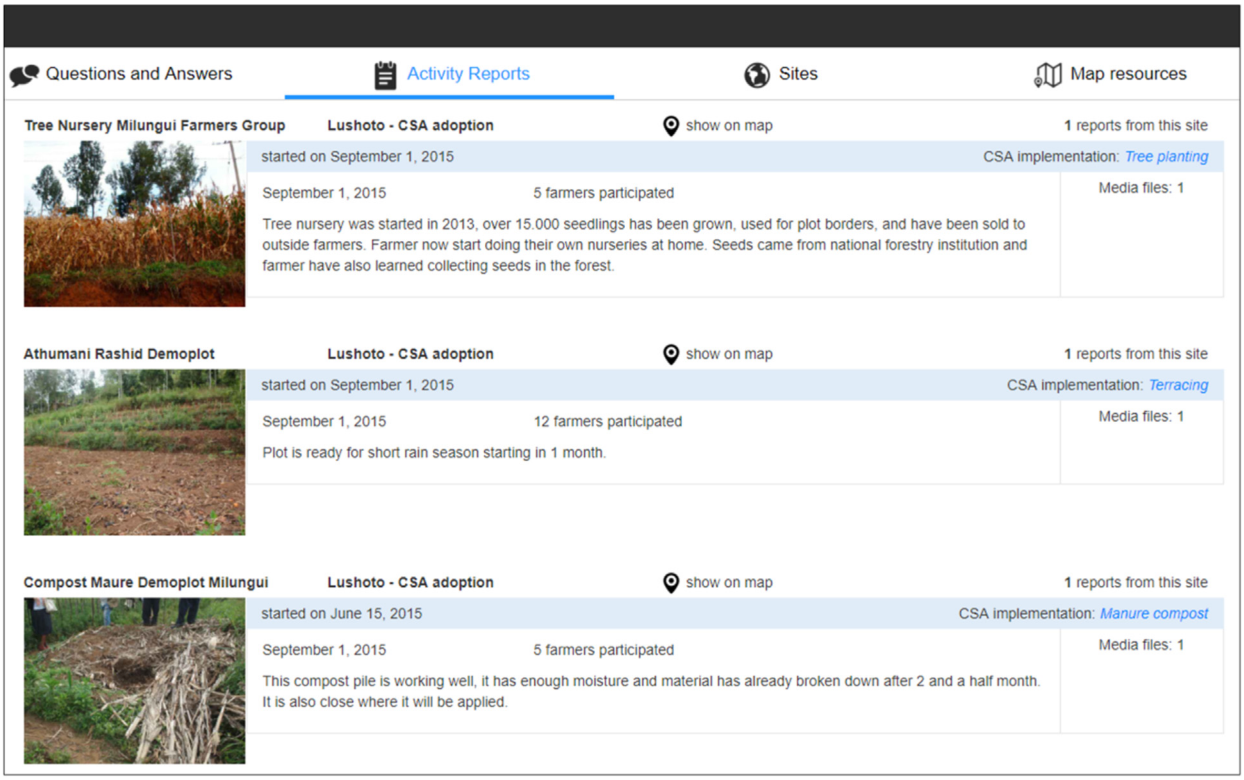

Fig. 6. Screenshot showing uploaded information by facilitators to GeoFarmer web-dashboard.

have a higher share of respondents.

We also found, from survey rounds where we tested different options, that the response rate of IVR calls in Lushoto depended on the way farmers were contacted. For example, both the time of the day when farmers were called and the prior announcement of the call, with information how the call was related to the project-specific participatory work and demonstrations, markedly influence the response rate (Fig. 9). The first two calls (Call 1, Call 2) were carried out between March and April 2015 with a response rate of 21% and 17% respectively. Social studies report response rates for IVR surveys of 20% to 30% (Dillman et al., 2009). For these calls, we did not inform farmers about the planned IVR calls, and we called them at any daytime (Call 1) and early in the morning as suggested by local experts (Call 2). Before Call 3, which was carried out in July 2015, we applied several measures

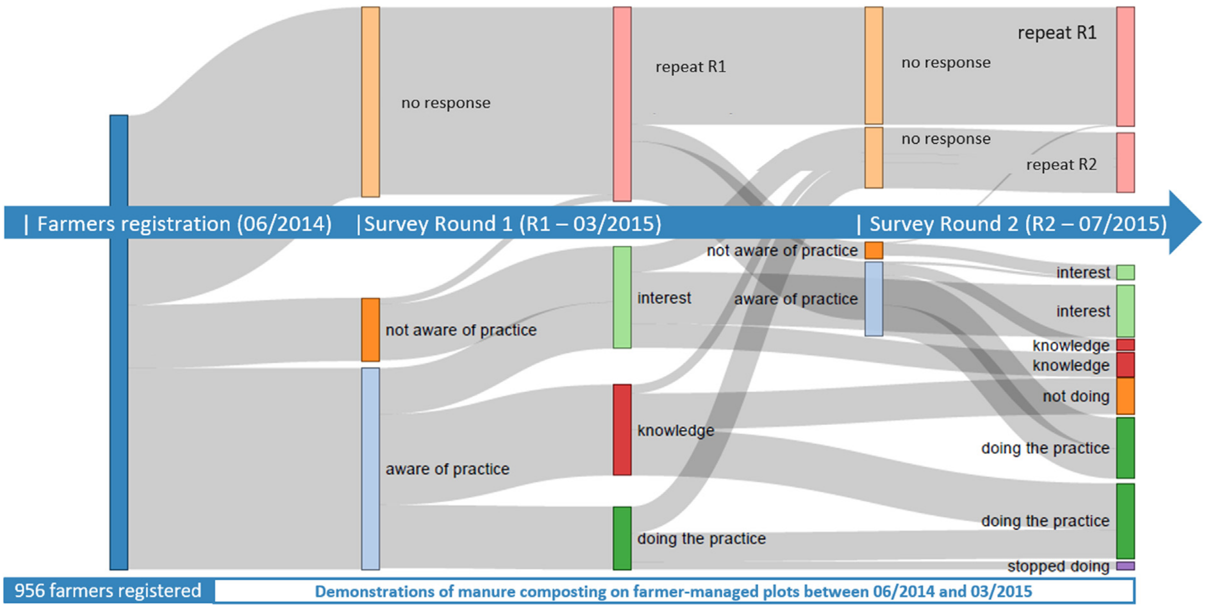

Fig. 7. Farmers' adoption of manure composting in Lushoto. The diagram shows the timeline of surveys from registered farmers in the first bar on the left (blue). Bars two and three show results from the first survey round, and bars four and five show results from the second survey round. At the end of each survey round (bars three and five), farmers are grouped based on their responses. The groups, in turn, determine the set of questions for the next survey round (see question tree in Fig. 3). Sankey diagram created with d3.js Sankey diagram http://bost.ocks.org/mike/sankey/. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

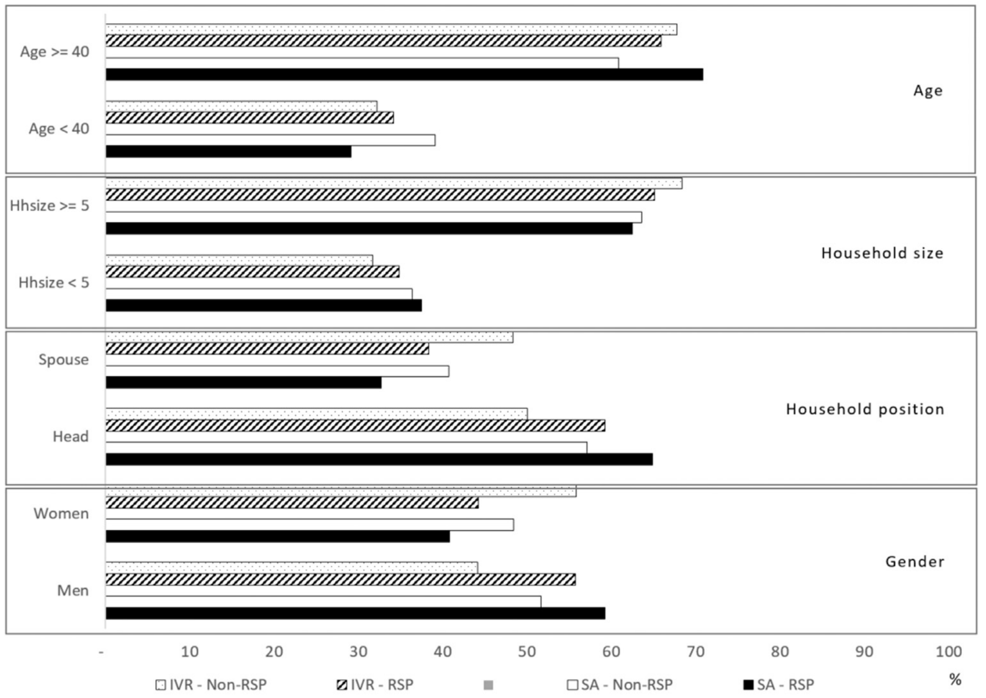

Fig. 8. Demographic characteristics of Respondents (RSP) versus non-respondents (Non-RSP) for both, interactive voice response surveys (IVR) and smartphone application (SA).

to improve the response rate of farmers to the IVR surveys. The new approach consisted of three measures for improving the response rates on IVR calls. First, we announced the planned IVR surveys to farmers through our local project members. Second, we asked farmers about their preference of daytime for the call; they preferred in the late evening when they usually are back from their fields. Third, we sent a text message 30 min before the actual call. These three measures together increased the response rate to 40% in Call 3.

Fig. 10 compares the performance of face-to-face surveys using the GeoFarmer smartphone application (SA) carried out by the facilitators, and the IVR calls in Lushoto. It shows that the face-to-face response rate is better (between 65% and 89%) than the response rate from IVR calls (between 19% and 40%). The overall response rate of both methods face-to-face and IVR calls in 5Q round one and two in Lushoto were 49% and 55% respectively.

At the end of our pilot in Tanzania, we asked both facilitators and farmers if they found GeoFarmer to be a useful tool for carrying out surveys and collecting information. One of the facilitators in Lushoto said: *"Using the tablets, we can show pictures to farmers that we took on other farms, and the collection of surveys is more convenient using the tablets,"* Tanzania, June 2014. Farmer's favored IVR call surveys, as one farmer in Lushoto during a field visit, said: *"It takes little of my time and I can attend the phone call anywhere, even when I am working on my field,"* (translated from Swahili, Tanzania, June 2015). The IVR surveys in Lushoto took approximately two to three minutes of their time for each survey round, and farmers could participate in them wherever they were and at almost any time. However, even with the improved measures doing the IVR surveys, the farmer response rate was lower as compared to face-to-face surveys that were carried out by the youth facilitators on the smartphone application.

3.2.2. *Experiences from testing IVR calls in Uganda and Colombia*

Based on the Lushoto experience, we optimized the IVR surveys by first evaluating the local cultural context for operating phone calls with farmers, and we obtained response rates of 46% in Uganda and 43% in Colombia.

In Nwoya Uganda, despite the low mobile data coverage, with the offline capacity, we registered 355 farmers in GeoFarmer and carried out the IVR surveys. The questions in the surveys were in the Acholi language. The surveys were designed to obtain information on the adoption of smart agricultural practices. One hundred and sixty-four farmers answered the IVR surveys, and, 143 farmers listened to the complete introduction, 19 hung up before the introduction finished and 29 farmers did not pick up the phone. Farmers were asked questions

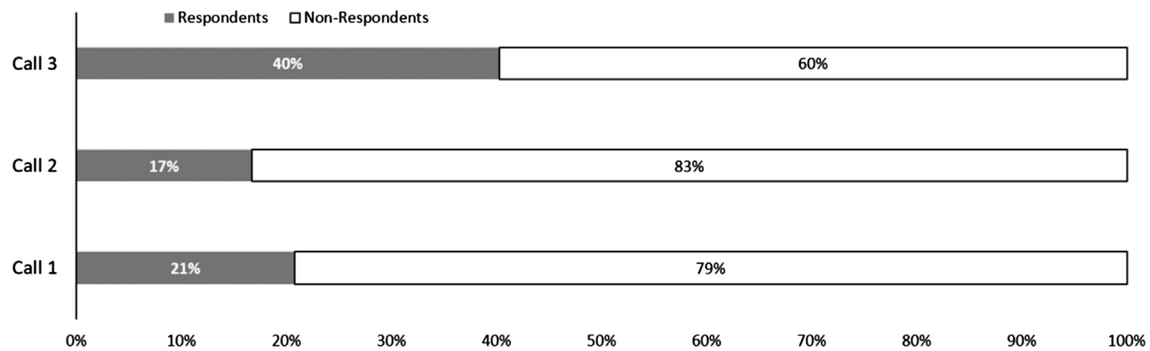

Fig. 9. The response rate of farmers in Lushoto increased during three calls and applying several measures to improve the response rate.

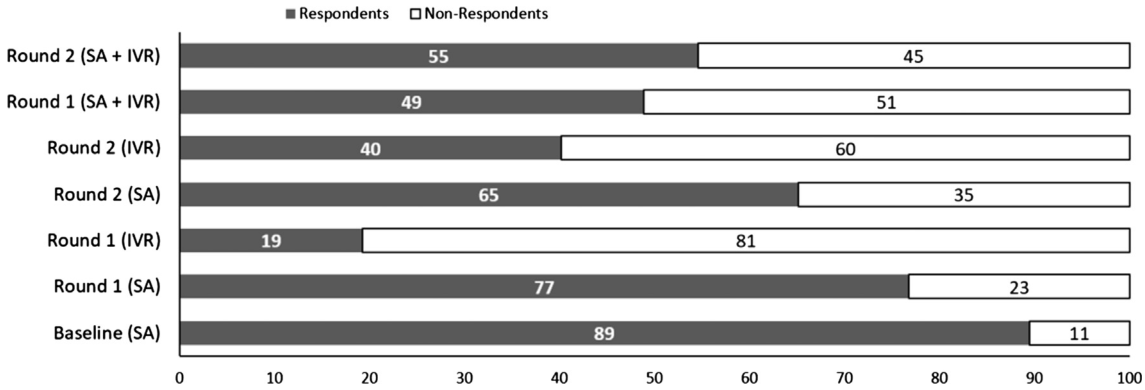

Fig. 10. Comparison of response rate on smartphone application (SA) and interactive-voice-response (IVR) calls in Lushoto, showing two rounds of surveys (Round 1 and Round 2).

about the *row-planting*, a practice which has been demonstrated previously in the region by the project. At the end of the IVR survey, we asked them to record their full name and confirm if they are male or female in a final question. We did this to verify the name with the name on the list of registered farmers in our database. Like in the first pilot, we organized the surveys as question trees of five questions following the 5Q approach, and we derived typologies of responses.

In the Cauca department in Colombia in 2016, we carried out one IVR survey including 1240 farmers across the Cauca department. At this time, using our experiences from previous IVR surveys, we achieved a 43% response rate on our first phone call to farmers. We did not use the GeoFarmer smartphone application in this pilot. We asked questions regarding farmers' perception about climate risks in the context of other risks on agricultural production. Results show that 14% of farmers in Cauca are most worried about climate change and 28% perceive climate risks highest among other risks.

3.2.3. *Experiences from testing GeoFarmer in Ghana*

During the year 2017, GeoFarmer was used to set up a comprehensive monitoring effort in the CCAFS CSVs. Together with the CCAFS team, we designed a set of indicators, related questions and survey blocks as modules that we tested in additional pilots during 2017, in Colombia and Ghana. Because of the length of survey modules, we decided to use the smartphone application for carrying out the surveys and did not use the IVR surveys. The offline mode was fundamental because of low internet connectivity in the study area. Ghana CSV was a first productive data collection where our youth facilitators collected more than 60.000 data records in offline mode from five survey modules during two weeks. They synchronized the data between server and smartphone application once a day when they had internet coverage through the mobile phone network, mostly when they finished their day and when they met at the main village.

4. Synthesis of lessons learned

In many developing countries, smartphone usage and internet coverage have increased significantly in recent years (Aker and Mbiti, 2010). Although the connectivity gap is expected to close shortly, last mile internet connectivity and lack of broadband access at village level is often a problem (Rao, 2007). We had functional internet connectivity in our first pilot in Tanzania, but experienced low connectivity in the other pilots. However, in all pilots, internet connection sometimes failed or was very unstable, and before we had implemented the synchronization mode, we were often not able to use the application. The offline and synchronization capability that was introduced primarily resolved this problem, as evidenced by the experience in Ghana with more than 60,000 records from 356 farmers collected in two weeks with poor internet access.

Another lesson learned is that digital illiteracy is a limitation for using ICT solutions in the context of small farmers in developing countries. Usability studies and the evaluation of Human-Computer Interaction (HCI) are an essential step in developing meaningful applications for users of marginalized communities with low ICT-skills. Within the GeoCitizen study, researchers carried out an in-depth HCI evaluation of its mobile app (Atzmanstorfer et al., 2016). We did not find it necessary to repeat this study for the GeoFarmer. However, observations of the facilitators during the training sessions, such as altering the visibility of buttons or reducing the number of steps to carry out a specific task, were incorporated into the application. Nevertheless, continuous improvement of the usability of the GeoFarmer application is necessary. Improvements can be mainly achieved by close interaction with the GeoFarmer developers and the facilitators.

In the pilots, there was a wide range of user types. Not all of the users were capable of using the GeoFarmer application. Facilitators were required to collect information. It is difficult to create a high-quality intuitive, easy to use app that can be used by the digitally semi-literate user but also has functionalities that have a high level of cognitive activity. This topic is still under-appreciated in the field of participatory tools, and further research in addressing user-friendliness and human-centered design approaches is needed (Çöltekin et al., 2010; Kramers, 2008). Developers of participatory tools mostly address the functionality of the system and the visualization of data and pay little attention to the user's needs (Resch et al., 2014). Users' needs are often left out the development process due to cost and time restrictions for analyzing the user's needs (Watanabe et al., 2009). We suggest that future research and development of participatory ICT tools should take more into account user needs, preferences, skills, and capabilities, and focus on co-creation and co-development approaches for the design of ICT solutions. Applications should be improved so that more people can use them without the need for facilitators. Especially during our first pilot in Tanzania, we observed that the functionalities of more complex tasks like triggering a discussion-process by commenting on others point-observations, was difficult even for the facilitators. This aspect of usability needs further attention: too much attention is frequently given to providing information for researchers and not enough to how the farmers can perceive benefits from the sharing of knowledge.

Successful digital agriculture applications must take account of site-specific social and cultural differences. Furthermore, they are more likely to be adequately used if they form part of ongoing initiatives that have already gained farmers' trust. For example, in the case of the first Colombia pilot, we worked through the partner Agronet, a Colombian agro advisory services initiative which farmers already knew and trusted. Agronet has been operational since 2005 to provide crop-related information to farmers. Most likely, because Agronet is well-known with farmers, the response rate on our first pilot with IVR surveys was high. Other studies in non-agriculture social science experiments reached 28% for IVR calls (Dillman et al., 2009), in our pilots, we first reached 17% and 21% in Tanzania and improved the response rate to 40% in the second round of IVR calls, 43% in the first Colombian pilot and 46% in Uganda. However, in the second pilot in Colombia, our experiences show that the farmers had little confidence in the phone-based surveys and response rates were low. Low cellphone connectivity in the area, with farmers lacking expertise with mobile telephones, appears to be the most likely cause of the flat response.

In agriculture research, the move towards two-way communication models between scientists and researchers and the lay population involves: (i) data on what is happening in the field (data capture); (ii) centralized databases and analysis of the data (data management and analysis) and (iii) interpretation of the information derived from the data analysis so that farmers can use it to make better-informed decisions (interpretation) (Cock et al., 2011). For the first pilot studies, we have used GeoFarmer mainly for data capture, and we have tested simple ways of two-way communication between farmers and agricultural practitioners. Another application of GeoFarmer could be in the field of citizen science.

Citizen science is based on establishing networks of non-scientists who participate and contribute to data collection and analysis of researcher-led projects. Citizen science makes science more inclusive, enabling scientists and citizens to co-create knowledge. The citizen science approach has been used by environmental researchers to allow the participation of large numbers of local stakeholders in initiatives addressing global change (Theobald et al., 2015; van Etten, 2011). Steinke et al. (2017) used a citizen science approach proposed by Van Etten (2011) for a farmer-managed variety selection trial in Honduras and showed that aggregated observations had sufficient validity. In such citizen science project, researchers are heavily involved in data capture and interpretation, with traditional researchers taking the leading role in data management and analysis, and the farmers and extension agents in charge of the interpretation and use of the information generated to make decisions.

Future research on ICT applications that enables two-way feedback and co-creation in citizen science projects should focus on improving usability and develop interfaces that are responsive to ICT literacy, like providing different user-experience and functionality for lay and expert users. A next version of GeoFarmer should integrate IVR functionalities in the systems' API and use the different means of interaction context specific. For example, some farmers interacting themselves with the smartphone applications, others with the support of youth facilitators and in case of low internet connectivity or barriers of illiterately through IVR calls. Also, more research needs to be done to understand the barriers to and enablers for using such a system for information and knowledge sharing and in participatory citizen science projects.

5. Conclusion

Based on the premise that farmers can manage their crops and farms better if they can communicate their experiences, both positive and negative, with each other and with experts, we developed a tool GeoFarmer that expedites information sharing. We chose a digital system based on internet communication technology (ICT) as a cost-effective means for farmers to share experiences themselves and with experts and others interested in agriculture. During the development process we emphasized farmer participation in the design and testing of the system, GeoFarmer, so as to ensure both usability in areas with poor digital infrastructure and low levels of digital literacy and also that the overall system met farmers needs for information sharing, and the use of that information to make better decisions.

GeoFarmer is based on the GeoCitizen framework. The system comprises a multilayer architecture with modular components communicating with a central cloud application and database for safely storing and syncing data being sent from its components. It provides a sync-functionality for on/offline operation in rural areas with limited access to internet connectivity. The original GeoCitizen modules were adapted to characterize farming conditions and to collect and share experiences of small-scale farmers. GeoFarmer has to be tailored to each specific geographical domain and each of which requires a moderator. Trained facilitators ensure the participation of small-scale farmers with limited capacity to access or manage ICTs like smartphones. For data collections, IVR call functionalities complement the smartphone application. The design and development process of GeoFarmer was carried out in an iterative process from lessons learned in several pilot test sites, including scientists from different disciplines and feedback from users.

GeoFarmer was successfully used in five projects within four geographical domains in Tanzania, Uganda, Colombia, and Ghana. We used it to evaluate climate-smart agricultural practices on farmer managed demonstration plots in Tanzania and Uganda, designed as citizen science projects, and for monitoring and evaluation of indicators on outcomes of ongoing transdisciplinary research in CCAFS climate-smart villages. Results show the specifications of the developed system and experiences from testing GeoFarmer in the five projects. GeoFarmer was designed as a modular and customizable system for near real-term data flows between system users, i.e., experts to farmers and farmers to farmers, which support processes of co-innovation and can be used for Citizen Science projects in the agricultural sector. It allows efficient feedback from and monitoring of farmers' implementation of agricultural practices and technologies.

Both facilitators and farmers found GeoFarmer to be a useful tool for carrying out surveys and collecting information. Farmers favored IVR call surveys as they took little of their time and were convenient when they were programmed in advance. However, the farmer response rate was weak when the mobile phone connectivity was poor, or, when we did not inform farmers and provide the context to a specific project activity before the IVR calls. There was a wide range of ICT capacity amongst the users. Facilitators widened the scope of users and enabled the inclusion of farmers with lower levels of digital literacy. However, future design and testing of Human-Computer Interfaces, like GeoFarmer, should include the participation of users with limited ICT skills, to prevent the need for facilitators. Also, currently IVR information from the IVR service is not readily transferred to the GeoFarmer API: data transfer between the two components needs to be improved.

This initial use of GeoFarmer indicates that it provides a means for farmers to communicate and share experiences interactively between themselves and with experts as they continually try new agricultural practices. We suggest that after this first step it can now be adapted and used for more comprehensive monitoring and evaluation of farmers' attitudes and practices, and also to provide for farmers to share information and interchange ideas on how to better manage their crops and farms. However, the initial tests indicate that, even with facilitators, the feedback loops that form part of the discussion process with questions and answers shared between users' needs to be further developed.

Acknowledgment

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Part III

Part THREE: Appendix

Appendix A

DSSAT model configurations

Examples of DSSAT X-Files:

1. Drybeans in Lushoto (First planting season)

```
*EXP.DETAILS: CCAFS BENCHMARK SITE CURRENT AND FUTURE CLIMATE-Lushoto Tanzania

*GENERAL
@PEOPLE
B. Rodríguez, M. Fisher, L. Winowiecki, A. Eitzinger, P. Laderach.
@ADDRESS
CIAT, Cali-Colombia.
@SITE
Soil samples in the Hoima Area, UGANDA.

*TREATMENTS                        -------------FACTOR LEVELS------------
@N R O C TNAME.................... CU FL SA IC MP MI MF MR MC MT ME MH SM
1  1 1 0  CW +S 1+NoFert+FPd        1  1  0  1  1  0  1  0  0  0  0  0  1
2  1 1 0  CW +S 2+NoFert+FPd        1  2  0  1  1  0  1  0  0  0  0  0  1
3  1 1 0  CW +S 3+NoFert+FPd        1  3  0  1  1  0  1  0  0  0  0  0  1
4  1 1 0  CW +S 4+NoFert+FPd        1  4  0  1  1  0  1  0  0  0  0  0  1
5  1 1 0  CW +S 5+NoFert+FPd        1  5  0  1  1  0  1  0  0  0  0  0  1
6  1 1 0  CW +S 6+NoFert+FPd        1  6  0  1  1  0  1  0  0  0  0  0  1
7  1 1 0  CW +S 7+NoFert+FPd        1  7  0  1  1  0  1  0  0  0  0  0  1
8  1 1 0  CW +S 8+NoFert+FPd        1  8  0  1  1  0  1  0  0  0  0  0  1
9  1 1 0  CW +S 9+NoFert+FPd        1  9  0  1  1  0  1  0  0  0  0  0  1
10 1 1 0  CW +S10+NoFert+FPd        1 10  0  1  1  0  1  0  0  0  0  0  1
11 1 1 0  CW +S11+NoFert+FPd        1 11  0  1  1  0  1  0  0  0  0  0  1
12 1 1 0  CW +S12+NoFert+FPd        1 12  0  1  1  0  1  0  0  0  0  0  1
13 1 1 0  CW +S13+NoFert+FPd        1 13  0  1  1  0  1  0  0  0  0  0  1
14 1 1 0  CW +S14+NoFert+FPd        1 14  0  1  1  0  1  0  0  0  0  0  1
15 1 1 0  CW +S15+NoFert+FPd        1 15  0  1  1  0  1  0  0  0  0  0  1
16 1 1 0  CW +S16+NoFert+FPd        1 16  0  1  1  0  1  0  0  0  0  0  1
17 1 1 0  CW +S 1+InorFert+FPd      1  1  0  1  1  0  2  0  0  0  0  0  1
18 1 1 0  CW +S 2+InorFert+FPd      1  2  0  1  1  0  2  0  0  0  0  0  1
19 1 1 0  CW +S 3+InorFert+FPd      1  3  0  1  1  0  2  0  0  0  0  0  1
20 1 1 0  CW +S 4+InorFert+FPd      1  4  0  1  1  0  2  0  0  0  0  0  1
21 1 1 0  CW +S 5+InorFert+FPd      1  5  0  1  1  0  2  0  0  0  0  0  1
22 1 1 0  CW +S 6+InorFert+FPd      1  6  0  1  1  0  2  0  0  0  0  0  1
23 1 1 0  CW +S 7+InorFert+FPd      1  7  0  1  1  0  2  0  0  0  0  0  1
24 1 1 0  CW +S 8+InorFert+FPd      1  8  0  1  1  0  2  0  0  0  0  0  1
25 1 1 0  CW +S 9+InorFert+FPd      1  9  0  1  1  0  2  0  0  0  0  0  1
26 1 1 0  CW +S10+InorFert+FPd      1 10  0  1  1  0  2  0  0  0  0  0  1
27 1 1 0  CW +S11+InorFert+FPd      1 11  0  1  1  0  2  0  0  0  0  0  1
28 1 1 0  CW +S12+InorFert+FPd      1 12  0  1  1  0  2  0  0  0  0  0  1
29 1 1 0  CW +S13+InorFert+FPd      1 13  0  1  1  0  2  0  0  0  0  0  1
30 1 1 0  CW +S14+InorFert+FPd      1 14  0  1  1  0  2  0  0  0  0  0  1
31 1 1 0  CW +S15+InorFert+FPd      1 15  0  1  1  0  2  0  0  0  0  0  1
32 1 1 0  CW +S16+InorFert+FPd      1 16  0  1  1  0  2  0  0  0  0  0  1
33 1 1 0  CW +S 1+Manure+FPd        1  1  0  1  1  0  0  1  0  0  0  0  1
34 1 1 0  CW +S 2+Manure+FPd        1  2  0  1  1  0  0  1  0  0  0  0  1
35 1 1 0  CW +S 3+Manure+FPd        1  3  0  1  1  0  0  1  0  0  0  0  1
36 1 1 0  CW +S 4+Manure+FPd        1  4  0  1  1  0  0  1  0  0  0  0  1
37 1 1 0  CW +S 5+Manure+FPd        1  5  0  1  1  0  0  1  0  0  0  0  1
38 1 1 0  CW +S 6+Manure+FPd        1  6  0  1  1  0  0  1  0  0  0  0  1
39 1 1 0  CW +S 7+Manure+FPd        1  7  0  1  1  0  0  1  0  0  0  0  1
40 1 1 0  CW +S 8+Manure+FPd        1  8  0  1  1  0  0  1  0  0  0  0  1
41 1 1 0  CW +S 9+Manure+FPd        1  9  0  1  1  0  0  1  0  0  0  0  1
42 1 1 0  CW +S10+Manure+FPd        1 10  0  1  1  0  0  1  0  0  0  0  1
43 1 1 0  CW +S11+Manure+FPd        1 11  0  1  1  0  0  1  0  0  0  0  1
44 1 1 0  CW +S12+Manure+FPd        1 12  0  1  1  0  0  1  0  0  0  0  1
45 1 1 0  CW +S13+Manure+FPd        1 13  0  1  1  0  0  1  0  0  0  0  1
46 1 1 0  CW +S14+Manure+FPd        1 14  0  1  1  0  0  1  0  0  0  0  1
47 1 1 0  CW +S15+Manure+FPd        1 15  0  1  1  0  0  1  0  0  0  0  1
48 1 1 0  CW +S16+Manure+FPd        1 16  0  1  1  0  0  1  0  0  0  0  1
49 1 1 0  CA +S 1+NoFert+FPd        2  1  0  1  1  0  1  0  0  0  0  0  1
50 1 1 0  CA +S 2+NoFert+FPd        2  2  0  1  1  0  1  0  0  0  0  0  1
51 1 1 0  CA +S 3+NoFert+FPd        2  3  0  1  1  0  1  0  0  0  0  0  1
52 1 1 0  CA +S 4+NoFert+FPd        2  4  0  1  1  0  1  0  0  0  0  0  1
53 1 1 0  CA +S 5+NoFert+FPd        2  5  0  1  1  0  1  0  0  0  0  0  1
54 1 1 0  CA +S 6+NoFert+FPd        2  6  0  1  1  0  1  0  0  0  0  0  1
55 1 1 0  CA +S 7+NoFert+FPd        2  7  0  1  1  0  1  0  0  0  0  0  1
56 1 1 0  CA +S 8+NoFert+FPd        2  8  0  1  1  0  1  0  0  0  0  0  1
57 1 1 0  CA +S 9+NoFert+FPd        2  9  0  1  1  0  1  0  0  0  0  0  1
58 1 1 0  CA +S10+NoFert+FPd        2 10  0  1  1  0  1  0  0  0  0  0  1
59 1 1 0  CA +S11+NoFert+FPd        2 11  0  1  1  0  1  0  0  0  0  0  1
60 1 1 0  CA +S12+NoFert+FPd        2 12  0  1  1  0  1  0  0  0  0  0  1
61 1 1 0  CA +S13+NoFert+FPd        2 13  0  1  1  0  1  0  0  0  0  0  1
62 1 1 0  CA +S14+NoFert+FPd        2 14  0  1  1  0  1  0  0  0  0  0  1
```

```
63 1 1 0  CA +S15+NoFert+FPd        2 15  0  1  1  0  1  0  0  0  0  0  1
64 1 1 0  CA +S16+NoFert+FPd        2 16  0  1  1  0  1  0  0  0  0  0  1
65 1 1 0  CA +S 1+InorFert+FPd      2  1  0  1  1  0  2  0  0  0  0  0  1
66 1 1 0  CA +S 2+InorFert+FPd      2  2  0  1  1  0  2  0  0  0  0  0  1
67 1 1 0  CA +S 3+InorFert+FPd      2  3  0  1  1  0  2  0  0  0  0  0  1
68 1 1 0  CA +S 4+InorFert+FPd      2  4  0  1  1  0  2  0  0  0  0  0  1
69 1 1 0  CA +S 5+InorFert+FPd      2  5  0  1  1  0  2  0  0  0  0  0  1
70 1 1 0  CA +S 6+InorFert+FPd      2  6  0  1  1  0  2  0  0  0  0  0  1
71 1 1 0  CA +S 7+InorFert+FPd      2  7  0  1  1  0  2  0  0  0  0  0  1
72 1 1 0  CA +S 8+InorFert+FPd      2  8  0  1  1  0  2  0  0  0  0  0  1
73 1 1 0  CA +S 9+InorFert+FPd      2  9  0  1  1  0  2  0  0  0  0  0  1
74 1 1 0  CA +S10+InorFert+FPd      2 10  0  1  1  0  2  0  0  0  0  0  1
75 1 1 0  CA +S11+InorFert+FPd      2 11  0  1  1  0  2  0  0  0  0  0  1
76 1 1 0  CA +S12+InorFert+FPd      2 12  0  1  1  0  2  0  0  0  0  0  1
77 1 1 0  CA +S13+InorFert+FPd      2 13  0  1  1  0  2  0  0  0  0  0  1
78 1 1 0  CA +S14+InorFert+FPd      2 14  0  1  1  0  2  0  0  0  0  0  1
79 1 1 0  CA +S15+InorFert+FPd      2 15  0  1  1  0  2  0  0  0  0  0  1
80 1 1 0  CA +S16+InorFert+FPd      2 16  0  1  1  0  2  0  0  0  0  0  1
81 1 1 0  CA +S 1+Manure+FPd        2  1  0  1  1  0  0  1  0  0  0  0  1
82 1 1 0  CA +S 2+Manure+FPd        2  2  0  1  1  0  0  1  0  0  0  0  1
83 1 1 0  CA +S 3+Manure+FPd        2  3  0  1  1  0  0  1  0  0  0  0  1
84 1 1 0  CA +S 4+Manure+FPd        2  4  0  1  1  0  0  1  0  0  0  0  1
85 1 1 0  CA +S 5+Manure+FPd        2  5  0  1  1  0  0  1  0  0  0  0  1
86 1 1 0  CA +S 6+Manure+FPd        2  6  0  1  1  0  0  1  0  0  0  0  1
87 1 1 0  CA +S 7+Manure+FPd        2  7  0  1  1  0  0  1  0  0  0  0  1
88 1 1 0  CA +S 8+Manure+FPd        2  8  0  1  1  0  0  1  0  0  0  0  1
89 1 1 0  CA +S 9+Manure+FPd        2  9  0  1  1  0  0  1  0  0  0  0  1
90 1 1 0  CA +S10+Manure+FPd        2 10  0  1  1  0  0  1  0  0  0  0  1
91 1 1 0  CA +S11+Manure+FPd        2 11  0  1  1  0  0  1  0  0  0  0  1
92 1 1 0  CA +S12+Manure+FPd        2 12  0  1  1  0  0  1  0  0  0  0  1
93 1 1 0  CA +S13+Manure+FPd        2 13  0  1  1  0  0  1  0  0  0  0  1
94 1 1 0  CA +S14+Manure+FPd        2 14  0  1  1  0  0  1  0  0  0  0  1
95 1 1 0  CA +S15+Manure+FPd        2 15  0  1  1  0  0  1  0  0  0  0  1
96 1 1 0  CA +S16+Manure+FPd        2 16  0  1  1  0  0  1  0  0  0  0  1

*CULTIVARS
@C CR INGENO CNAME
 1 BN IB0014 Canadian Wonder+
 2 BN IF2011 Calima

*FIELDS
@L ID_FIELD WSTA....  FLSA  FLOB  FLDT  FLDD  FLDS  FLST SLTX  SLDP  ID_SOIL
FLNAME
 1 Point1   LT01       -99     0 DR000     0     0 00000 C       50  TZ_LUTZ001  S1
 2 Point2   LT01       -99     0 DR000     0     0 00000 C       50  TZ_LUTZ002  S2
 3 Point3   LT02       -99     0 DR000     0     0 00000 C       50  TZ_LUTZ003  S3
 4 Point4   LT02       -99     0 DR000     0     0 00000 L       50  TZ_LUTZ004  S4
 5 Point5   LT01       -99     0 DR000     0     0 00000 C       50  TZ_LUTZ005  S5
 6 Point6   LT01       -99     0 DR000     0     0 00000 C       50  TZ_LUTZ006  S6
 7 Point7   LT02       -99     0 DR000     0     0 00000 L       50  TZ_LUTZ007  S7
 8 Point8   LT02       -99     0 DR000     0     0 00000 C       50  TZ_LUTZ008  S8
 9 Point9   LT01       -99     0 DR000     0     0 00000 C       50  TZ_LUTZ009  S9
10 Poin10   LT01       -99     0 DR000     0     0 00000 C       50  TZ_LUTZ010
S10
11 Poin11   LT02       -99     0 DR000     0     0 00000 C       50  TZ_LUTZ011
S11
12 Poin12   LT02       -99     0 DR000     0     0 00000 C       50  TZ_LUTZ012
S12
13 Poin13   LT01       -99     0 DR000     0     0 00000 C       50  TZ_LUTZ013
S13
14 Poin14   LT01       -99     0 DR000     0     0 00000 C       50  TZ_LUTZ014
S14
15 Poin15   LT02       -99     0 DR000     0     0 00000 C       50  TZ_LUTZ015
S15
16 Poin16   LT02       -99     0 DR000     0     0 00000 C       50  TZ_LUTZ016
S16

*INITIAL CONDITIONS
@C   PCR ICDAT  ICRT  ICND  ICRN  ICRE  ICWD ICRES ICREN ICREP ICRIP ICRID ICNAME
 1    BN 01034    50     0     1     1   -99    50    .8     0  100    15   -99
@C  ICBL  SH2O  SNH4  SNO3
 1     5   -99     1     1
 1    15   -99     1     1
 1    30   -99     1     1
 1    45   -99     1     1
 1    60   -99     1     1
 1    90   -99     1     1

*PLANTING DETAILS
```

```
@P PDATE EDATE  PPOP  PPOE  PLME  PLDS  PLRS  PLRD  PLDP  PLWT  PAGE  PENV  PLPH
SPRL                            PLNAME
 1   -99   -99     8     8     S     R    30     0     5   -99   -99   -99   -99
-99                            February 28th and April 15th

*FERTILIZERS (INORGANIC)
@F FDATE  FMCD  FACD  FDEP  FAMN  FAMP  FAMK  FAMC  FAMO  FOCD FERNAME
 1     0 FE006   -99     0     0   -99   -99   -99   -99   -99 -99
 2     0 FE006   -99     4    21   -99   -99   -99   -99   -99 -99

*RESIDUES AND ORGANIC FERTILIZER
@R RDATE  RCOD  RAMT  RESN  RESP  RESK  RINP  RDEP
 1 01044 RE003  2000   1.6   0.4   2.5   100    15

*SIMULATION CONTROLS
@N GENERAL     NYERS NREPS START SDATE RSEED SNAME.................... SMODEL
 1 GE             29     1     S 01034 2150  Hoima-Uganda CLIMATE CHANGE
@N OPTIONS     WATER NITRO SYMBI PHOSP POTAS DISES CHEM TILL CO2
 1 OP              Y     Y     Y     N     N     N    N    N   M
@N METHODS     WTHER INCON LIGHT EVAPO INFIL PHOTO HYDRO NSWIT MESOM MESEV MESOL
 1 ME              M     M     E     R     S     L     R     1     P     S     1
@N MANAGEMENT  PLANT IRRIG FERTI RESID HARVS
 1 MA              A     N     D     R     M
@N OUTPUTS     FNAME OVVEW SUMRY FROPT GROUT CAOUT WAOUT NIOUT MIOUT DIOUT VBOSE
CHOUT OPOUT
 1 OU              N     Y     Y     1     N     N     N     N     N     N     N
N     N

@  AUTOMATIC MANAGEMENT
@N PLANTING    PFRST PLAST PH2OL PH2OU PH2OD PSTMX PSTMN
 1 PL          01059 01104    40   100    30    40    10
@N IRRIGATION  IMDEP ITHRL ITHRU IROFF IMETH IRAMT IREFF
 1 IR            -99   -99   -99   -99   -99   -99   -99
@N NITROGEN    NMDEP NMTHR NAMNT NCODE NAOFF
 1 NI            -99   -99   -99   -99   -99
@N RESIDUES    RIPCN RTIME RIDEP
 1 RE            -99   -99   -99
@N HARVEST     HFRST HLAST HPCNP HPCNR
 1 HA              0 01365   100     0
```

2. Maize in Hoima (Second planting season)

```
*EXP.DETAILS: CCAFS BENCHMARK SITE CURRENT AND FUTURE CLIMATE- Hoima Uganda

*GENERAL
@PEOPLE
B. Rodríguez, M. Fisher, L. Winowiecki, A. Eitzinger, P. Laderach.
@ADDRESS
CIAT, Cali-Colombia.
@SITE
Soil samples in the Hoima Area, UGANDA.

*TREATMENTS                        -------------FACTOR LEVELS------------
@N R O C TNAME.................... CU  FL  SA  IC  MP  MI  MF  MR  MC  MT  ME  MH  SM
1  1 1 0  H.O+S 1+NoFert+SPd        1   1   0   1   1   0   0   0   0   0   0   0   1
2  1 1 0  H.O+S 2+NoFert+SPd        1   2   0   1   1   0   0   0   0   0   0   0   1
3  1 1 0  H.O+S 3+NoFert+SPd        1   3   0   1   1   0   0   0   0   0   0   0   1
4  1 1 0  H.O+S 4+NoFert+SPd        1   4   0   1   1   0   0   0   0   0   0   0   1
5  1 1 0  H.O+S 5+NoFert+SPd        1   5   0   1   1   0   0   0   0   0   0   0   1
6  1 1 0  H.O+S 6+NoFert+SPd        1   6   0   1   1   0   0   0   0   0   0   0   1
7  1 1 0  H.O+S 7+NoFert+SPd        1   7   0   1   1   0   0   0   0   0   0   0   1
8  1 1 0  H.O+S 8+NoFert+SPd        1   8   0   1   1   0   0   0   0   0   0   0   1
9  1 1 0  H.O+S 9+NoFert+SPd        1   9   0   1   1   0   0   0   0   0   0   0   1
10 1 1 0  H.O+S10+NoFert+SPd        1  10   0   1   1   0   0   0   0   0   0   0   1
11 1 1 0  H.O+S11+NoFert+SPd        1  11   0   1   1   0   0   0   0   0   0   0   1
12 1 1 0  H.O+S12+NoFert+SPd        1  12   0   1   1   0   0   0   0   0   0   0   1
13 1 1 0  H.O+S13+NoFert+SPd        1  13   0   1   1   0   0   0   0   0   0   0   1
14 1 1 0  H.O+S14+NoFert+SPd        1  14   0   1   1   0   0   0   0   0   0   0   1
15 1 1 0  H.O+S15+NoFert+SPd        1  15   0   1   1   0   0   0   0   0   0   0   1
16 1 1 0  H.O+S16+NoFert+SPd        1  16   0   1   1   0   0   0   0   0   0   0   1
17 1 1 0  H.O+S 1+InorFert+SPd      1   1   0   1   1   0   1   0   0   0   0   0   1
18 1 1 0  H.O+S 2+InorFert+SPd      1   2   0   1   1   0   1   0   0   0   0   0   1
19 1 1 0  H.O+S 3+InorFert+SPd      1   3   0   1   1   0   1   0   0   0   0   0   1
20 1 1 0  H.O+S 4+InorFert+SPd      1   4   0   1   1   0   1   0   0   0   0   0   1
21 1 1 0  H.O+S 5+InorFert+SPd      1   5   0   1   1   0   1   0   0   0   0   0   1
22 1 1 0  H.O+S 6+InorFert+SPd      1   6   0   1   1   0   1   0   0   0   0   0   1
23 1 1 0  H.O+S 7+InorFert+SPd      1   7   0   1   1   0   1   0   0   0   0   0   1
24 1 1 0  H.O+S 8+InorFert+SPd      1   8   0   1   1   0   1   0   0   0   0   0   1
25 1 1 0  H.O+S 9+InorFert+SPd      1   9   0   1   1   0   1   0   0   0   0   0   1
26 1 1 0  H.O+S10+InorFert+SPd      1  10   0   1   1   0   1   0   0   0   0   0   1
27 1 1 0  H.O+S11+InorFert+SPd      1  11   0   1   1   0   1   0   0   0   0   0   1
28 1 1 0  H.O+S12+InorFert+SPd      1  12   0   1   1   0   1   0   0   0   0   0   1
29 1 1 0  H.O+S13+InorFert+SPd      1  13   0   1   1   0   1   0   0   0   0   0   1
30 1 1 0  H.O+S14+InorFert+SPd      1  14   0   1   1   0   1   0   0   0   0   0   1
31 1 1 0  H.O+S15+InorFert+SPd      1  15   0   1   1   0   1   0   0   0   0   0   1
32 1 1 0  H.O+S16+InorFert+SPd      1  16   0   1   1   0   1   0   0   0   0   0   1
33 1 1 0  H.O+S 1+Manure+SPd        1   1   0   1   1   0   0   1   0   0   0   0   1
34 1 1 0  H.O+S 2+Manure+SPd        1   2   0   1   1   0   0   1   0   0   0   0   1
35 1 1 0  H.O+S 3+Manure+SPd        1   3   0   1   1   0   0   1   0   0   0   0   1
36 1 1 0  H.O+S 4+Manure+SPd        1   4   0   1   1   0   0   1   0   0   0   0   1
37 1 1 0  H.O+S 5+Manure+SPd        1   5   0   1   1   0   0   1   0   0   0   0   1
38 1 1 0  H.O+S 6+Manure+SPd        1   6   0   1   1   0   0   1   0   0   0   0   1
39 1 1 0  H.O+S 7+Manure+SPd        1   7   0   1   1   0   0   1   0   0   0   0   1
40 1 1 0  H.O+S 8+Manure+SPd        1   8   0   1   1   0   0   1   0   0   0   0   1
41 1 1 0  H.O+S 9+Manure+SPd        1   9   0   1   1   0   0   1   0   0   0   0   1
42 1 1 0  H.O+S10+Manure+SPd        1  10   0   1   1   0   0   1   0   0   0   0   1
43 1 1 0  H.O+S11+Manure+SPd        1  11   0   1   1   0   0   1   0   0   0   0   1
44 1 1 0  H.O+S12+Manure+SPd        1  12   0   1   1   0   0   1   0   0   0   0   1
45 1 1 0  H.O+S13+Manure+SPd        1  13   0   1   1   0   0   1   0   0   0   0   1
46 1 1 0  H.O+S14+Manure+SPd        1  14   0   1   1   0   0   1   0   0   0   0   1
47 1 1 0  H.O+S15+Manure+SPd        1  15   0   1   1   0   0   1   0   0   0   0   1
48 1 1 0  H.O+S16+Manure+SPd        1  16   0   1   1   0   0   1   0   0   0   0   1
49 1 1 0  FM6+S 1+NoFert+SPd        2   1   0   1   1   0   0   0   0   0   0   0   1
50 1 1 0  FM6+S 2+NoFert+SPd        2   2   0   1   1   0   0   0   0   0   0   0   1
51 1 1 0  FM6+S 3+NoFert+SPd        2   3   0   1   1   0   0   0   0   0   0   0   1
52 1 1 0  FM6+S 4+NoFert+SPd        2   4   0   1   1   0   0   0   0   0   0   0   1
53 1 1 0  FM6+S 5+NoFert+SPd        2   5   0   1   1   0   0   0   0   0   0   0   1
54 1 1 0  FM6+S 6+NoFert+SPd        2   6   0   1   1   0   0   0   0   0   0   0   1
55 1 1 0  FM6+S 7+NoFert+SPd        2   7   0   1   1   0   0   0   0   0   0   0   1
56 1 1 0  FM6+S 8+NoFert+SPd        2   8   0   1   1   0   0   0   0   0   0   0   1
57 1 1 0  FM6+S 9+NoFert+SPd        2   9   0   1   1   0   0   0   0   0   0   0   1
58 1 1 0  FM6+S10+NoFert+SPd        2  10   0   1   1   0   0   0   0   0   0   0   1
59 1 1 0  FM6+S11+NoFert+SPd        2  11   0   1   1   0   0   0   0   0   0   0   1
60 1 1 0  FM6+S12+NoFert+SPd        2  12   0   1   1   0   0   0   0   0   0   0   1
61 1 1 0  FM6+S13+NoFert+SPd        2  13   0   1   1   0   0   0   0   0   0   0   1
62 1 1 0  FM6+S14+NoFert+SPd        2  14   0   1   1   0   0   0   0   0   0   0   1
63 1 1 0  FM6+S15+NoFert+SPd        2  15   0   1   1   0   0   0   0   0   0   0   1
64 1 1 0  FM6+S16+NoFert+SPd        2  16   0   1   1   0   0   0   0   0   0   0   1
```

```
65 1 1 0  FM6+S 1+InorFert+SPd      2  1  0  1  1  0  1  0  0  0  0  0  1
66 1 1 0  FM6+S 2+InorFert+SPd      2  2  0  1  1  0  1  0  0  0  0  0  1
67 1 1 0  FM6+S 3+InorFert+SPd      2  3  0  1  1  0  1  0  0  0  0  0  1
68 1 1 0  FM6+S 4+InorFert+SPd      2  4  0  1  1  0  1  0  0  0  0  0  1
69 1 1 0  FM6+S 5+InorFert+SPd      2  5  0  1  1  0  1  0  0  0  0  0  1
70 1 1 0  FM6+S 6+InorFert+SPd      2  6  0  1  1  0  1  0  0  0  0  0  1
71 1 1 0  FM6+S 7+InorFert+SPd      2  7  0  1  1  0  1  0  0  0  0  0  1
72 1 1 0  FM6+S 8+InorFert+SPd      2  8  0  1  1  0  1  0  0  0  0  0  1
73 1 1 0  FM6+S 9+InorFert+SPd      2  9  0  1  1  0  1  0  0  0  0  0  1
74 1 1 0  FM6+S10+InorFert+SPd      2 10  0  1  1  0  1  0  0  0  0  0  1
75 1 1 0  FM6+S11+InorFert+SPd      2 11  0  1  1  0  1  0  0  0  0  0  1
76 1 1 0  FM6+S12+InorFert+SPd      2 12  0  1  1  0  1  0  0  0  0  0  1
77 1 1 0  FM6+S13+InorFert+SPd      2 13  0  1  1  0  1  0  0  0  0  0  1
78 1 1 0  FM6+S14+InorFert+SPd      2 14  0  1  1  0  1  0  0  0  0  0  1
79 1 1 0  FM6+S15+InorFert+SPd      2 15  0  1  1  0  1  0  0  0  0  0  1
80 1 1 0  FM6+S16+InorFert+SPd      2 16  0  1  1  0  1  0  0  0  0  0  1
81 1 1 0  FM6+S 1+Manure+SPd        2  1  0  1  1  0  0  1  0  0  0  0  1
82 1 1 0  FM6+S 2+Manure+SPd        2  2  0  1  1  0  0  1  0  0  0  0  1
83 1 1 0  FM6+S 3+Manure+SPd        2  3  0  1  1  0  0  1  0  0  0  0  1
84 1 1 0  FM6+S 4+Manure+SPd        2  4  0  1  1  0  0  1  0  0  0  0  1
85 1 1 0  FM6+S 5+Manure+SPd        2  5  0  1  1  0  0  1  0  0  0  0  1
86 1 1 0  FM6+S 6+Manure+SPd        2  6  0  1  1  0  0  1  0  0  0  0  1
87 1 1 0  FM6+S 7+Manure+SPd        2  7  0  1  1  0  0  1  0  0  0  0  1
88 1 1 0  FM6+S 8+Manure+SPd        2  8  0  1  1  0  0  1  0  0  0  0  1
89 1 1 0  FM6+S 9+Manure+SPd        2  9  0  1  1  0  0  1  0  0  0  0  1
90 1 1 0  FM6+S10+Manure+SPd        2 10  0  1  1  0  0  1  0  0  0  0  1
91 1 1 0  FM6+S11+Manure+SPd        2 11  0  1  1  0  0  1  0  0  0  0  1
92 1 1 0  FM6+S12+Manure+SPd        2 12  0  1  1  0  0  1  0  0  0  0  1
93 1 1 0  FM6+S13+Manure+SPd        2 13  0  1  1  0  0  1  0  0  0  0  1
94 1 1 0  FM6+S14+Manure+SPd        2 14  0  1  1  0  0  1  0  0  0  0  1
95 1 1 0  FM6+S15+Manure+SPd        2 15  0  1  1  0  0  1  0  0  0  0  1
96 1 1 0  FM6+S16+Manure+SPd        2 16  0  1  1  0  0  1  0  0  0  0  1

*CULTIVARS
@C CR INGENO CNAME
 1 MZ IB0064 H.OBREGON
 2 MZ IB0056 FM 6

*FIELDS
@L ID_FIELD WSTA....  FLSA  FLOB  FLDT  FLDD  FLDS  FLST SLTX  SLDP  ID_SOIL
FLNAME
 1 Point1   HG01       -99     0 DR000     0     0 00000 C       50  UG_HOUG001  S1
 2 Point2   HG01       -99     0 DR000     0     0 00000 C       50  UG_HOUG002  S2
 3 Point3   HG02       -99     0 DR000     0     0 00000 C       50  UG_HOUG003  S3
 4 Point4   HG02       -99     0 DR000     0     0 00000 C       50  UG_HOUG004  S4
 5 Point5   HG01       -99     0 DR000     0     0 00000 C       50  UG_HOUG005  S5
 6 Point6   HG01       -99     0 DR000     0     0 00000 C       50  UG_HOUG006  S6
 7 Point7   HG02       -99     0 DR000     0     0 00000 C       50  UG_HOUG007  S7
 8 Point8   HG02       -99     0 DR000     0     0 00000 C       50  UG_HOUG008  S8
 9 Point9   HG03       -99     0 DR000     0     0 00000 C       50  UG_HOUG009  S9
10 Poin10   HG03       -99     0 DR000     0     0 00000 C       50  UG_HOUG010
S10
11 Poin11   HG04       -99     0 DR000     0     0 00000 C       50  UG_HOUG011
S11
12 Poin12   HG04       -99     0 DR000     0     0 00000 C       50  UG_HOUG012
S12
13 Poin13   HG03       -99     0 DR000     0     0 00000 C       50  UG_HOUG013
S13
14 Poin14   HG03       -99     0 DR000     0     0 00000 C       50  UG_HOUG014
S14
15 Poin15   HG04       -99     0 DR000     0     0 00000 C       50  UG_HOUG015
S15
16 Poin16   HG04       -99     0 DR000     0     0 00000 C       50  UG_HOUG016
S16

*INITIAL CONDITIONS
@C   PCR ICDAT  ICRT  ICND  ICRN  ICRE  ICWD ICRES ICREN ICREP ICRIP ICRID ICNAME
 1    MZ 01180    80     0     1     1   -99    50    .8     0  100     15   -99
@C  ICBL  SH2O  SNH4  SNO3
 1     5   -99     1     1
 1    15   -99     1     1
 1    30   -99     1     1
 1    45   -99     1     1
 1    60   -99     1     1
 1    90   -99     1     1

*PLANTING DETAILS
@P PDATE EDATE  PPOP  PPOE  PLME  PLDS  PLRS  PLRD  PLDP  PLWT  PAGE  PENV  PLPH
SPRL                        PLNAME
```

```
 1   -99   -99     8     8     S     R    50     0     5   -99   -99   -99   -99
-99                     July 15ht-September 1st

*FERTILIZERS (INORGANIC)
@F FDATE  FMCD  FACD  FDEP  FAMN  FAMP  FAMK  FAMC  FAMO  FOCD FERNAME
 1     0 FE006   -99     5     9    10     0   -99   -99   -99 -99
 1    45 FE005   -99     5    23     0     0   -99   -99   -99 -99

*RESIDUES AND ORGANIC FERTILIZER
@R RDATE  RCOD  RAMT  RESN  RESP  RESK  RINP  RDEP
 1 01180 RE003  2000   1.6   0.4   2.5   100    15

*SIMULATION CONTROLS
@N GENERAL     NYERS NREPS START SDATE RSEED SNAME.................... SMODEL
 1 GE             28     1     S 01180 2150  Hoima-Uganda CLIMATE CHANGE
@N OPTIONS     WATER NITRO SYMBI PHOSP POTAS DISES CHEM TILL CO2
 1 OP              Y     Y     N     N     N     N    N    N   M
@N METHODS     WTHER INCON LIGHT EVAPO INFIL PHOTO HYDRO NSWIT MESOM MESEV MESOL
 1 ME              M     M     E     R     S     L     R     1     P     S     1
@N MANAGEMENT  PLANT IRRIG FERTI RESID HARVS
 1 MA              A     N     D     R     M
@N OUTPUTS     FNAME OVVEW SUMRY FROPT GROUT CAOUT WAOUT NIOUT MIOUT DIOUT VBOSE
CHOUT OPOUT
 1 OU              N     Y     Y     1     N     N     N     N     N     N     N
N     N

@  AUTOMATIC MANAGEMENT
@N PLANTING    PFRST PLAST PH2OL PH2OU PH2OD PSTMX PSTMN
 1 PL          01200 01245    40   100    30    40    10
@N IRRIGATION  IMDEP ITHRL ITHRU IROFF IMETH IRAMT IREFF
 1 IR            -99   -99   -99   -99   -99   -99   -99
@N NITROGEN    NMDEP NMTHR NAMNT NCODE NAOFF
 1 NI            -99   -99   -99   -99   -99
@N RESIDUES    RIPCN RTIME RIDEP
 1 RE            -99   -99   -99
@N HARVEST     HFRST HLAST HPCNP HPCNR
 1 HA              0 01365   100     0
```

3. Soil input file for Rakai (16 samples)

```
*SOILS: General DSSAT Soil Input File

*UG_RKUG001  LDSF        C        50 LDSF DATABASE, SOIL UG001
@SITE        COUNTRY          LAT     LONG  SCS FAMILY
 Rakai       Uganda         -0.72   31.42  -99
@ SCOM  SALB  SLU1  SLDR  SLRO  SLNF  SLPF  SMHB  SMPX  SMKE
    BN   .13     6   0.4    88     1     1 SA011 SA013 SA013
@  SLB  SLMH  SLLL  SDUL  SSAT  SRGF  SSKS  SBDM  SLOC  SLCL  SLSI  SLCF  SLNI
SLHW  SLHB  SCEC  SADC
    20   -99  .341  .467  .557     1   2.6  1.13  1.66    78    18   -99   .17
5.4   -99  12.7   -99
    50   -99  .336  .469  .532  .497   2.6  1.20  0.74    90     8   -99   .10
5.4   -99  10.0   -99
@  SLB  SLPX  SLPT  SLPO CACO3  SLAL  SLFE  SLMN  SLBS  SLPA  SLPB  SLKE  SLMG
SLNA  SLSU  SLEC  SLCA
    20   8.4   -99   -99   -99   -99   -99   -99   -99   -99   -99  0.21  1.88
0.22   -99  0.90   -99
    50   3.3   -99   -99   -99   -99   -99   -99   -99   -99   -99  0.34  1.52
0.41   -99  0.20   -99

*UG_RKUG002  LDSF        C        50 LDSF DATABASE, SOIL UG002
@SITE        COUNTRY          LAT     LONG  SCS FAMILY
 Rakai       Uganda         -0.71   31.41  -99
@ SCOM  SALB  SLU1  SLDR  SLRO  SLNF  SLPF  SMHB  SMPX  SMKE
    BN   .13     6   0.4    91     1     1 SA011 SA013 SA013
@  SLB  SLMH  SLLL  SDUL  SSAT  SRGF  SSKS  SBDM  SLOC  SLCL  SLSI  SLCF  SLNI
SLHW  SLHB  SCEC  SADC
    20   -99  .343  .465  .566     1   2.9  1.11  1.98    77    18   -99   .23
5.7   -99  14.4   -99
    50   -99  .338  .463  .537  .497   2.9  1.18  1.00    83    13   -99   .13
5.3   -99  10.1   -99
@  SLB  SLPX  SLPT  SLPO CACO3  SLAL  SLFE  SLMN  SLBS  SLPA  SLPB  SLKE  SLMG
SLNA  SLSU  SLEC  SLCA
    20   8.1   -99   -99   -99   -99   -99   -99   -99   -99   -99  0.35  2.86
0.24   -99  1.28   -99
    50   4.9   -99   -99   -99   -99   -99   -99   -99   -99   -99  0.21  1.68
0.33   -99  0.45   -99
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*UG_RKUG003  LDSF        C        50 LDSF DATABASE, SOIL UG003
@SITE        COUNTRY          LAT     LONG  SCS FAMILY
 Rakai       Uganda         -0.67   31.42  -99
@ SCOM  SALB  SLU1  SLDR  SLRO  SLNF  SLPF  SMHB  SMPX  SMKE
    BN   .13     6   0.6    88     1     1 SA011 SA013 SA013
@  SLB  SLMH  SLLL  SDUL  SSAT  SRGF  SSKS  SBDM  SLOC  SLCL  SLSI  SLCF  SLNI
SLHW  SLHB  SCEC  SADC
    20   -99  .326  .454  .592     1   4.7  1.03  3.12    60    30   -99   .27
7.9   -99  28.0   -99
    50   -99  .331  .466  .554  .497   4.7  1.14  1.66    69    26   -99   .14
7.8   -99  18.1   -99
@  SLB  SLPX  SLPT  SLPO CACO3  SLAL  SLFE  SLMN  SLBS  SLPA  SLPB  SLKE  SLMG
SLNA  SLSU  SLEC  SLCA
    20   -99   -99   -99   -99   -99   -99   -99   -99   -99   -99  1.93  5.17
0.30   -99  1.30   -99
    50   -99   -99   -99   -99   -99   -99   -99   -99   -99   -99  2.27  3.23
0.24   -99  0.60   -99

*UG_RKUG004  LDSF        C        50 LDSF DATABASE, SOIL UG004
@SITE        COUNTRY          LAT     LONG  SCS FAMILY
 Rakai       Uganda         -0.65   31.41  -99
@ SCOM  SALB  SLU1  SLDR  SLRO  SLNF  SLPF  SMHB  SMPX  SMKE
    BN   .13     6   0.6    88     1     1 SA011 SA013 SA013
@  SLB  SLMH  SLLL  SDUL  SSAT  SRGF  SSKS  SBDM  SLOC  SLCL  SLSI  SLCF  SLNI
SLHW  SLHB  SCEC  SADC
    20   -99  .301  .449  .573     1   4.2  1.05  2.15    53    36   -99   .20
6.8   -99  15.9   -99
    50   -99  .318  .466  .557  .497   4.2  1.10  0.97    65    30   -99   .11
6.5   -99  11.1   -99
@  SLB  SLPX  SLPT  SLPO CACO3  SLAL  SLFE  SLMN  SLBS  SLPA  SLPB  SLKE  SLMG
SLNA  SLSU  SLEC  SLCA
    20   8.5   -99   -99   -99   -99   -99   -99   -99   -99   -99  1.05  3.32
0.19   -99  0.59   -99
    50   1.6   -99   -99   -99   -99   -99   -99   -99   -99   -99  0.80  2.58
0.24   -99  0.18   -99

*UG_RKUG005  LDSF        C        50 LDSF DATABASE, SOIL UG005
@SITE        COUNTRY          LAT     LONG  SCS FAMILY
 Rakai       Uganda         -0.72   31.44  -99
@ SCOM  SALB  SLU1  SLDR  SLRO  SLNF  SLPF  SMHB  SMPX  SMKE
    BN   .13     6   0.4    88     1     1 SA011 SA013 SA013
@  SLB  SLMH  SLLL  SDUL  SSAT  SRGF  SSKS  SBDM  SLOC  SLCL  SLSI  SLCF  SLNI
SLHW  SLHB  SCEC  SADC
    20   -99  .346  .469  .569     1   3.2  1.10  2.03    82    14   -99   .20
6.0   -99  13.2   -99
    50   -99  .337  .469  .534  .497   3.2  1.19  0.84    83    16   -99   .10
5.3   -99  13.2   -99
@  SLB  SLPX  SLPT  SLPO CACO3  SLAL  SLFE  SLMN  SLBS  SLPA  SLPB  SLKE  SLMG
SLNA  SLSU  SLEC  SLCA
    20  21.5   -99   -99   -99   -99   -99   -99   -99   -99   -99  1.36  2.43
0.23   -99  0.79   -99
    50   3.4   -99   -99   -99   -99   -99   -99   -99   -99   -99  0.98  1.69
1.01   -99  0.31   -99

*UG_RKUG006  LDSF        C        50 LDSF DATABASE, SOIL UG006
@SITE        COUNTRY          LAT     LONG  SCS FAMILY
 Rakai       Uganda         -0.70   31.44  -99
@ SCOM  SALB  SLU1  SLDR  SLRO  SLNF  SLPF  SMHB  SMPX  SMKE
    BN   .13     6   0.4    91     1     1 SA011 SA013 SA013
@  SLB  SLMH  SLLL  SDUL  SSAT  SRGF  SSKS  SBDM  SLOC  SLCL  SLSI  SLCF  SLNI
SLHW  SLHB  SCEC  SADC
    20   -99  .322  .449  .555     1   3.1  1.13  1.82    63    28   -99   .17
6.4   -99  11.8   -99
    50   -99  .329  .452  .536  .497   3.1  1.18  1.13    71    23   -99   .10
5.9   -99   8.6   -99
@  SLB  SLPX  SLPT  SLPO CACO3  SLAL  SLFE  SLMN  SLBS  SLPA  SLPB  SLKE  SLMG
SLNA  SLSU  SLEC  SLCA
    20  15.0   -99   -99   -99   -99   -99   -99   -99   -99   -99  0.90  2.39
0.21   -99  0.53   -99
    50   8.4   -99   -99   -99   -99   -99   -99   -99   -99   -99  0.38  1.81
0.27   -99  0.22   -99

*UG_RKUG007  LDSF        C        50 LDSF DATABASE, SOIL UG007
@SITE        COUNTRY          LAT     LONG  SCS FAMILY
 Rakai       Uganda         -0.67   31.44  -99
@ SCOM  SALB  SLU1  SLDR  SLRO  SLNF  SLPF  SMHB  SMPX  SMKE
    BN   .13     6  0.35    88     1     1 SA011 SA013 SA013
@  SLB  SLMH  SLLL  SDUL  SSAT  SRGF  SSKS  SBDM  SLOC  SLCL  SLSI  SLCF  SLNI
SLHW  SLHB  SCEC  SADC
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    20   -99  .331  .453  .546     1   2.0  1.13  1.86    68    24   -99   .15
5.6   -99  13.3   -99
    50   -99  .306  .452  .505  .497   2.0  1.24  0.54    61    33   -99   .06
5.3   -99   7.5   -99
@  SLB  SLPX  SLPT  SLPO CACO3  SLAL  SLFE  SLMN  SLBS  SLPA  SLPB  SLKE  SLMG
SLNA  SLSU  SLEC  SLCA
    20   9.8   -99   -99   -99   -99   -99   -99   -99   -99   -99  0.31  2.11
0.21   -99  0.44   -99
    50   3.6   -99   -99   -99   -99   -99   -99   -99   -99   -99  0.14  1.00
0.26   -99  0.23   -99

*UG_RKUG008  LDSF        C        50 LDSF DATABASE, SOIL UG008
@SITE        COUNTRY          LAT     LONG  SCS FAMILY
 Rakai       Uganda         -0.66   31.44  -99
@ SCOM  SALB  SLU1  SLDR  SLRO  SLNF  SLPF  SMHB  SMPX  SMKE
    BN   .13     6   0.1    91     1     1 SA011 SA013 SA013
@  SLB  SLMH  SLLL  SDUL  SSAT  SRGF  SSKS  SBDM  SLOC  SLCL  SLSI  SLCF  SLNI
SLHW  SLHB  SCEC  SADC
    20   -99  .330  .447  .558     1   0.4  1.13  1.94    67    23   -99   .17
5.2   -99  10.9   -99
    50   -99  .336  .459  .533  .497   0.4  1.19  0.96    79    15   -99   .11
5.1   -99   6.2   -99
@  SLB  SLPX  SLPT  SLPO CACO3  SLAL  SLFE  SLMN  SLBS  SLPA  SLPB  SLKE  SLMG
SLNA  SLSU  SLEC  SLCA
    20   4.3   -99   -99   -99   -99   -99   -99   -99   -99   -99  0.19  1.51
0.27   -99  0.39   -99
    50   2.3   -99   -99   -99   -99   -99   -99   -99   -99   -99  0.14  0.70
0.20   -99  0.18   -99

*UG_RKUG009  LDSF        C        50 LDSF DATABASE, SOIL UG009
@SITE        COUNTRY          LAT     LONG  SCS FAMILY
 Rakai       Uganda         -0.72   31.46  -99
@ SCOM  SALB  SLU1  SLDR  SLRO  SLNF  SLPF  SMHB  SMPX  SMKE
    BN   .13     6  0.25    91     1     1 SA011 SA013 SA013
@  SLB  SLMH  SLLL  SDUL  SSAT  SRGF  SSKS  SBDM  SLOC  SLCL  SLSI  SLCF  SLNI
SLHW  SLHB  SCEC  SADC
    20   -99  .336  .461  .547     1   1.6  1.16  1.35    76    20   -99   .13
5.1   -99   8.2   -99
    50   -99  .336  .461  .531  .497   1.6  1.20  0.80    83    13   -99   .09
5.1   -99   4.9   -99
@  SLB  SLPX  SLPT  SLPO CACO3  SLAL  SLFE  SLMN  SLBS  SLPA  SLPB  SLKE  SLMG
SLNA  SLSU  SLEC  SLCA
    20  10.1   -99   -99   -99   -99   -99   -99   -99   -99   -99  0.36  0.80
0.35   -99  0.28   -99
    50   3.0   -99   -99   -99   -99   -99   -99   -99   -99   -99  0.33  0.57
0.25   -99  0.14   -99

*UG_RKUG010  LDSF        C        50 LDSF DATABASE, SOIL UG010
@SITE        COUNTRY          LAT     LONG  SCS FAMILY
 Rakai       Uganda         -0.69   31.47  -99
@ SCOM  SALB  SLU1  SLDR  SLRO  SLNF  SLPF  SMHB  SMPX  SMKE
    BN   .13     6   0.6    88     1     1 SA011 SA013 SA013
@  SLB  SLMH  SLLL  SDUL  SSAT  SRGF  SSKS  SBDM  SLOC  SLCL  SLSI  SLCF  SLNI
SLHW  SLHB  SCEC  SADC
    20   -99  .273  .392  .525     1   5.0  1.22  1.37    46    30   -99   .15
6.2   -99  12.6   -99
    50   -99  .293  .404  .516  .497   5.0  1.24  0.96    54    26   -99   .08
5.9   -99  10.0   -99
@  SLB  SLPX  SLPT  SLPO CACO3  SLAL  SLFE  SLMN  SLBS  SLPA  SLPB  SLKE  SLMG
SLNA  SLSU  SLEC  SLCA
    20  14.5   -99   -99   -99   -99   -99   -99   -99   -99   -99  0.28  2.77
0.26   -99  0.48   -99
    50   5.5   -99   -99   -99   -99   -99   -99   -99   -99   -99  0.15  2.19
0.27   -99  0.21   -99

*UG_RKUG011  LDSF        C        50 LDSF DATABASE, SOIL UG011
@SITE        COUNTRY          LAT     LONG  SCS FAMILY
 Rakai       Uganda         -0.68   31.45  -99
@ SCOM  SALB  SLU1  SLDR  SLRO  SLNF  SLPF  SMHB  SMPX  SMKE
    BN   .13     6   0.1    91     1     1 SA011 SA013 SA013
@  SLB  SLMH  SLLL  SDUL  SSAT  SRGF  SSKS  SBDM  SLOC  SLCL  SLSI  SLCF  SLNI
SLHW  SLHB  SCEC  SADC
    20   -99  .344  .463  .572     1   0.7  1.09  2.24    76    19   -99   .22
4.6   -99   6.4   -99
    50   -99  .332  .461  .544  .497   0.7  1.16  1.37    72    23   -99   .14
4.6   -99   4.6   -99
@  SLB  SLPX  SLPT  SLPO CACO3  SLAL  SLFE  SLMN  SLBS  SLPA  SLPB  SLKE  SLMG
SLNA  SLSU  SLEC  SLCA
    20   8.5   -99   -99   -99   -99   -99   -99   -99   -99   -99  0.24  0.49
0.32   -99  0.36   -99
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    50   4.7   -99   -99   -99   -99   -99   -99   -99   -99   -99  0.17  0.37
0.35   -99  0.27   -99

*UG_RKUG012  LDSF        C        50 LDSF DATABASE, SOIL UG012
@SITE        COUNTRY          LAT     LONG  SCS FAMILY
 Rakai       Uganda         -0.66   31.46  -99
@ SCOM  SALB  SLU1  SLDR  SLRO  SLNF  SLPF  SMHB  SMPX  SMKE
    BN   .13     6   0.4    91     1     1 SA011 SA013 SA013
@  SLB  SLMH  SLLL  SDUL  SSAT  SRGF  SSKS  SBDM  SLOC  SLCL  SLSI  SLCF  SLNI
SLHW  SLHB  SCEC  SADC
    20   -99  .284  .402  .524     1   3.4  1.22  1.24    50    29   -99   .12
6.0   -99  10.7   -99
    50   -99  .296  .402  .508  .497   3.4  1.26  0.69    56    23   -99   .06
5.8   -99   8.6   -99
@  SLB  SLPX  SLPT  SLPO CACO3  SLAL  SLFE  SLMN  SLBS  SLPA  SLPB  SLKE  SLMG
SLNA  SLSU  SLEC  SLCA
    20   7.6   -99   -99   -99   -99   -99   -99   -99   -99   -99  0.18  2.08
0.25   -99  0.44   -99
    50   2.0   -99   -99   -99   -99   -99   -99   -99   -99   -99  0.12  1.72
0.27   -99  0.23   -99

*UG_RKUG013  LDSF        C        50 LDSF DATABASE, SOIL UG013
@SITE        COUNTRY          LAT     LONG  SCS FAMILY
 Rakai       Uganda         -0.72   31.49  -99
@ SCOM  SALB  SLU1  SLDR  SLRO  SLNF  SLPF  SMHB  SMPX  SMKE
    BN   .13     6  0.35    91     1     1 SA011 SA013 SA013
@  SLB  SLMH  SLLL  SDUL  SSAT  SRGF  SSKS  SBDM  SLOC  SLCL  SLSI  SLCF  SLNI
SLHW  SLHB  SCEC  SADC
    20   -99  .303  .413  .545     1   1.9  1.16  1.82    55    26   -99   .14
7.1   -99  13.7   -99
    50   -99  .320  .413  .512  .497   1.9  1.25  0.62    68    15   -99   .09
6.6   -99  10.0   -99
@  SLB  SLPX  SLPT  SLPO CACO3  SLAL  SLFE  SLMN  SLBS  SLPA  SLPB  SLKE  SLMG
SLNA  SLSU  SLEC  SLCA
    20   -99   -99   -99   -99   -99   -99   -99   -99   -99   -99  0.59  2.84
0.20   -99  0.54   -99
    50  48.7   -99   -99   -99   -99   -99   -99   -99   -99   -99  0.41  2.00
0.23   -99  0.27   -99

*UG_RKUG014  LDSF        C        50 LDSF DATABASE, SOIL UG014
@SITE        COUNTRY          LAT     LONG  SCS FAMILY
 Rakai       Uganda         -0.70   31.49  -99
@ SCOM  SALB  SLU1  SLDR  SLRO  SLNF  SLPF  SMHB  SMPX  SMKE
    BN   .13     6   0.6    88     1     1 SA011 SA013 SA013
@  SLB  SLMH  SLLL  SDUL  SSAT  SRGF  SSKS  SBDM  SLOC  SLCL  SLSI  SLCF  SLNI
SLHW  SLHB  SCEC  SADC
    20   -99  .296  .410  .510     1   6.4  1.26  0.66    56    25   -99   .10
4.8   -99   9.9   -99
    50   -99  .309  .420  .509  .497   6.4  1.26  0.54    62    23   -99   .06
5.7   -99   4.3   -99
@  SLB  SLPX  SLPT  SLPO CACO3  SLAL  SLFE  SLMN  SLBS  SLPA  SLPB  SLKE  SLMG
SLNA  SLSU  SLEC  SLCA
    20  26.3   -99   -99   -99   -99   -99   -99   -99   -99   -99  0.30  1.26
0.47   -99  1.19   -99
    50   9.0   -99   -99   -99   -99   -99   -99   -99   -99   -99  0.18  0.69
0.52   -99  0.24   -99

*UG_RKUG015  LDSF        CL       50 LDSF DATABASE, SOIL UG015
@SITE        COUNTRY          LAT     LONG  SCS FAMILY
 Rakai       Uganda         -0.68   31.48  -99
@ SCOM  SALB  SLU1  SLDR  SLRO  SLNF  SLPF  SMHB  SMPX  SMKE
    BN   .13     6   0.1    84     1     1 SA011 SA013 SA013
@  SLB  SLMH  SLLL  SDUL  SSAT  SRGF  SSKS  SBDM  SLOC  SLCL  SLSI  SLCF  SLNI
SLHW  SLHB  SCEC  SADC
    20   -99  .231  .375  .491     1   0.5  1.31  0.43    37    36   -99   .04
5.8   -99   5.9   -99
    50   -99  .250  .385  .504  .497   0.5  1.27  0.83    41    34   -99   .08
5.6   -99   4.1   -99
@  SLB  SLPX  SLPT  SLPO CACO3  SLAL  SLFE  SLMN  SLBS  SLPA  SLPB  SLKE  SLMG
SLNA  SLSU  SLEC  SLCA
    20   8.0   -99   -99   -99   -99   -99   -99   -99   -99   -99  0.13  1.03
0.39   -99  0.37   -99
    50   4.7   -99   -99   -99   -99   -99   -99   -99   -99   -99  0.07  0.66
0.32   -99  0.17   -99

*UG_RKUG016  LDSF        CL       50 LDSF DATABASE, SOIL UG016
@SITE        COUNTRY          LAT     LONG  SCS FAMILY
 Rakai       Uganda         -0.65   31.48  -99
@ SCOM  SALB  SLU1  SLDR  SLRO  SLNF  SLPF  SMHB  SMPX  SMKE
    BN   .13     6   0.4    76     1     1 SA011 SA013 SA013
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@  SLB  SLMH  SLLL  SDUL  SSAT  SRGF  SSKS  SBDM  SLOC  SLCL  SLSI  SLCF  SLNI
SLHW  SLHB  SCEC  SADC
    20   -99  .222  .342  .480     1   2.7  1.34  0.38    35    30   -99   .04
5.5   -99   2.8   -99
    50   -99  .219  .335  .492  .497   2.7  1.30  1.00    33    28   -99   .10
5.3   -99   5.7   -99
@  SLB  SLPX  SLPT  SLPO CACO3  SLAL  SLFE  SLMN  SLBS  SLPA  SLPB  SLKE  SLMG
SLNA  SLSU  SLEC  SLCA
    20   3.2   -99   -99   -99   -99   -99   -99   -99   -99   -99  0.06  0.54
0.25   -99  0.16   -99
    50   7.6   -99   -99   -99   -99   -99   -99   -99   -99   -99  0.13  1.17
0.31   -99  0.40   -99
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4. Weather input file for Lushoto (1 year)

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*WEATHER Lushoto-Tanzania Climate 1 (soil 1,2,5,6,9,10,13,14), 1979-2005

@ INSI      LAT     LONG  ELEV   TAV   AMP REFHT WNDHT
  L101    -4.85    38.35   -99  18.8 10.25  0.00  0.00
@DATE  SRAD  TMAX  TMIN  RAIN
79001  22.7  25.8  15.5  72.3
79002  19.9  24.8  14.8   0.0
79003  23.2  25.6  15.2  21.4
79004  22.6  23.3  15.1   0.0
79005  19.2  24.3  14.4   0.1
79006  25.5  28.1  14.6   1.2
79007  22.1  23.8  15.8   6.4
79008  23.3  24.6  15.4   5.2
79009  16.8  19.7  14.4   0.0
79010  19.9  21.8  14.1   7.3
79011  22.7  22.9  13.4   0.0
79012  21.3  23.9  15.4   0.1
79013  20.6  22.6  14.9   0.0
79014  23.5  28.2  12.8   0.3
79015  22.9  24.9  14.5   0.0
79016  17.8  24.7  14.0   1.8
79017  20.4  24.6  15.8   0.0
79018  23.5  26.5  15.6   0.9
79019  23.0  25.4  14.4   0.0
79020  24.9  27.1  13.1   0.2
79021  21.7  25.9  15.7   0.6
79022  21.4  25.2  15.0   9.6
79023  22.5  25.9  14.9   0.0
79024  21.3  27.2  14.4   0.5
79025  23.4  27.0  13.9   0.2
79026  20.9  26.6  15.0   0.0
79027  18.5  24.0  15.3   0.7
79028  24.2  26.2  15.2   0.0
79029  22.1  24.5  15.7   8.1
79030  23.0  24.9  16.1   1.7
79031  20.1  23.8  15.6  76.6
79032  17.1  22.5  15.9  27.7
79033  16.4  21.2  16.3   7.9
79034  21.1  22.3  16.4   0.0
79035  21.2  25.1  15.6   0.0
79036  23.2  26.1  14.9   4.6
79037  20.8  24.4  16.4   0.0
79038  23.7  27.5  15.2   7.9
79039  20.8  22.7  15.5   0.0
79040  25.4  26.0  14.4   1.2
79041  25.0  26.1  15.6   3.0
79042  21.9  25.4  15.4  30.4
79043  23.5  25.4  15.4   0.0
79044  21.4  25.3  15.3   6.2
79045  23.5  24.7  15.5   0.2
79046  25.5  25.6  14.7   0.8
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79052  23.0  26.9  14.8   6.4
79053  23.9  26.9  14.3   0.0
79054  20.8  26.8  15.1   3.3
79055  15.8  22.7  15.3   0.0
79056  23.1  23.8  15.0   0.8
79057  23.7  24.8  15.1   1.4
79058  19.7  24.1  15.7   7.9
79059  23.0  25.5  15.0   0.0
79060  21.4  25.0  14.9   0.0
79061  23.3  26.7  14.0   0.0
```

79062	22.0	29.3	13.8	0.0
79063	23.3	27.4	13.9	0.0
79064	25.0	29.4	13.5	0.0
79065	24.1	28.9	14.3	0.0
79066	21.8	28.5	14.6	0.0
79067	23.4	28.5	14.6	0.0
79068	22.9	27.7	14.7	0.0
79069	20.4	26.0	15.1	2.5
79070	19.4	22.7	15.7	16.8
79071	20.9	23.1	15.5	15.6
79072	19.5	23.0	15.5	0.7
79073	22.8	25.7	14.3	19.0
79074	17.4	22.5	15.0	0.9
79075	17.8	22.7	15.7	16.9
79076	16.1	22.2	15.6	0.2
79077	18.9	24.4	15.7	0.0
79078	21.9	24.8	14.3	0.6
79079	21.5	23.1	14.6	7.8
79080	19.7	23.6	15.8	0.3
79081	22.2	24.4	15.3	6.0
79082	22.2	22.9	15.8	0.0
79083	19.8	23.4	15.6	0.2
79084	19.2	23.1	15.4	0.0
79085	19.0	23.7	15.2	0.8
79086	23.9	26.1	14.6	0.9
79087	20.1	23.8	14.1	19.2
79088	20.3	24.2	13.7	0.1
79089	19.7	23.4	13.4	0.0
79090	20.5	24.0	13.4	12.9
79091	22.5	23.3	14.2	0.0
79092	18.1	25.7	13.1	0.0
79093	24.0	28.0	11.2	0.2
79094	21.0	24.8	14.9	9.8
79095	18.4	22.8	15.6	7.6
79096	19.6	26.3	13.7	4.3
79097	16.0	25.9	13.8	6.9
79098	14.6	22.3	15.5	0.0
79099	16.3	23.4	14.6	13.8
79100	19.6	24.8	14.1	17.5
79101	20.7	26.6	13.4	13.0
79102	20.0	25.8	14.2	6.3
79103	16.9	23.1	15.0	3.2
79104	18.1	22.3	14.7	22.9
79105	13.8	21.6	14.6	0.0
79106	16.3	21.8	14.9	22.6
79107	14.6	22.1	14.6	0.0
79108	18.9	24.4	15.1	8.0
79109	16.4	22.7	15.4	18.1
79110	17.0	22.7	14.9	2.1
79111	16.0	21.4	15.4	15.3
79112	16.6	21.7	15.3	2.5
79113	18.5	24.2	13.9	3.6
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79115	17.0	21.8	15.7	0.0
79116	16.2	23.4	14.3	6.1
79117	15.8	22.3	15.0	4.0
79118	18.0	23.1	14.6	0.0
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79120	18.1	22.7	14.8	0.0
79121	18.4	24.3	13.9	8.4
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79123	14.2	21.2	14.8	0.0
79124	13.7	21.7	14.4	0.0
79125	16.5	21.8	14.1	32.6
79126	13.2	20.9	14.6	0.0
79127	13.1	20.4	14.6	19.9
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79131	13.8	21.5	14.2	0.0
79132	12.3	20.2	14.9	82.6
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79134	16.0	23.7	13.3	0.0
79135	16.0	22.5	14.1	0.0
79136	15.2	22.1	13.7	0.0
79137	14.0	22.7	13.5	10.1
79138	16.0	22.5	13.5	2.4
79139	15.7	22.6	13.5	0.0
79140	15.2	22.3	14.3	0.0
79141	15.7	22.0	12.5	12.0

79142	13.3	21.7	12.2	0.0
79143	14.9	21.7	13.9	23.9
79144	14.0	21.1	13.6	0.0
79145	14.2	21.6	13.7	0.0
79146	15.7	23.0	13.1	0.0
79147	16.9	22.2	13.2	0.0
79148	16.9	22.4	13.6	0.0
79149	13.6	21.0	13.8	10.9
79150	16.5	22.1	13.9	47.6
79151	16.2	22.4	13.4	0.0
79152	14.2	22.1	13.2	18.1
79153	13.0	20.2	12.9	0.0
79154	15.1	21.1	12.9	27.9
79155	13.4	20.8	12.5	0.9
79156	15.8	20.7	12.3	0.0
79157	18.1	22.6	11.9	0.0
79158	13.6	21.4	13.1	0.0
79159	15.7	21.8	12.6	17.7
79160	12.5	19.9	12.9	0.0
79161	16.9	21.6	12.1	0.0
79162	17.6	21.3	11.7	0.0
79163	14.0	21.5	11.3	0.0
79164	16.6	21.8	11.7	0.0
79165	16.0	21.5	11.3	0.0
79166	15.9	22.0	12.3	0.0
79167	13.9	21.5	11.7	0.0
79168	15.8	22.0	11.3	0.0
79169	14.9	21.6	12.2	0.0
79170	13.2	20.6	11.3	8.5
79171	14.0	20.2	11.2	8.2
79172	15.5	20.8	11.4	0.0
79173	13.5	21.4	10.8	0.0
79174	12.8	21.0	10.7	1.4
79175	13.4	20.8	11.3	0.0
79176	13.8	21.2	11.7	0.0
79177	16.8	22.3	11.1	0.0
79178	13.8	21.3	11.7	0.0
79179	14.8	20.7	11.9	0.0
79180	17.1	22.0	12.4	0.0
79181	13.6	20.3	11.7	17.8
79182	14.9	19.6	11.6	4.0
79183	16.0	19.9	10.9	2.2
79184	16.1	20.8	11.6	0.0
79185	13.9	20.9	12.3	0.0
79186	14.4	20.2	11.5	0.0
79187	17.2	21.8	10.7	8.7
79188	13.3	19.1	11.0	0.0
79189	15.3	21.3	11.3	0.6
79190	16.1	20.4	11.6	0.0
79191	13.7	21.0	10.8	0.2
79192	15.3	20.5	12.6	1.4
79193	16.0	20.9	11.8	0.0
79194	15.5	20.3	11.6	0.0
79195	15.5	20.9	11.4	0.0
79196	14.9	20.6	10.8	0.0
79197	14.1	19.6	11.4	0.0
79198	14.1	21.6	11.4	0.0
79199	14.8	20.4	11.0	0.0
79200	17.9	20.3	11.4	0.0
79201	14.7	20.2	11.1	0.0
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79203	16.0	21.0	10.9	0.0
79204	14.3	21.5	10.5	0.1
79205	16.7	20.8	10.3	0.0
79206	16.0	21.2	11.0	1.8
79207	15.4	20.6	10.4	4.9
79208	16.7	20.7	10.9	0.0
79209	16.0	21.4	10.4	0.0
79210	15.6	20.9	11.2	0.0
79211	13.5	20.4	11.3	0.0
79212	16.1	20.9	10.5	1.3
79213	15.7	20.8	10.9	0.1
79214	16.1	21.6	12.5	0.4
79215	18.1	20.7	11.0	0.0
79216	17.0	21.3	10.2	0.0
79217	17.3	23.0	11.4	0.6
79218	17.0	22.2	11.9	0.0
79219	15.7	22.2	11.1	12.0
79220	18.1	21.7	12.4	2.8
79221	14.3	21.5	11.9	1.6

79222	15.6	22.2	11.9	0.0
79223	16.6	21.8	11.9	0.0
79224	17.8	21.6	11.6	2.2
79225	16.1	21.0	11.6	1.7
79226	14.6	21.2	11.3	0.4
79227	14.7	21.2	11.1	10.8
79228	13.3	21.3	12.2	0.4
79229	15.5	22.2	12.4	5.8
79230	17.9	22.8	12.1	0.0
79231	14.0	20.7	12.6	0.0
79232	17.2	22.1	11.9	0.6
79233	19.1	22.4	11.7	0.0
79234	17.7	22.0	12.1	0.0
79235	15.2	21.9	11.6	0.0
79236	18.2	22.9	11.5	0.0
79237	16.1	20.6	11.9	0.0
79238	17.7	22.9	11.7	0.0
79239	13.5	21.3	12.2	0.0
79240	16.2	21.6	11.7	0.0
79241	18.4	22.8	10.1	1.0
79242	17.2	21.9	10.3	0.0
79243	16.0	22.6	11.5	5.8
79244	16.1	22.7	11.3	0.0
79245	19.2	22.7	12.4	0.0
79246	21.6	23.6	12.2	0.0
79247	18.2	22.1	12.0	1.6
79248	18.7	22.9	11.3	0.0
79249	18.2	21.6	12.6	0.6
79250	18.2	21.5	10.5	10.7
79251	21.0	23.4	10.0	0.0
79252	23.4	23.5	11.4	0.0
79253	20.9	22.3	10.9	22.1
79254	19.0	22.3	10.5	0.0
79255	18.5	22.2	11.8	0.0
79256	20.4	21.9	11.7	0.0
79257	18.4	22.3	11.5	0.0
79258	16.6	23.1	11.2	2.7
79259	20.3	22.9	10.2	0.0
79260	21.6	22.4	10.1	0.0
79261	19.9	22.9	12.0	4.5
79262	16.1	21.7	13.3	0.0
79263	19.1	22.5	11.5	0.0
79264	16.6	22.5	11.5	0.7
79265	21.2	22.9	12.0	0.0
79266	20.5	23.3	11.6	0.0
79267	22.1	24.4	11.1	0.0
79268	17.5	23.2	12.2	0.0
79269	20.2	22.4	11.7	0.0
79270	20.2	21.9	11.4	0.0
79271	21.4	23.3	11.0	0.0
79272	19.3	22.3	12.3	2.5
79273	17.3	19.6	12.8	0.0
79274	21.3	22.2	11.6	0.0
79275	24.5	22.9	11.0	0.0
79276	20.2	23.7	11.7	0.0
79277	19.7	24.3	11.5	3.0
79278	21.0	22.8	11.7	0.0
79279	18.6	22.9	11.6	0.3
79280	19.7	23.5	11.2	2.4
79281	20.3	24.7	13.0	8.7
79282	23.0	24.4	12.7	0.0
79283	21.3	23.1	12.4	1.7
79284	19.5	23.9	12.3	0.2
79285	20.2	24.4	11.9	0.0
79286	19.4	23.7	12.0	20.3
79287	19.4	21.4	13.6	5.1
79288	21.0	22.7	13.1	0.0
79289	20.0	23.0	12.6	0.0
79290	19.6	23.0	11.8	0.0
79291	23.1	23.9	11.3	8.2
79292	19.7	22.1	12.3	0.0
79293	20.7	23.2	12.1	0.0
79294	20.2	24.7	11.9	0.0
79295	23.7	25.3	12.4	0.0
79296	18.8	22.7	12.5	0.0
79297	20.6	23.7	11.8	0.0
79298	21.5	24.2	12.4	0.0
79299	23.8	24.8	11.5	0.1
79300	18.9	24.2	11.8	1.7
79301	18.9	23.0	12.0	0.0

79302	20.3	23.7	12.8	0.3
79303	19.6	23.5	13.4	2.1
79304	20.4	24.3	13.2	0.0
79305	24.0	25.1	13.0	0.0
79306	21.6	25.0	14.0	0.0
79307	19.2	25.4	13.8	0.0
79308	22.9	26.7	14.2	11.2
79309	20.2	26.5	14.3	8.5
79310	20.3	24.4	14.7	0.0
79311	18.4	23.9	15.1	23.6
79312	18.0	22.6	13.7	0.0
79313	21.3	25.0	13.2	20.0
79314	18.3	23.8	14.7	0.0
79315	21.5	23.9	14.7	1.4
79316	22.1	24.7	14.4	0.0
79317	18.8	23.8	14.4	0.0
79318	19.5	24.3	14.2	0.0
79319	21.5	24.1	13.6	0.0
79320	22.1	26.5	13.4	0.0
79321	20.0	24.9	13.9	0.0
79322	22.2	25.2	13.8	0.0
79323	21.9	26.2	14.1	2.1
79324	18.9	23.8	14.6	1.6
79325	21.3	25.5	14.2	0.0
79326	21.3	26.9	13.8	1.2
79327	20.5	26.1	14.8	9.2
79328	22.2	26.5	15.5	0.0
79329	21.2	25.5	14.6	0.0
79330	21.3	23.0	14.2	0.0
79331	22.1	25.6	13.7	0.0
79332	20.0	25.5	15.6	0.0
79333	21.7	26.2	15.3	0.0
79334	18.3	23.8	15.5	0.0
79335	19.5	24.5	15.6	15.5
79336	19.8	26.7	16.0	0.0
79337	23.1	25.8	14.6	0.0
79338	23.7	26.1	14.8	0.0
79339	19.5	23.3	16.3	2.0
79340	20.6	27.8	15.1	0.0
79341	21.7	25.4	16.5	4.5
79342	18.9	23.3	15.6	0.5
79343	21.6	25.2	14.8	29.1
79344	24.4	25.9	14.7	0.0
79345	21.7	26.8	15.0	0.0
79346	20.8	26.6	16.0	0.0
79347	19.8	25.6	15.7	0.2
79348	21.2	26.1	15.2	4.7
79349	21.9	28.5	15.3	0.1
79350	18.5	23.7	16.3	0.0
79351	20.3	25.2	15.5	0.0
79352	23.6	26.1	15.2	0.0
79353	23.6	25.1	15.6	5.2
79354	22.0	25.5	15.1	0.0
79355	18.5	27.3	15.0	0.2
79356	21.5	25.8	16.2	0.2
79357	20.9	25.7	16.5	0.0
79358	21.1	25.9	16.2	0.0
79359	23.6	27.3	15.5	0.0
79360	21.7	25.7	15.9	0.0
79361	20.2	26.3	15.0	0.0
79362	21.3	25.9	16.3	12.0
79363	19.4	23.8	16.4	1.1
79364	18.8	23.2	16.5	37.6
79365	20.4	22.8	16.5	0.0

Appendix B

Materials for Fieldwork in Cauca

Directrices para las entrevistas de expertos

Introducción

Soy estudiante de una Universidad en Alemania y juntos con instituciones colombianos estamos estudiando el desarrollo rural en el departamento de Cauca. Seleccionamos a usted como experto sabiendo que usted sabe que impulsa y qué dificulta el desarrollo rural en esta parte del país (de su punto de vista como experto).

Le puedo primero hacer unos preguntas personales y su rol que tenga en la región?

Fecha de la entrevista ______________________________

Duración de la entrevista ______________________________

Lugar de la entrevista ______________________________

Información socio-demográfica

Nombre completo ______________________________

Edad (año de nacimiento) ______________________________

Genero ______________________________

Educación ______________________________

Profesión ______________________________

Vinculo en la región (Institución) ______________________________

Frecuencia de contacto con productores en la región ______________________________

Definir los riesgos para los medios de vida

Que son los preocupaciones principales en Cauca?

A que riesgos principales en la vida rural están expuestos los agricultores en Cauca?

Que son facilitadores y barreras para agricultores para responder con acción?

1. Que impide que las personas toman medidas (creencias de adaptación)?

2. Que motiva que las personas toman medidas (motivación de adaptación)?

Ordenar los (a) preocupaciones, (b) riesgos, (c) barreras para adaptación y (d) motivaciones para adaptación según su importancia

1. Lo más importante
2. …
3. De menor importancia

Utilice 1 tarjeta para cada respuesta!

Ejemplos para preocupaciones:

- *No estar sano*
- *No puedo enviar a los niños a la escuela*

Ejemplos para riesgos

- *Degradación del suelo*
- *seguridad*

Ejemplos para barreras

- *Falta de recursos económicos*
- *Espere a ayuda del gobierno*

Ejemplos para motivación

- *Quieren mejor futuro para los niños*
- *Hacer lo mismo que los demás*

Ordenar las tarjetas sobre la mesa y toma una foto!

Que es importante para la vida rural?

Ahora, quiero que me ayudes en definir que es importante para la vida rural en el departamento de Cauca, por ejemplo que es importante para generar ingresos a través de actividades agropecuarias. Le voy a dar unos ejemplos de elementos y usted luego me nombra elementos que son importantes para agricultores.

____

____

____

____

____

____

____

____

____

____

Ordenar elementos según su importancia

1. Lo más importante
2. Segundo más importante
3. …
4. De menor importancia

Asignar los elementos a los medio de vida

Capital humano	**Capital natural**
Capital físico	**Capital financiero**

Utilice 1 tarjeta para cada respuesta!

2 ejemplos para cada capital:

Maquinas

Herramientas agrícolas

Formación / capacitación

Educación

Suelo

Bosque

Subsidios

Créditos

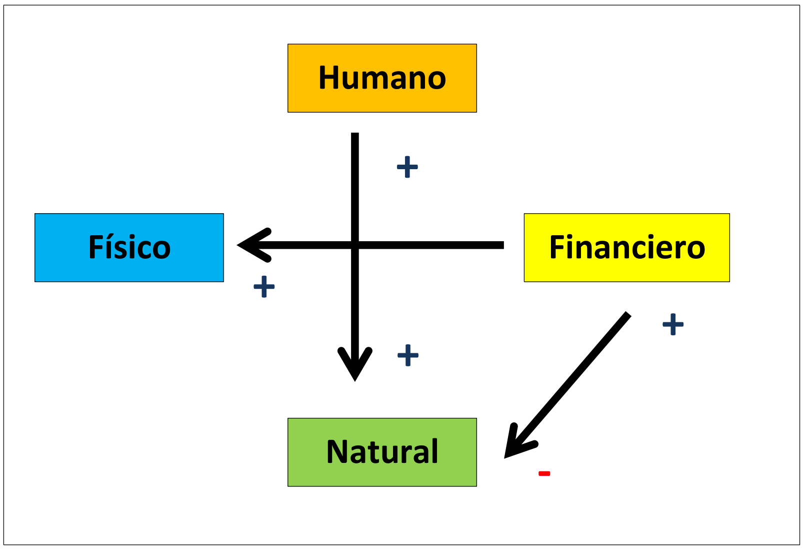
Ordenar tarjetas sobre la mesa (toma foto)

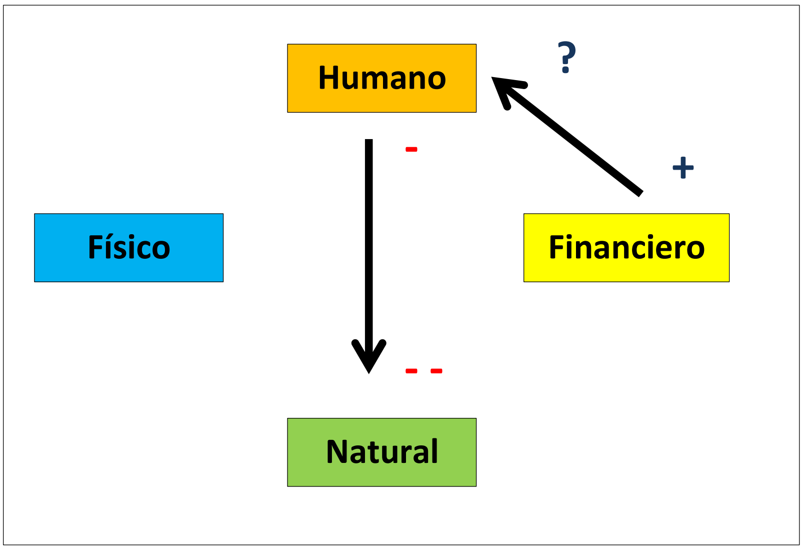
Ordenar por importancia para los agricultores

Agrupar tarjetas alrededor capitales (toma foto)

- C.Humano – capacidad de ser económicamente productivo
- C.Natural – son recursos naturales disponibles
- C.Físico - activos realizados por los procesos de producción
- C.Financiero – reservas accesibles para consumir o producir

Explica cómo los capitales dependen el uno del otro



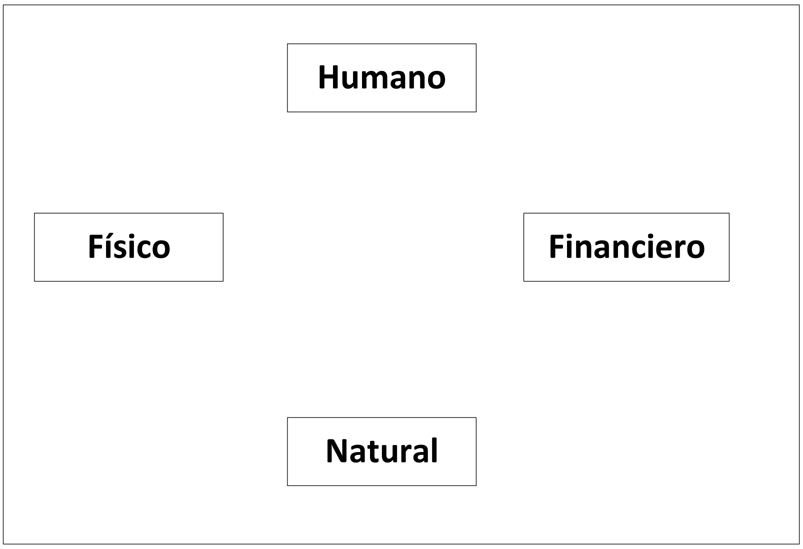


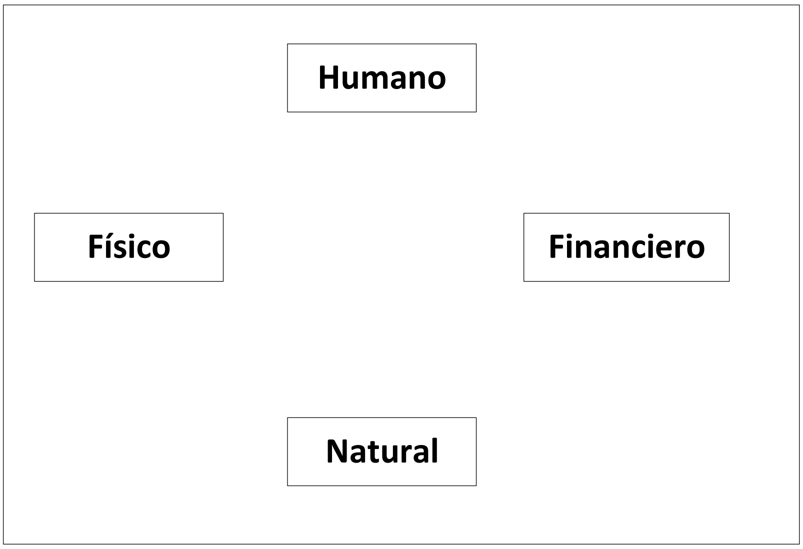
Señala en los gráficos la dependencia!

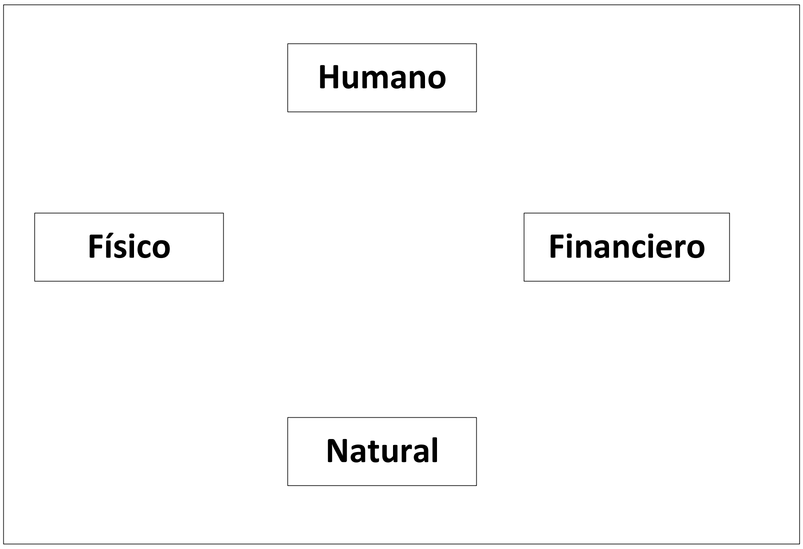
Usa todas las combinaciones posibles

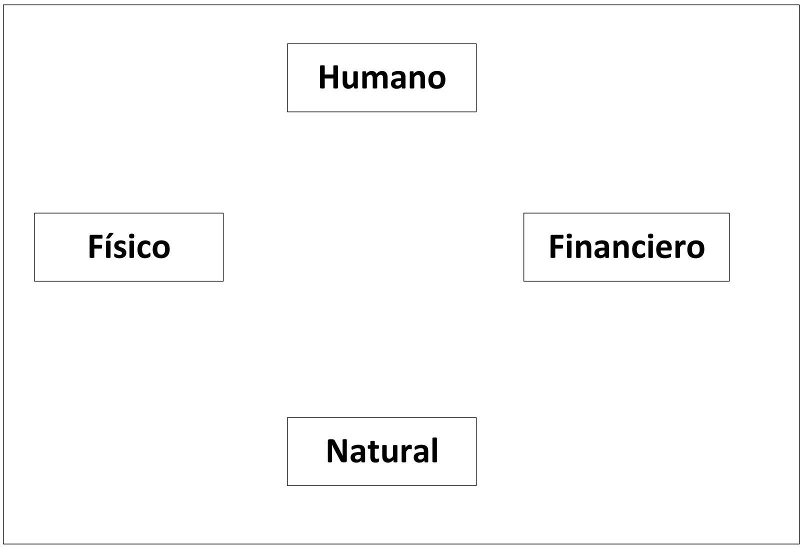
Ejemplo 1: Si aumenta el capital humano, también aumenta el capital físico.

Ejemplo 2: Si baja el capital natural, bajo el capital financiero mucho!


Humano
Físico
Financiero
Natural


Humano
Físico
Financiero
Natural


Humano
Físico
Financiero
Natural


Humano
Físico
Financiero
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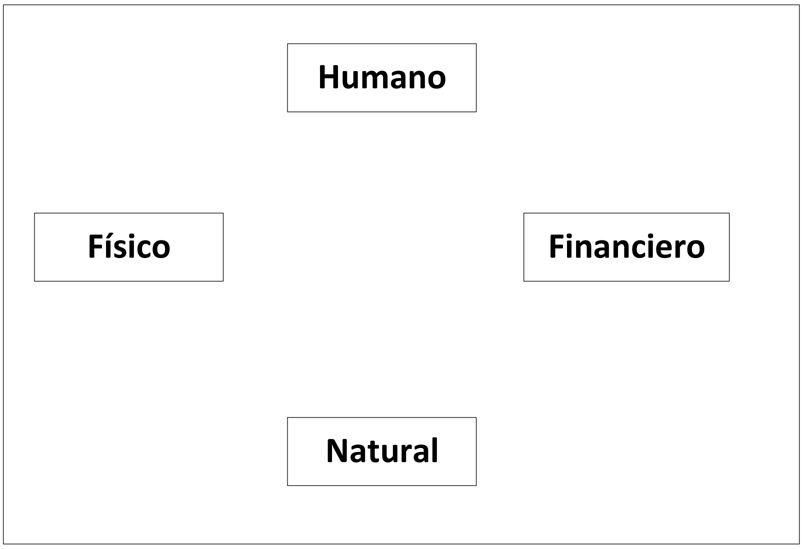
Humano
Físico
Financiero
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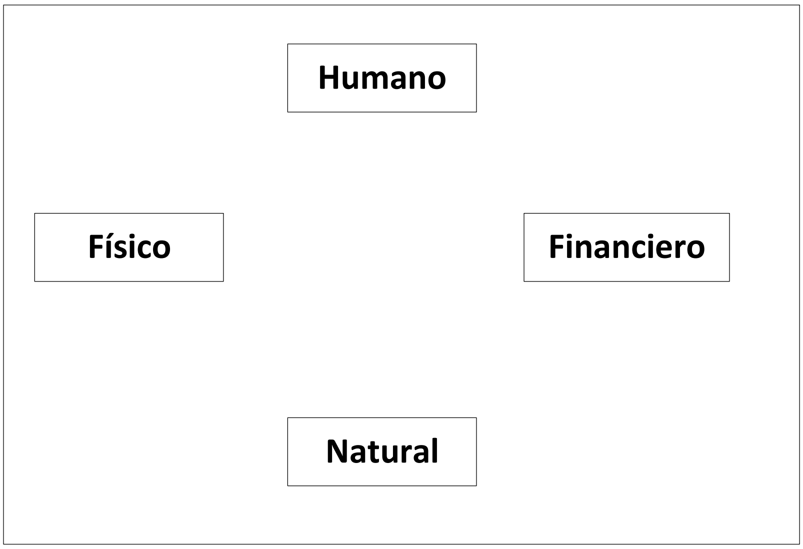
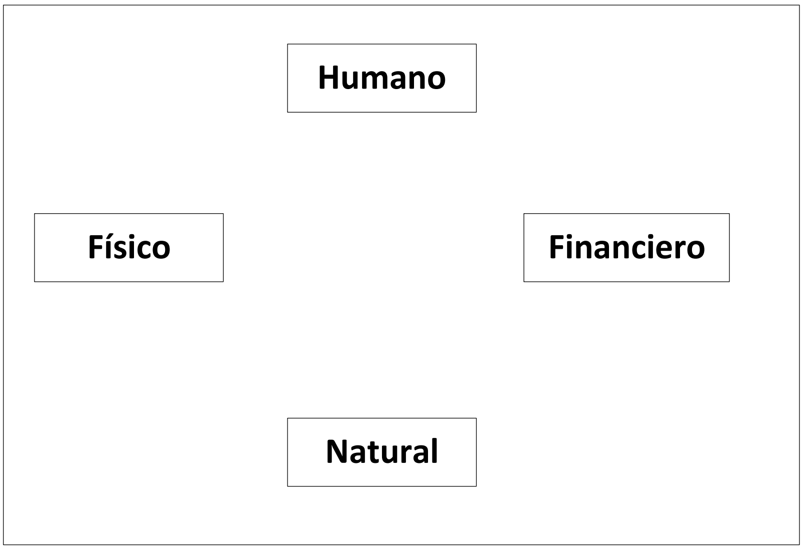
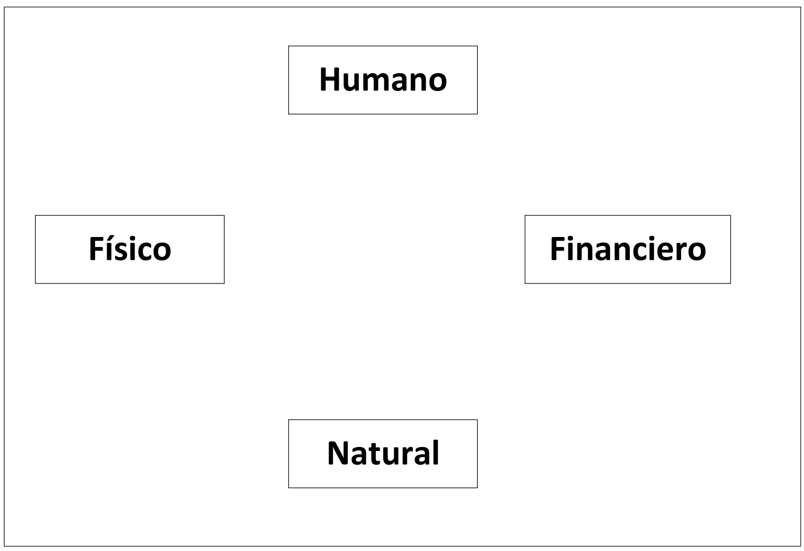

Humano
Físico
Financiero
Natural

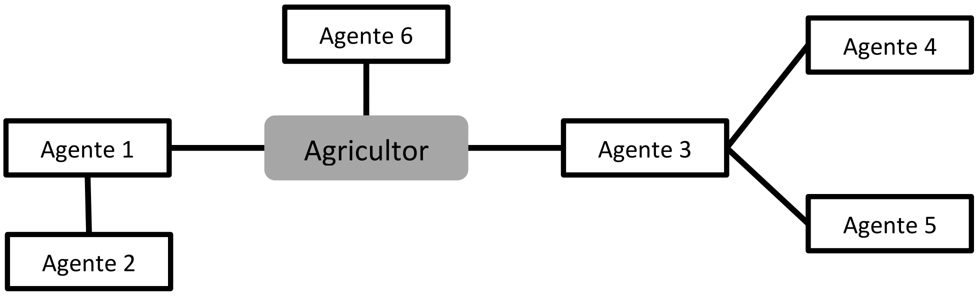

Humano
Físico
Financiero
Natural


Humano
Físico
Financiero
Natural

Definición del capital social

Ahora queremos identificar el rol específico de las redes sociales de los agricultores y el acceso a recursos. Por favor, haga una lista de instituciones con cuales los agricultores están conectados.

Ejemplo:



Su institución ____

Agente 1 ____

Agente 2 ____

Agente 3 ____

Agente 4 ____

Agente 5 ____

Agente 6 ____

Agente 7 ____

Agente 8 ____

Agente 9 ____

Agente 10 ____

Agente 11 ____

Agente 12 ____

Agente 13 ____

Por favor dibuja en un papel una red (como el ejemplo) de los agentes que menciono ahora:

Agricultor

Riesgos para los medios de vida de los campesinos en el Cauca

Les agradezco a todos que me ayudaron con la entrevista durante las últimas semanas en Popayan y Cali! Después de haber analizado sus respuestas he agrupado las respuestas en categorías. Como próximo paso les pido que me ayuden nuevamente en ordenar las categorías de respuestas (de todos) según su criterio individual.

Que son los preocupaciones principales en el Cauca?

Por favor ordenar las categorías de "Preocupaciones de los campesinos en el Cauca" según su criterio individual. Selecciona la preocupación más grande con rango 1, sigue con el segundo más grande con 2, después 3,…, hasta el último (16).

	Seguridad y orden publico (Conflicto armado, Cultivos ilegales, Inseguridad)
	Riesgos climáticos (Cambios del tiempo, sequía, falta de lluvia)
	Gobernabilidad (apoyo institucional, políticas adecuadas, T.L.C., inversión del estado)
	Comercialización (Fluctuación de precios, Intermediarios, costos altos)
	Infraestructura productiva (incentivos para pequeños productores, infraestructura productiva)
	Acceso a dinero (faltan recursos económicos, trabas para créditos, faltan ingresos)
	Pobreza (alta pobreza)
	Acceso a la tierra (falta formalización, falta acceso)
	Acceso recursos naturales (falta agua)
	Degradación del ambiente (suelos degradados, perdida de biodiversidad)
	Seguridad alimentaria (Calidad de alimentos, sobreania alimentaria)
	Explotación recursos naturales (proyectos minero-energéticos)
	Brecha generacional (falta de relevo)
	Oportunidades laborales
	Servicios públicos (servicios de estado para salud, técnicos y sociales)
	Grupos étnicos (Interacción entre grupos étnicos)

A que riesgos están expuestos los agricultores en el Cauca?

Por favor ordenar las categorías de "Riesgos de los campesinos en el Cauca" según su criterio individual. Selecciona el riesgo más grande con rango 1, sigue con el segundo más grande con 2, después 3,..., hasta el último (10).

	Inseguridad y Violencia (actores armados, desplazamiento, bloqueos viales)
	Clima y tiempo (Cambio climático y riesgos climáticos)
	Producción (riesgos económicos, perdida de tierra, perdida de producción, costos)
	Comercialización (Fluctuación precios/demanda, sostenibilidad de ingresos)
	Degradación recursos naturales (suelos, erosión, caudales, fumigacion, contaminación)
	Gobernabilidad y políticas (T.L.C., poder confiar en instituciones)
	Vulnerabilidad social (salud, bienestar, pobreza, desnutrición, inseguridad alimentaria)
	Sociedad y tradicional (Perdida de tradición, saberes ancestrales, competencia desleal)
	Mala planeacion (Uso del suelo inadecuado, no sostenible, paquetes tecnológicos sin capacitación)
	Explotación recursos naturales (explotación agua, minería, cultivos ilícitos)

Que barreras para tomar medidas frente estos riesgos?

Por favor ordenar las categorías de "Barreras para tomar medidas frente los riesgos" según su criterio individual. Selecciona la barrera más grande con rango 1, sigue con el segundo más grande con 2, después 3,..., hasta el último (13).

	Capacitad adaptiva (Falta relevo generacional, formación, nivel educación, conocimiento)
	Institucionalitad (Centralismo del estado, Falta apoyo del estado, falta asistencia técnica, innovación)
	Políticas nacional (Políticas del sector agro-pecuario, modelo de desarrollo económico)
	Recursos económicos (Recursos económicos, acceso a créditos, faltan recursos para adaptación)
	Organización comunal (Falta organización, comercialización en mano intermediarios, liderazgo, espacios actuación)
	Tradición (Falta de conciencias (valores), cultura paternalista, costumbres históricos)
	Diversidad natural (Diversidad natural, recursos hídricos, condiciones topográficos)
	Seguridad (Delincuencia común, Persecución de los lideres, Impotencia frente tema seguridad)
	Infraestructura (vial y vivienda deficiente)
	Propiedad legal (Falta propiedad legal)
	Productividad (Falta mano de obra, Falta tecnología)
	Conocimiento riesgos climáticos (no hay conocimiento del comportamiento del clima)
	Comercialización (coordinación en volumen y tiempo)

Que motivación para tomar medidas?

Por favor ordenar las categorías de "Motivaciones para tomar medidas frente los riesgos" según su criterio individual. Selecciona la motivación más grande con rango 1, sigue con el segundo más grande con 2, después 3,..., hasta el último (8).

	Arraigo por la tierra (Ancestro ser campesino, defender intereses y territorio, ser propietario)
	Calidad de vida (Mejorada, una vida integral, esperanza, subsistencia, autonomía)
	Interés económico (aumentar ingreso, comodidad, rentabilidad, mejorar precios)
	Interés familiar (bien de la familia, autogestion, los hijos son un motor)
	Evidencia (Ver la evidencia, copiar el otro, políticas con cara al campo)
	Colectividad (organizarse colectivamente, asciociativitad)
	Aptitud para cultivar (la zona es apto para cultivar sostenible y sustentable, bajar la vulnerabilidad cambio climático)
	Seguridad alimentaria (sobreviviencia)

En la última pregunta les pido ordenar también los 4 capitales de los medios de vida según su importancia para los campesinos en el Cauca.

Por favor ordenar los capitales de medios de vida según su criterio individual. Selecciona el capital más grande con rango 1, sigue con el segundo más grande con 2, después 3,..., hasta el último (4).

	Capital Natural
	Capital Humano
	Capital Financiero
	Capital Físico

Si tienen más preguntas sobre la investigación, no duda en contactarme:

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Universidad Ludwig Maximilian en Munich, Alemania

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Muchas Gracias!

Formulario para las entrevistas de productores

Introducción de la actividad

Somos del Centro Internacional de Agricultura Tropical en Palmira. Trabajamos en un proyecto con Ecohabitats, una Fundación aquí en Popayan, estamos estudiando el desarrollo rural en el departamento de Cauca. Seleccionamos a usted como un productor de la zona sabiendo que usted sabe mucho sobre la vida en la zona rural de Popayán.

(Sin mencionar temas específicos como cambio climático)

Introducción del entrevistador

Mi nombre es ……, soy ….

Fecha de la entrevista	______________________
Duración de la entrevista	______________________
Lugar de la entrevista	______________ [nombre común del sitio]
	COORDENADAS GPS
latitud	______________ [decimal degree]
longitud	______________ [decimal degree]
altitud	______________ [m.s.n.m]

Introducción del entrevistado

Primero le pido que se presente con nombre, edad y su actividad principal.

Información socio-demográfica (llena encuesta)

Nombre completo ______________________________

Edad ______________________________ año de nacimiento

Genero ☐ Masculino ☐ Femenino

Estado civil ☐ Casado(o convivencia) ☐ Soltero ☐ Viudo

Cuantas **personas** en el hogar ______________________________

Su **posición** en el hogar ☐ Jefe ☐ Esposo/Esposa ☐ hijo/hija ☐ otro

Nivel de **educación** ☐ Primaria ☐ Secundaria ☐ Pregrado ☐ Universitario

Profesión o actividades laborales ______________________________

Tamaño de la finca ______________________________ hectáreas

Propiedad **formalizado** (formalizado/en proceso/no) ☐ Formalizado ☐ en proceso ☐ no formalizado

Cuanto **tiempo** trabaja la finca ______________________________ años

Fuente de ingreso principal ______________________________

Ha vivido en **otro lugar** ☐ NO ☐ SI, Donde: ______________________________

Tiene un teléfono móvil ☐ NO ☐ SI, Numero: ______________________________

Es suyo ☐ NO ☐ SI

Cuando **NO** es suyo, de quien es ☐ Pareja ☐ Hijo ☐ Amigo/Vecino ______________________________

Ingreso anual (*no obligatorio) * Actividades agrícolas: ______________________________

* Otros: ______________ cual son: ______________

* Remesas: ______________________________

Parte I: Definir los riesgos para los medios de vida

Que son los preocupaciones principales en Cauca?

Foto del resultado (u orden de números de las tarjetas)

Otros que nombra el productor:

A que riesgos principales en la vida rural están expuestos los agricultores en Cauca?

Foto del resultado (u orden de números de las tarjetas)

Otros que nombra el productor:

Que barreras hay para tomar medidas y responder con acción a estos preocupaciones y riesgos?

Foto del resultado (u orden de números de las tarjetas)

Otros que nombra el productor:

Que son las motivaciones para responder con acción a estos preocupaciones y riesgos?

Foto del resultado (u orden de números de las tarjetas)

Otros que nombra el productor:

Parte II: Definición de capitales individuales

Explicación de los 4 capitales de los medios de vida con ejemplos

Humano

La capacidad de él y su familia para ser económicamente productivo,….

Financiero

Reservas de recursos económicos accesibles para producir, vivir y consumir,…

Físico

Son los elementos que necesita para sus actividades y procesos de producción,…

Natural

Son los recursos naturales disponibles para su vida y actividades en el campo,…

Muestra al productor todas las imágenes y le pregunta las 3 preguntas

1. **Que puedes ver en este imagen?**
2. **Que representa eso para ti (y tu vida)**
3. **A cuales de estos capitales piensas se encaja mejor: capital humano, físico, natural o financiero**

Llena la tabla

# del imagen	Nombre que asigna el productor	Grupo de Capital	Explicación del productor por qué?

Ordenar los capitales individuales **Escribe Capitales en orden**

Por favor ordenar los 4 montones de imágenes de capitales individuales según su importancia

1. ______________________________

2. ______________________________

3. ______________________________

4. ______________________________

Explicación de efectos entre los capitales	
De quien aprendió como trabajar la tierra?	1
Quien le ayuda en la finca?	1
Hay jóvenes que trabajan en la finca y que van a seguir un día?	1.2
Esta recibiendo capacitación de afuera sobre prácticas y paquetes tecnológicos?	1
De donde recibe las semillas?	2.1
Tiene dentro de su finca zonas árbolizados o bosques?	3
Hay bosques al lado de su finca?	3
De donde recibe su agua?	2.3
La tierra de sus cultivos ha cambiado durante el tiempo?	3
Era más fácil antes trabajar la tierra?	3.1
Que ha cambiado?	3
Los recursos como agua o suelos han cambiado?	3
Esta observando el clima antes y durante la siembra?	1.3
Esta recibiendo información de afuera sobre el clima, como pronósticos?	1
como maneja usted las variaciones del clima y tiempo (sequia, ...)	1.2
Usted se siente preparado para los variaciones del clima?	1.2

	
Cuantos lotes tienes en su finca?	2
Ha cambiado el uso de los lotes?	2.3
Que ha cambiado?	2.3
Ha cambiado las practicas como trabajar la tierra?	1.2
Quisieras tener mas lotes para la siembra?	2.3
Usted ve el orden público como un riesgo para la producción en su finca?	1.2
Como le afectan los proyectos de minería en la zona?	2.3
Como podría aumentar la cosecha sin aumentar la tierra?	2
Como podría aumentar sus ingresos?	2.4
Hay oportunidades laborales en la zona?	4.1
A quien vende sus productos?	2.4
Quisiera vender a mercados más lejos?	4
Como estable son los precios?	4
Usted piensa que las instituciones del estado le están ayudando?	4.2
Que haría cuando tendría más recursos económicos disponible?	4
Usted hizo ya un crédito?	4

Parte II: Definición del capital social **Toma Foto del resultado (red social del productor)**

Si usted está aquí en el centro *(tarjeta con nombre del productor)*, arregla los demás representantes al redor suyo considerando como cerca se siente a cada uno de ellos?

1. **Si siente que el Representante 1 y el 2 son igual cerca, se pone igual cerca**
2. **Si siente mas cerca al 1 que al 2, ponga la tarjeta del 1 mas cerca que el 2**
3. **Si siente que el 2 le conecta al 1, ponga la tarjeta del 2 entre el 1 y suyo.**
4. **Después de terminar piensa que falta un representante**

Otros representantes que nombra el productor:

Muchas Gracias por su tiempo!

Familiares	**Vecinos**
Jornaleros	**Líderes Junta acción comunal** 
Transportadores 	 **Tiendas**
Grupos de seguridad **Policía/Ejercito**	**Intermediarios**
Alcaldía Municipal ¡Progreso para Popayán! UMATA Unidad Municipal de Asistencia Técnica Agropecuaria - UMATA	Representantes de **Empresas Agroquímicas**
Representantes de **Procesadores Comercializadoras**	Asociaciones **Mujeres cabeza de familia**
Asociaciones **Padres de familia**	Asociación **Productores de café**

Asociación **Productores de panela**	Comité **Acueducto**
Grupos **Culturales, Deporte**	Grupos **Religiosos**
Grupos **Familias en acción**	**Hospital**
Alcaldía Municipal **Representantes Alcaldía**	**Representantes Gobernación**
Corpoica ica **Instituciones nacionales**	**Políticos**
Fundaciones locales (e.g. Ecohabitats)	**Cooperativas locales** (e.g. Cosurca)
Fedepanela	**Fedecafé**

Banco Agrario de Colombia **Bancos formales**	**Prestamistas** "Gota Gota"
MinAgricultura Ministerio de Agricultura y Desarrollo Rural **Programa de Formalización**	USAID COLOMBIA DEL PUEBLO DE LOS ESTADOS UNIDOS DE AMÉRICA Representantes **Cooperación internacional**
CIAT **Centro Internacional de Agricultura Tropical**	CGIAR PROGRAMA DE INVESTIGACIÓN DE CGIAR EN **Cambio Climático, Agricultura y Seguridad Alimentaria** CCAFS

Livelihood capitals linked by experts

Human increase	1.2	1.3	1.4	2.1	2.3	2.4	3.1	3.2	3.4	4.1	4.2	4.3
1	1	-1	1		-1							-1
2	1	-1	1									
3	1		1									
4		-1	1									
5	1	-1	1								1	-1
6	1	1	1								1	
7	1	-1			-1							
8	1	-1	1									
9	1	1	1									
10	1	-1	-1			-1						
11	1	1	1		1						1	1
12	1	1	1									
13	1	1	1									
count	12	12	12	0	3	1	0	0	0	0	3	3
+	12	5	11	0	1	0	0	0	0	0	3	1
-	0	7	1	0	2	1	0	0	0	0	0	2

Human decrease	1.2	1.3	1.4	2.1	2.3	2.4	3.1	3.2	3.4	4.1	4.2	4.3
1	-1	-1	-1		1							1
2	-1	-1	-1									
3	-1		-1									
4	1		-1									
5	-1	1	-1		1						-1	
6	-1	-1	-1								-1	
7	-1	-1	-1									
8	-1	1	-1									
9	-1	-1	-1									
10	-1	1	-1									
11	-1	-1	-1		1						-1	-1
12	-1	-1	-1									
13	-1	-1	-1									
count	13	11	13	0	3	0	0	0	0	0	3	2
+	1	3	0	0	3	0	0	0	0	0	0	1
-	12	8	13	0	0	0	0	0	0	0	3	1

Natural increase	1.2	1.3	1.4	2.1	2.3	2.4	3.1	3.2	3.4	4.1	4.2	4.3
1									1			
2							1	1	1			
3								1	1			
4				1			1	1	1	1	1	
5									1	1	1	
6		1							1	1	1	
7							1	1	1	1		
8							-1	-1	-1			
9							1	1	1			
10								-1	-1			
11					-1		-1		1	-1	1	
12							1		1		1	
13							1		1			
count	0	1	0	1	1	0	8	7	13	5	5	0
+	0	1	0	1	0	0	6	5	11	4	5	0
-	0	0	0	0	1	0	2	2	2	1	0	0

Natural decrease	1.2	1.3	1.4	2.1	2.3	2.4	3.1	3.2	3.4	4.1	4.2	4.3
1					-1		-1		-1			
2							-1	-1	-1			
3							-1	-1	-1			
4				1		-1		1				
5							-1		-1	-1	-1	
6			-1				-1				-1	
7							-1	-1	-1			
8							-1	1	1			
9							-1	-1	-1			
10							-1	-1	-1			
11				1			1	1	-1	1	1	
12							-1	-1	-1			
13							-1	-1	-1			
count	0	0	1	2	1	1	12	10	11	2	3	0
+	0	0	0	2	0	0	1	3	1	1	1	0
-	0	0	1	0	1	1	11	7	10	1	2	0

Physical increase	1.2	1.3	1.4	2.1	2.3	2.4	3.1	3.2	3.4	4.1	4.2	4.3
1				1		1						
2				1	1	1						
3					-1	1				1		
4					-1	1			-1	1		
5		-1		1	-1	1						
6		1				1				1		
7				1	-1	1						
8				-1	-1	1						
9				-1	1	1						
10				1	-1	1						
11		-1		-1	-1	1				1		-1
12				1	1	1						
13				1		1						
count	0	3	0	10	10	13	0	0	1	4	0	1
+	0	1	0	7	3	13	0	0	0	4	0	0
-	0	2	0	3	7	0	0	0	1	0	0	1

Physical decrease	1.2	1.3	1.4	2.1	2.3	2.4	3.1	3.2	3.4	4.1	4.2	4.3
1				-1		-1						
2				-1	-1	-1						
3					1	-1				-1		
4				1		-1						
5		1		-1	1	-1						
6		-1				-1				-1		
7				-1	-1	-1						
8				-1	1	-1						
9				-1	-1	-1						
10				-1	1	-1						
11		1		1	1	-1						
12					-1	-1						
13				-1	-1	-1						
count	0	3	0	10	10	13	0	0	0	2	0	0
+	0	2	0	2	5	0	0	0	0	0	0	0
-	0	1	0	8	5	13	0	0	0	2	0	0

Financial increase	1.2	1.3	1.4	2.1	2.3	2.4	3.1	3.2	3.4	4.1	4.2	4.3
1										1	1	1
2										1	1	-1
3				1							1	-1
4									-1	1	1	-1
5	1	-1								1	1	-1
6		1								1	1	
7										1	1	-1
8										1	1	-1
9										1	1	1
10		-1			-1					1	1	-1
11		-1			-1					-1	1	-1
12										-1	1	-1
13										1	1	1
count	1	4	0	1	2	0	0	0	1	12	13	12
+	1	1	0	1	0	0	0	0	0	10	13	3
-	0	3	0	0	2	0	0	0	1	2	0	9

Financial decrease	1.2	1.3	1.4	2.1	2.3	2.4	3.1	3.2	3.4	4.1	4.2	4.3
1										-1	-1	1
2										-1	-1	-1
3										-1	-1	1
4					-1					1	-1	
5		1			1					-1	-1	1
6		-1								-1	-1	
7										-1	-1	-1
8										-1	-1	1
9										-1	-1	-1
10					-1					-1	1	1
11					1		-1			-1	-1	1
12										-1	-1	-1
13										-1	-1	-1
count	0	2	0	0	4	0	1	0	0	13	13	11
+	0	1	0	0	2	0	0	0	0	1	1	6
-	0	1	0	0	2	0	1	0	0	12	12	5

Comparison of experts and farmers rankings of four elements

	rank	weights	preocupaciones (worries)					
			Pobreza	Acceso al dinero	Gobernabilidad	Comercializacion	Riesgos Climaticos	Seguridad y orden Publico
			P 1	P 2	P 3	P 4	P 5	P 6
	1	6	11	8	7	3	14	11
	2	5	10	9	13	12	5	6
	3	4	5	7	13	13	9	10
	4	3	9	12	15	11	7	2
	5	2	19	18	8	6	3	1
	6	1	4	4	1	11	15	16
			3.5	3.4	3.8	3.2	3.2	2.8
Experts ranking			1	6	3	2	4	5
Farmers ranking (all 58)			2	3	1	5	4	6
Gualimbio (12 farmers)			3	3	1	6	5	2
La Meseta (11 farmers)			1	1	4	5	3	6
La Calera (11 farmers)			3	4	1	2	5	6
San Antonio (12 farmers)			2	5	3	3	1	6
Julumito Alto (12 farmers)			6	3	1	4	5	2

	rank	riesgos a la produccion					
		Mala planeacion	Produccion	Comercialicacion	Vulnerabilidad social	Inseguridad y Violencia	Clima y tiempo
		R 1	R 2	R 3	R 4	R 5	R 6
	1	6	15	7	16	7	1
	2	11	11	16	9	5	2
	3	9	8	9	13	12	5
	4	11	7	8	5	17	6
	5	2	3	2	3	8	31
	6	19	13	13	7	3	2
		3.2	3.7	3.4	3.8	3.2	2.0
Experts ranking		3	6	4	4	1	2
Farmers ranking (all 58)		5	2	3	1	4	6
Gualimbio (12 farmers)		2	3	4	1	4	6
La Meseta (11 farmers)		5	1	4	2	3	6
La Calera (11 farmers)		3	1	2	4	5	6
San Antonio (12 farmers)		2	4	5	1	2	6
Julumito Alto (12 farmers)		4	3	2	1	6	5

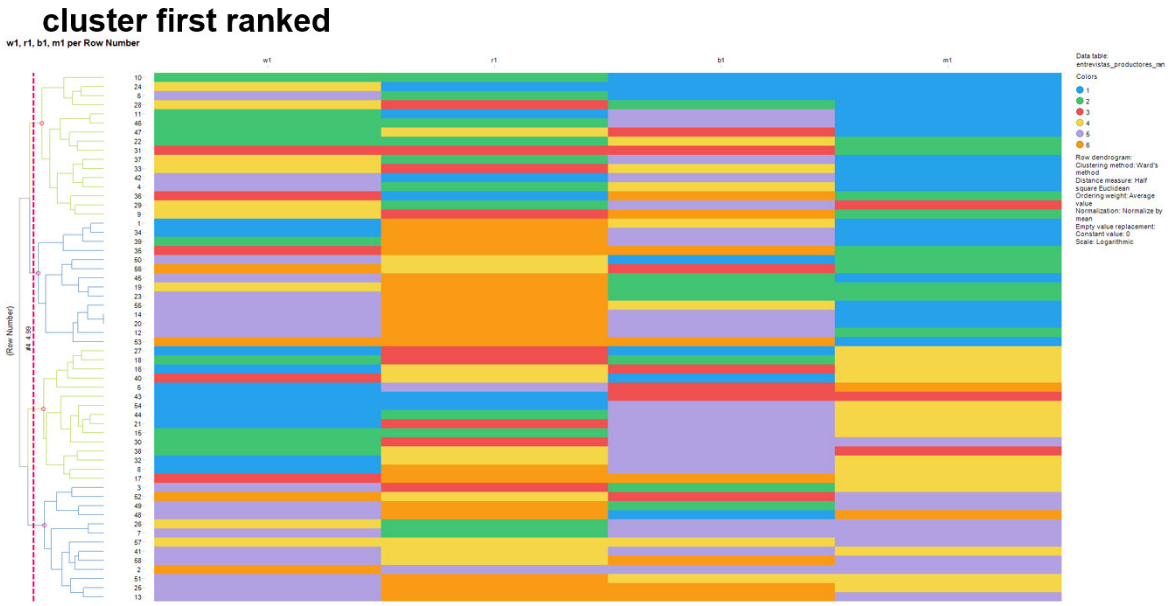
	rank	barreras para adaptacion					
		Polcticas nacionales	Riesgos climaticos	Capacidad adaptiva	Institucionalidad	Recursos economicos	Organizacion comunal
		B 1	B 2	B 3	B 4	B 5	B 6
	1	7	16	11	10	9	3
	2	7	10	11	9	9	9
	3	7	7	6	10	12	12
	4	7	8	7	12	10	11
	5	22	9	10	8	2	6
	6	8	7	12	8	13	7
		3.1	3.8	3.4	3.5	3.3	2.8
Experts ranking		1	6	2	3	5	4
Farmers ranking (all 58)		5	1	3	2	4	6
Gualimbio (12 farmers)		4	1	2	3	4	6
La Meseta (11 farmers)		5	2	3	4	1	6
La Calera (11 farmers)		4	1	2	2	6	5
San Antonio (12 farmers)		6	1	5	1	1	1
Julumito Alto (12 farmers)		3	4	1	1	6	5

	rank	motivaciones para adaptacion					
		Interes familiar	Calidad de vida	Interes economico	Arraigo por la tierra	Aptitud para sembrar	Seguridad alimentaria
		M 1	M 2	M 3	M 4	M 5	M 6
	1	19	10	7	12	4	5
	2	10	14	9	8	10	7
	3	3	7	8	12	11	18
	4	15	9	9	2	11	11
	5	9	11	11	7	14	5
	6	2	7	14	17	7	10
		4.2	3.7	3.1	3.4	3.2	3.3
Experts ranking		3	1	5	2	6	4
Farmers ranking (all 58)		1	2	6	3	5	4
Gualimbio (12 farmers)		1	2	4	3	5	6
La Meseta (11 farmers)		1	3	6	4	5	2
La Calera (11 farmers)		1	3	5	2	4	6
San Antonio (12 farmers)		1	5	4	2	6	3
Julumito Alto (12 farmers)		3	1	5	6	2	4

Comparison of experts and farmers rankings of livelihood capitals

		R 1	R 2	R 3	R 4		**Expert ranking**	**Farmers ranking (58)**	Gualimbio	La Meseta	La Calera	San Antonio	Julumito Alto
Natural	C 1	16	16	11	15	5	2	2	3	1	3	1	3
Humano	C 2	23	17	13	5	5	1	1	1	1	1	2	1
Fisico	C 3	3	12	18	27	4	4	4	4	3	4	4	4
Financiero	C 4	16	13	16	11	4	3	3	2	4	2	3	1

Result from cluster analysis of farmers rankings of four elements



Social Capital: Difference of perceived distance of actors to farmers

#	Actors group	Actors description	Perceived distance to actors: difference between experts vs. farmers	experts	STDEV experts	farmers	STDEV farmers	No. of Experts	No. of Farmers
1	Social groups	Parents' association	0.2	1.2	0.4	1.4	0.5	5	47
2	Social groups	Single mothers association	0.3	1.2	0.4	1.5	0.6	5	28
3	Social groups	Board of community leaders	0.0	1.4	0.7	1.5	0.6	7	56
4	Social groups	Village busdriver	0.4	1.0	0.00	1.4	0.6	4	53
5	Social groups	Family and relatives	0.2	1.0	0.00	1.2	0.4	5	56
6	Social groups	Families in action group	-0.3	2.0	0.00	1.7	0.7	1	50
7	Social groups	Local health service	0.0	1.7	0.47	1.6	0.7	3	55
8	Social groups	Neighbors	0.1	1.1	0.35	1.2	0.5	7	56
9	Social groups	Church and other religion groups	0.3	1.3	0.43	1.6	0.6	4	49
10	Social groups	Sports and culture groups	0.7	1.0	0.00	1.7	0.6	1	41
11	Production network	Coffee producer association	0.6	1.1	0.33	1.7	0.7	8	43
12	Production network	Sugarcane producer association	0.8	1.1	0.33	2.0	0.7	8	31
13	Production network	Market intermediary	1.3	1.0	0.00	2.3	0.6	7	33
14	Production network	Pesticide & input seller	1.4	1.3	0.45	2.7	0.5	7	23
15	Production network	Extensionists and technical assistance (Umata)	0.7	1.2	0.40	1.9	0.7	10	49
16	Production network	Stores in municipalities	1.0	1.0	0.00	2.0	0.7	1	45
17	Production network	Workers (Jornaleros)	0.4	1.0	0.00	1.4	0.6	1	50
18	Authorities	Bank institute (credits)	0.0	2.0	0.00	2.0	0.7	2	49
19	Production network	Fedecafé (Coffee Federation)	-0.1	2.0	0.58	1.9	0.7	6	51
20	Production network	Fedepanela (Sugarcane Federation)	-0.5	2.7	0.47	2.2	0.6	3	30
21	Authorities	National agriculture institutions (ICA, Corpoica)	0.6	2.0	0.00	2.6	0.5	2	17
22	Authorities	Ministry of Agriculture (landtitles)	0.8	1.4	0.80	2.2	0.7	5	27
23	Authorities	Police / Security groups / Soldiers	0.6	1.5	0.50	2.1	0.7	2	45
24	Authorities	Representatives from local government	0.9	2.0	0.00	2.9	0.3	4	22
25	Authorities	Representatives from municipality	0.9	1.7	0.46	2.6	0.6	10	34

Baseline data

user_id	100-199	200-299	300-399	400-499	500-599	
vereda	**integer**	**1**	**2**	**3**	**4**	**5**
		Gualimbio	La Meseta	La Calera	San Antonio	Julumito
entrevist	**text**					
name	**text**					
surname	**text**					
date	**date**					
duration	**integer**	**[min]**				
place	**text**					
lat	**numeric**	**[WGS84]**				
lon	**numeric**	**[WGS84]**				
alt	**integer**					
[crops]	**1**	**2**				
	main	changed				
coffee	**integer**					
sugarc	**integer**					
plantain	**integer**					
cassava	**integer**					
beans	**integer**					
maize	**integer**					
poultry	**integer**					
pasture	**integer**					
age	**integer**					
gender	**integer**	**1**	**2**			
		man	woman			
estcivil	**integer**	**1**	**2**	**3**		
		married	single	widow		
nbhm	**integer**					
hhpos	**integer**	**1**	**2**	**3**	**4**	
		head	spouse	child	other	
edu	**integer**	**1**	**2**	**3**	**4**	
		primary	secondary	terciary	university	
grado	**integer**					
profesion	**integer**	**1**	**2**	**3**	**4**	**5**
		farmer	household	both	student	other
area	**numeric**	**[hectares]**				
landtitle	**integer**	**1**	**2**	**3**	**4**	
		formalized	in process	not	rent	
timefarm	**integer**	**[years]**				
insource	**integer**	**1**	**2**	**3**	**4**	**5**
		coffee only	coffee/suga rcane	Agriculture only	Agriculture & other	non agriculture
insource_text	**text**					
otherplace	**integer**	**1**	**2**			
		si	no			

whereplace	**text**						
ownmob	**integer**	**1** si	**2** no				
numob	**integer**						
sumob	**integer**	**1** si	**2** no				
whomob	**integer**	**1** Spouse	**2** Child	**3** Friend/Neighbour	**4** Family		
incomeag	**integer**	[COP					
incomeother	**integer**	[COP					
incometype	**text**						
remitance	**integer**						

Risk perceptions

worother	**text**						
[worries]	**1** poverty	**2** money access	**3** goverability	**4** commerciali-sation	**5** climate risks	**6** security	
P1	integer						
P2	integer						
P3	integer						
P4	integer						
P5	integer						
P6	integer						
riskother	**text**						
[risks]	**1** wrong planning	**2** production	**3** commercialization	**4** Social vulnerability	**5** insecurity & violence	**6** Weather & Climate	
R1	integer						
R2	integer						
R3	integer						
R4	integer						
R5	integer						
R6	integer						
barother	**text**						
[adaptation barriers]	**1** National politics	**2** Climate risks	**3** Adaptive capacity	**4** Institutionality	**5** Economic ressources	**6** Community organization	
B1	integer						
B2	integer						
B3	integer						
B4	integer						
B5	integer						
B6	integer						
motother	**text**						

[motivation]	**1**	**2**	**3**	**4**	**5**	**6**
	Family wellbeing	Life quality	Economic interest	Rootedness	Land suitability	Food security
M1	integer					
M2	integer					
M3	integer					
M4	integer					
M5	integer					
M6	integer					
[capitals]	**1**	**2**	**3**	**4**		
	human	**natural**	**financial**	**physical**		
Cap1	integer					
Cap2	integer					
Cap3	integer					
Cap4	integer					

Capitals

imgn01[27]	**integer**	**1**	**2**	**3**
		yes	no	other sense
imgcap01[27]	**integer**	**1**	**2**	**3**
		yes	no	other sense
imgt01[27]	**integer**	**1**	**2**	**3**
		yes	no	other sense

Open Questions

coments	**integer**	**0**	**1**	**2**		
		no comments	difficulties in	good responding		
learned	**integer**	**1**	**2**	**3**	**4**	
		padres	capacity building	farmers colective	alone	
farmhelp	**integer**	**1**	**2**	**3**	4	
		nobody	family	family and outside	outside labor	
youngfut	**integer**	**1**	**2**			
		si	no			
capacit	**integer**	1	2	3	4	5
		si	no	si, no sirvio	si, no pudo	no hay
seeds	**integer**	**1**	**2**	**3**	**4**	
		self	buy	gift	mixed	
forest	**integer**	**1**	**2**	**3**		
		yes	no	some		
forestbord	**integer**	**1**	**2**			
		si	no	some		
water	**integer**	**1**	**2**	**3**		
		pipeline	own spring	close spring		

conchg	**integer**	**1** si	**2** no					
pastcon	**integer**	**1** si	**2** no					
conchg_t	**text**							
whatchgcon	**text**							
conchgtypq	**integer**	1 more summer	2 needs more input	3 better technology	4 climate change	5 soil less fertile	6 contami-nation	
watersoilchg	**integer**	**1** less water	**2** less fertile	**3** both	**4** no change	**5** improved water infrastructur	**6** climate variability	**7** other
climobserv	**integer**	**1** si	**2** no					
pronost	**integer**	**1** si	**2** no	**3** don't				
climvar	**integer**	**1** god	**2** stop activities in	**3** wait for rain	**4** nothing	**5** look for alternatives		
varprep	**integer**	**1** si	**2** no					
lotes	**integer**							
loteschg		1 si	2 no					
whatchglotes	**text**							
cropchg	**integer**	1 sugarcane to coffee	2 sugarcane to others	3 coffee to sugarcane	4 coffee to others	5 other to coffee	6 other to pasture	
chgpract	**integer**	**1** si	**2** no					
morelotes	**integer**	**1** si	**2** no					
secprodrisk	**integer**	**1** si	**2** no					
mining	**text**							
miningeff	**integer**	**1** polute	**2** effekt	**3** bring labor	**4** not here	**5** land tenure	**6** security	
incharv	**integer**	**1** si	**2** no					
incharv_t	**text**							
incincome	**text**							
incinctype	**integer**	**1** selfimprove	**2** help outside	**3**				
opplab	**integer**	**1**	**2**					

		si	no		
ventprod	**integer**	**1**	**2**	**3**	
		local market	cooperative	intermediari	
ventfar	**integer**	**1**	**2**		
		si	no		
pricestab	**integer**	**1**	**2**	**3**	
		low level	variable	fine	
helpgov	**integer**	**1**	**2**	**3**	
		si	no	si, poco	
moremoney	**integer**	**1**	**2**	**3**	**4**
		in agricultre	more land	housing & family	diversify
hadcredit	**integer**	**1**	**2**		
		si	no		

Appendix C

GeoFarmer manuals

CSA Implementer user manual mobile app v 1.0

International Center for Tropical Agriculture
Since 1967 / *Science to cultivate change*

RESEARCH PROGRAM ON Climate Change, Agriculture and Food Security

Climate Smart Technologies and Practices: Using Science Knowledge and Expert Feedback to Accelerate Local Adoption

Based on framework: GEOCIUDADANO

Editing: Anton Eitzinger and Tenesia Benjamin

Contact: International Center for Tropical Agriculture CIAT, Decision and Policy Analysis Program DAPA, Cali, Colombia | Tel: +57 2 4450000 |Email: *A.Eitzinger@cgiar.org*

Disclaimer:
This report has been prepared as part of the project "Using Science Knowledge and Expert Feedback to Accelerate Local Adoption: Climate Smart Technologies and Practices meet ICT tool" funded by the OPEC Fund for International Development OFID, a development finance institution of OPEC Member States, established to provide financial support for socio-economic development, particularly in low-income countries, and by the Climate Change, Agriculture and Food Security program CCAFS. This report has not been peer reviewed, any opinions stated herein are those of the author(s) and do not necessarily reflect the policies or opinions of CCAFS, donor agencies, or partners.

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Eitzinger, A., Sayula, G., Benjamin, T., Rodriguez, B., Winowiecki, L., Koech, J., Twyman, N., Läderach, P., Jarvis, A. 2015. Project Report: Using Science Knowledge and Expert Feedback to Accelerate Local Adoption: Climate Smart Technologies and Practices meet ICT tool. International Center for Tropical Agriculture CIAT. Cali, Colombia. Available online at: http://dapa.ciat.cgiar.org/

Based on framework: GEOCIUDADANO

01 Introduction

CSA Implementer is a mobile application for collaborative testing and learning of climate smart agriculture practices (CSA). This application can be used to manage farmers data and surveys in a database and to monitor ongoing activities on a demonstration or farmers plot.

The app was developed as part of the *project Climate Smart Technologies and Practices: Using Science Knowledge and Expert Feedback to Accelerate Local Adoption,* funded the OPEC Fund for International Development OFID, a development finance institution of OPEC Member States, established to provide financial support for socio-economic development, particularly in low-income countries, and by the Climate Change, Agriculture and Food Security program CCAFS.

Specific Objectives of this project were (1) Select and test appropriate Climate-Smart-Agriculture (CSA) practices for the Lushoto region, (2) develop application domains using land health indicators and modeled agronomic and environmental benefits for CSA practices and compare with domains of geographic locations having a current climate similar to the future climatic conditions of Lushoto; and (3) build an interactive platform to validate application domains through participatory workshops with local agriculture experts and stimulate a feedback loop of perceived usefulness from agriculture experts and scientists.

02 Installation

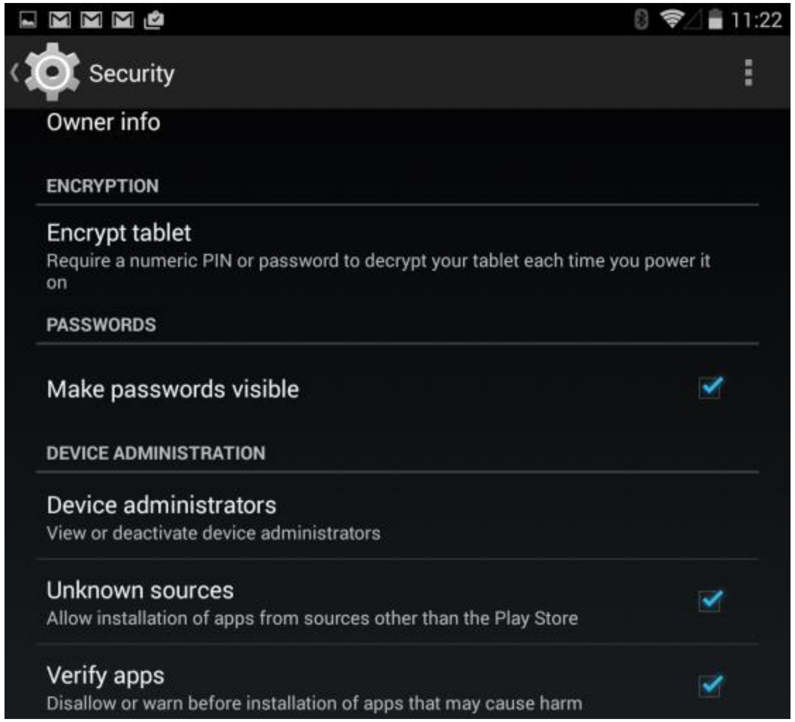
CSAImplementer-release.apk

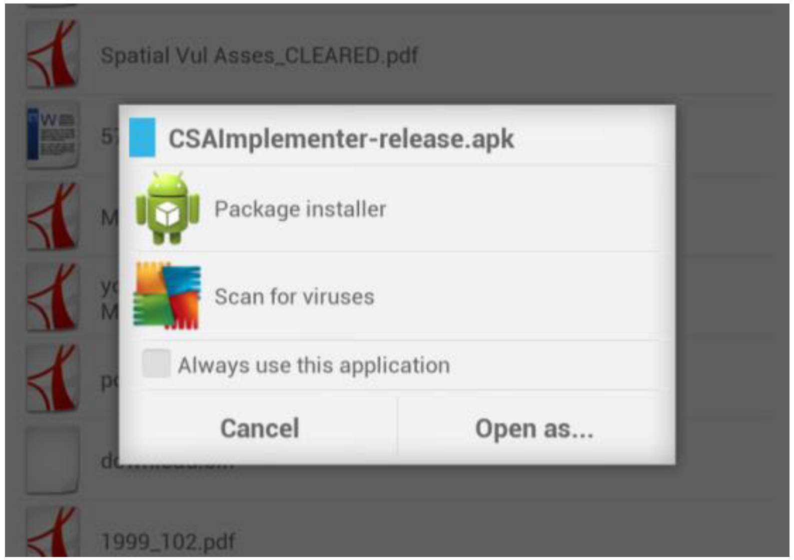
System (device) requirements:

- Android
- Front- & Back camera
- Mobile network
- 0.5 GB internal storage available

Steps

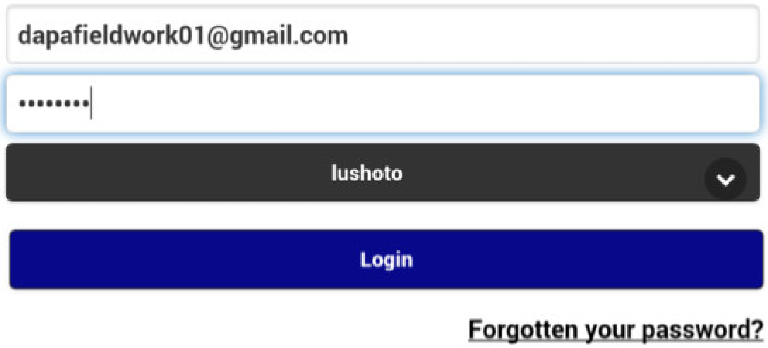
1. Make sure *security options* allows installation from unknown sources (other than Google Play store)
2. *Open apk* file with Package installer
3. Follow screen instructions

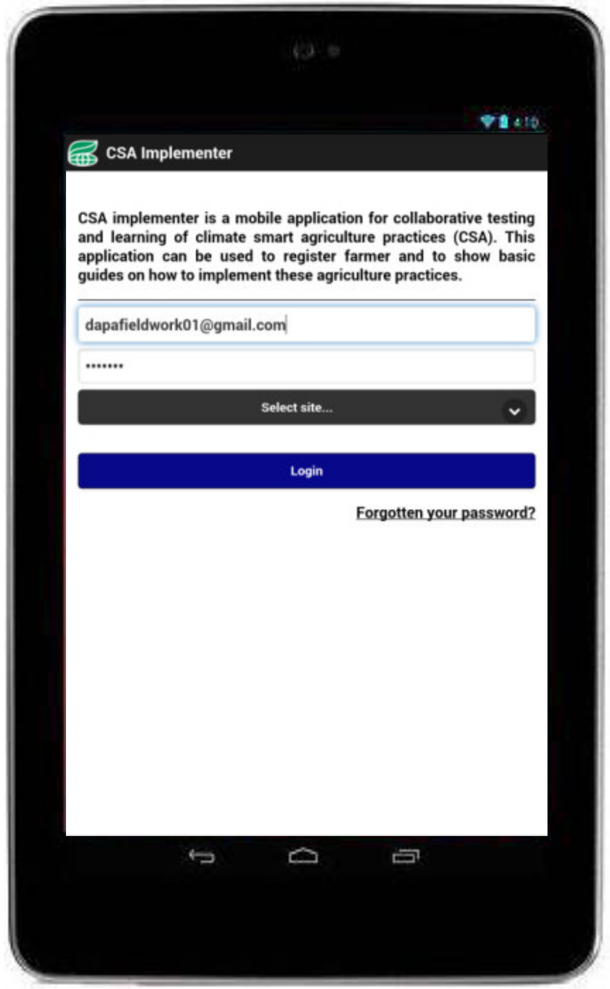




03 Create account

1. To create an **New** account, fill in email address and password
2. **Select your site** from the dropdown list (e.g lushoto)
3. Press **Login**





! For existing user login with your email and password

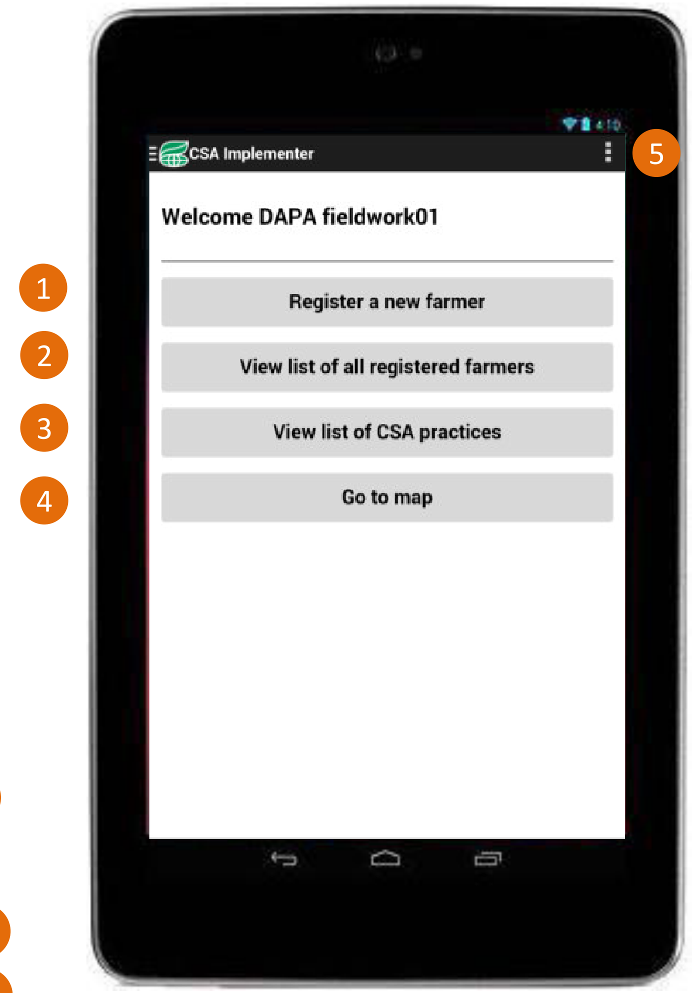
You must always select a site from the dropdown list

If you have forgotten your password , use link Forgotten your password?

04 Main menu

1. **Register a new CSA farmer**
   Use to add a new CSA farmer to the database
2. **View list of all registered farmers**
   Click to see all farmers in the database (on your selected site)
3. **View list of CSA practices**
   To see the list of all CSA practices available in the database and for the selected site
4. **Go to map**
   Change to the map view and see collected GPS information and other thematic map layers
5. **Go to settings**

6 Change to your preferred language
7 Close application (without logging out)
8 Logout (close application and user will be logged out)



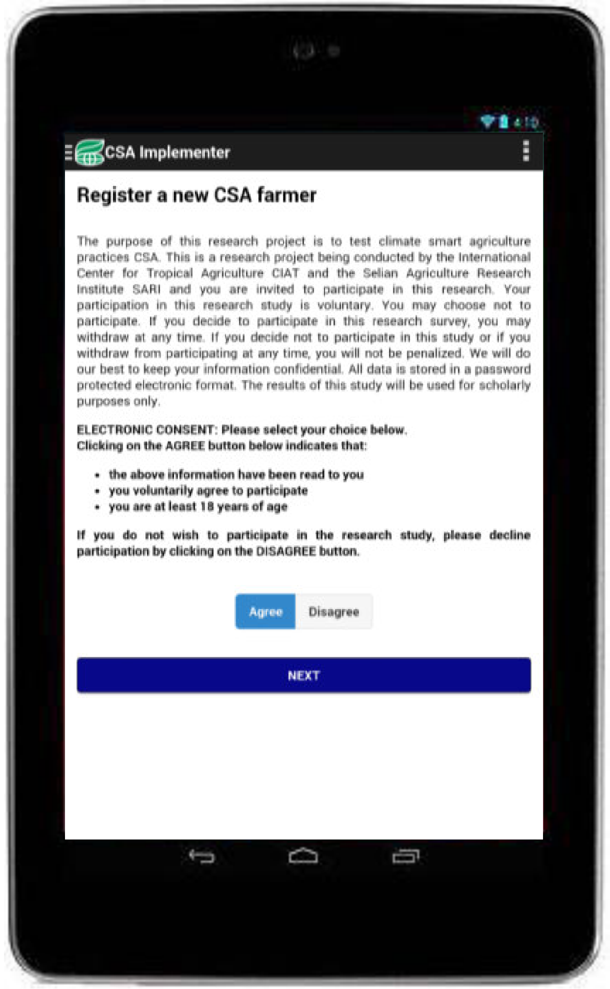
05 Register farmers

<u>Consent form:</u>

Before registering a new farmer, **the electronic consent** must be read to the farmer in order to make sure that he understands the purpose of the research and that he agrees to participate

1. Select Agree or Disagree
2. Click NEXT

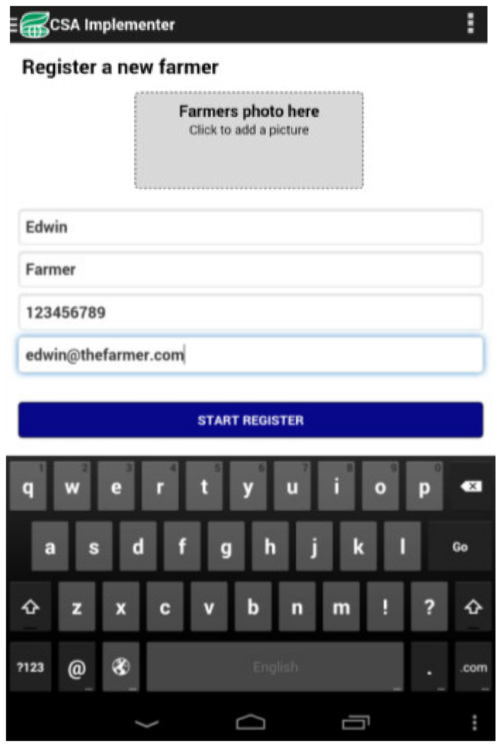
> ! If the farmer disagrees he can not be registered on in the database!

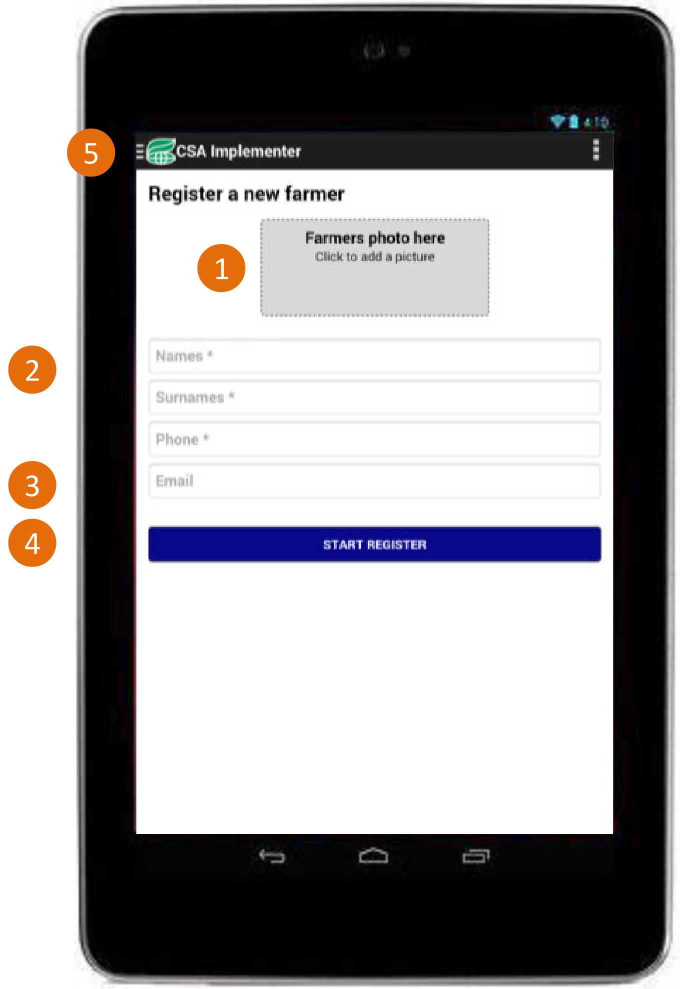


05 Register farmers

Register Farmer form:

1. Click first to **add a photo** of the farmer
2. **Fill** Names, Surnames and Mobile-phone number as **mandatory fields**
3. Add optional fields if available
4. START REGISTER
5. Go back to Main menu



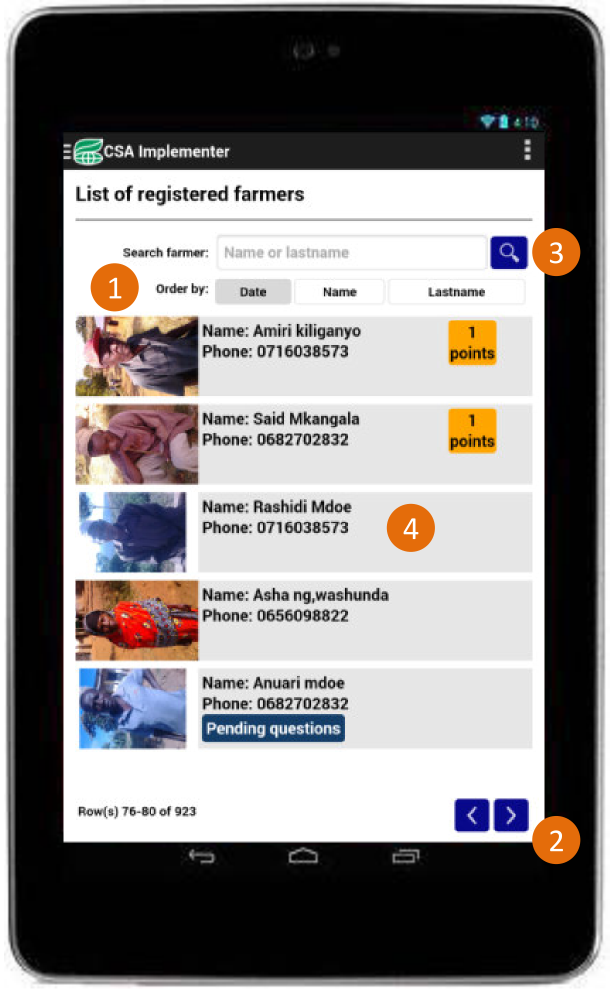


05 Register farmers

<u>List of registered farmers:</u>

After finishing the process of registering a farmer you will find this new farmer in the *"list of registered farmers (main menu)"*

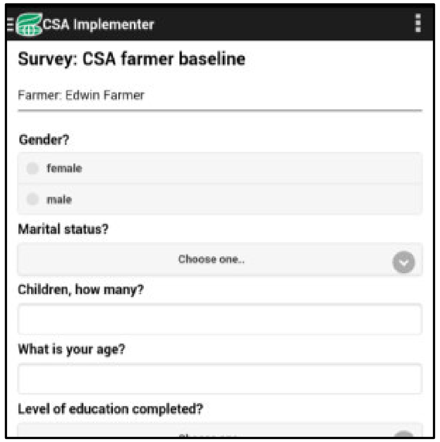
1. Sort farmers list by date, name or last name
2. Flip between pages of search results
3. Search for an individual farmer
4. Click on an individual farmer to see more details



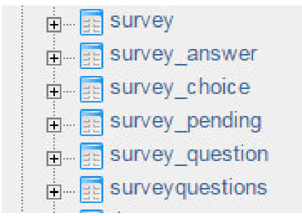
06 Add farmers data

Farmer details:

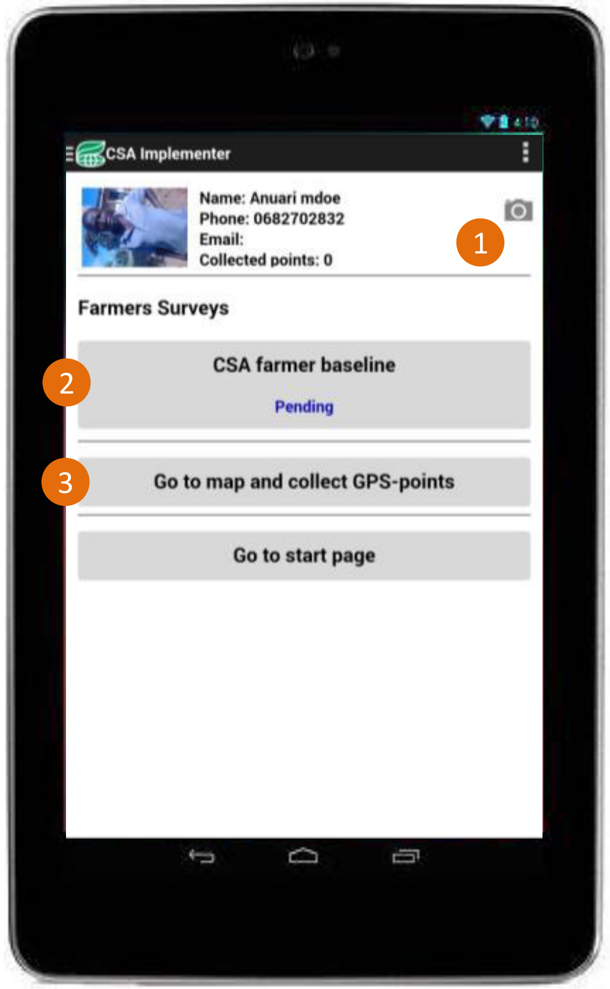
1. Change the main photo
2. Access to surveys
   - **Pending** surveys are ready for collecting the data



> ! New surveys can be created in the database



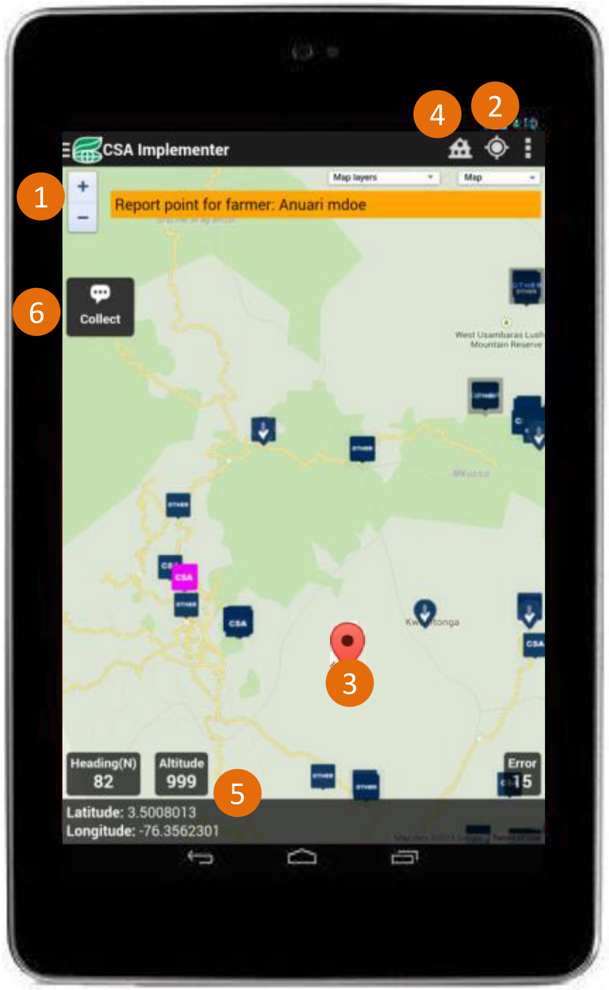
   - Results of finished surveys can be viewed by clicking on the survey
3. GPS points can be collected and related to the farmer

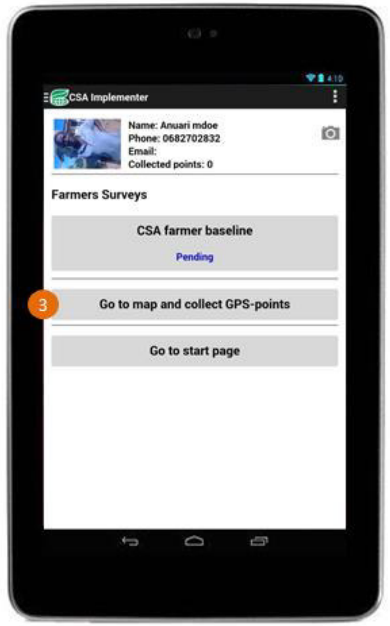


06 Add farmers data

Collect GPS points and relate to a farmer:

1. use +/- to zoom in/out
2. move to your actual location
   (using GPS signal from your device)
3. move marker to desired position
4. Move map to study site
   (e.g. lushoto)
5. shows GPS information
6. start collecting information





! More details on mapping functions in section: 08 Map view

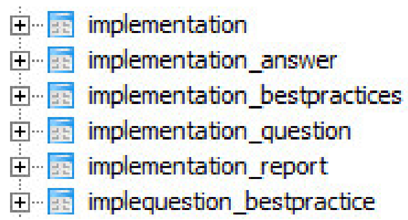
07 CSA practices

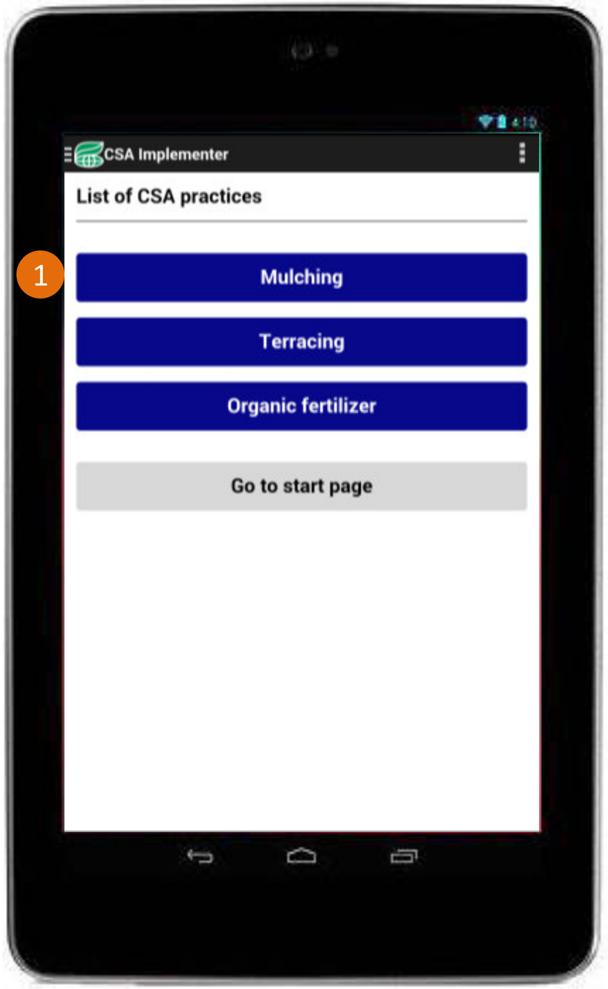
Library of CSA practices:

1 Click to access information on CSA practice

- Pictures
- Web-links (and local links e.g. videos)
- Uploaded documents

! New CSA practices can be added in the database





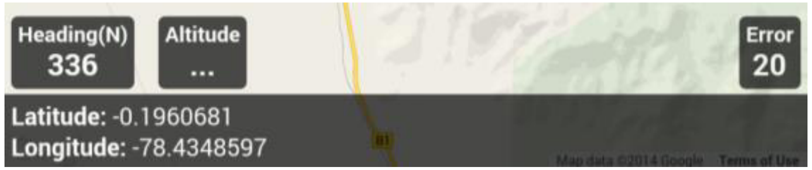
08 Map view

Zoom in/out,
Use on-screen zoom functions also

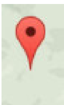
Select base-map and map layers

Zoom to full map-extent of project site (e.g. Lushoto)

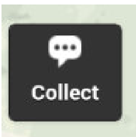
Zoom to your current position (GPS location of phone)



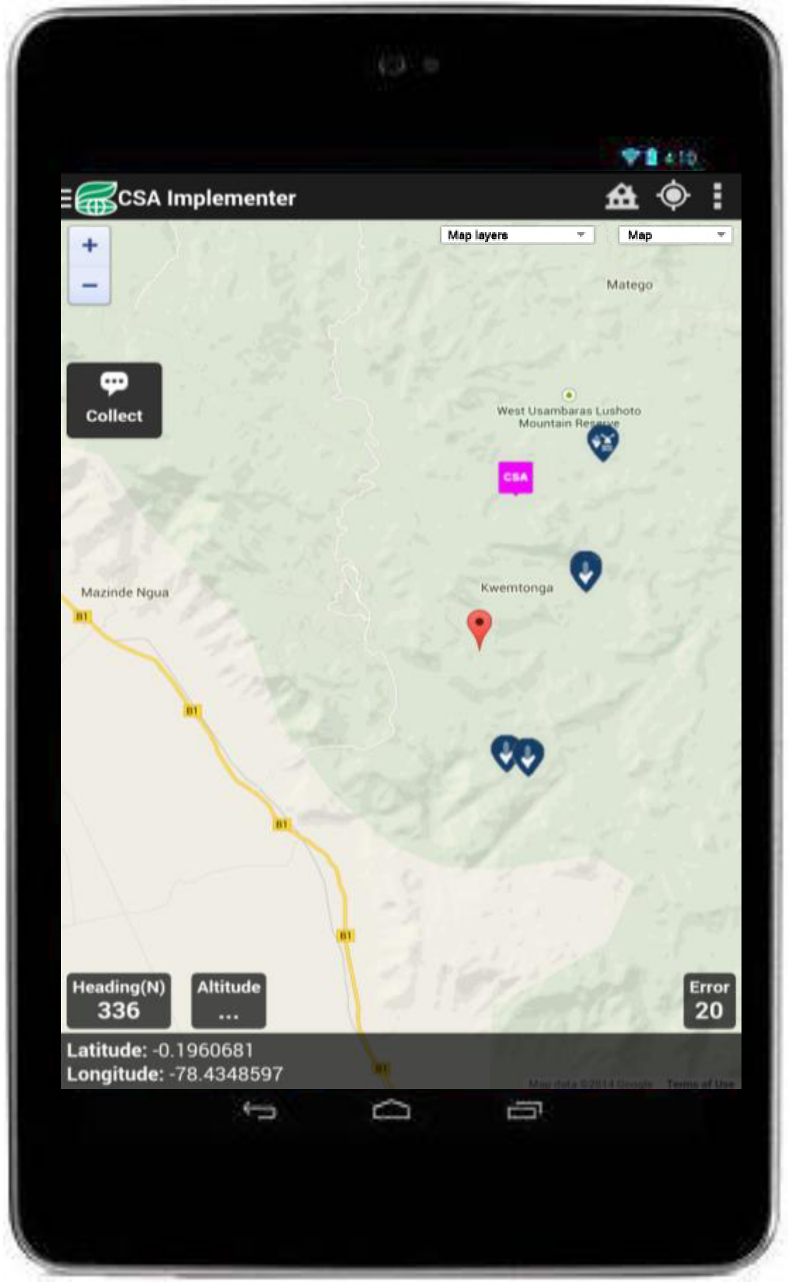
Shows latitude/longitude, altitude and estimated error)



Position GPS coordinates will taken from,
can be moved by drag and drop.

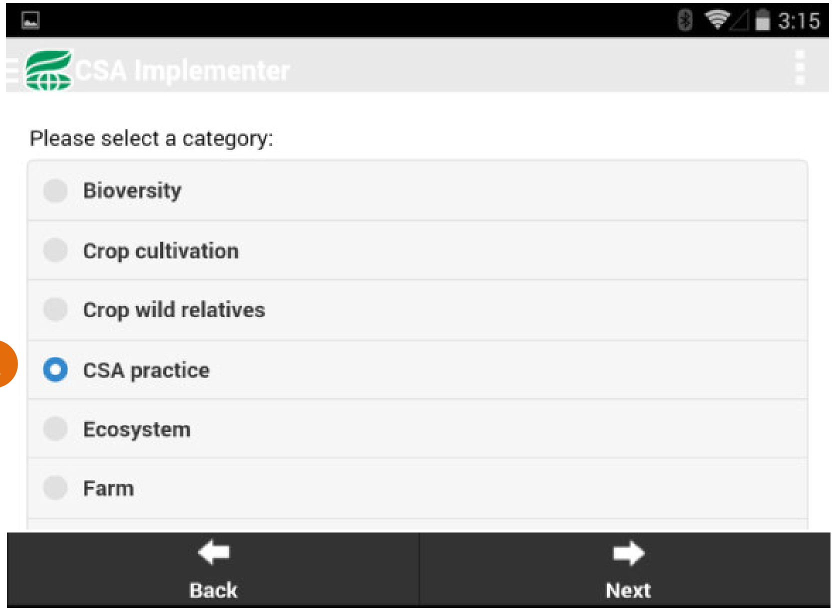


Start collecting a new point on the map

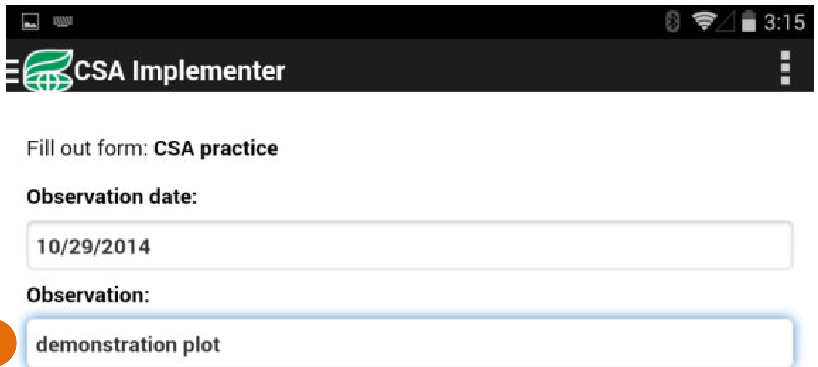


08 Map view

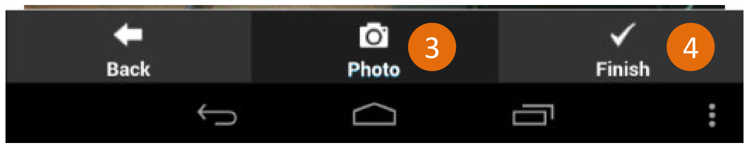
1 Select a category



2 Fill information



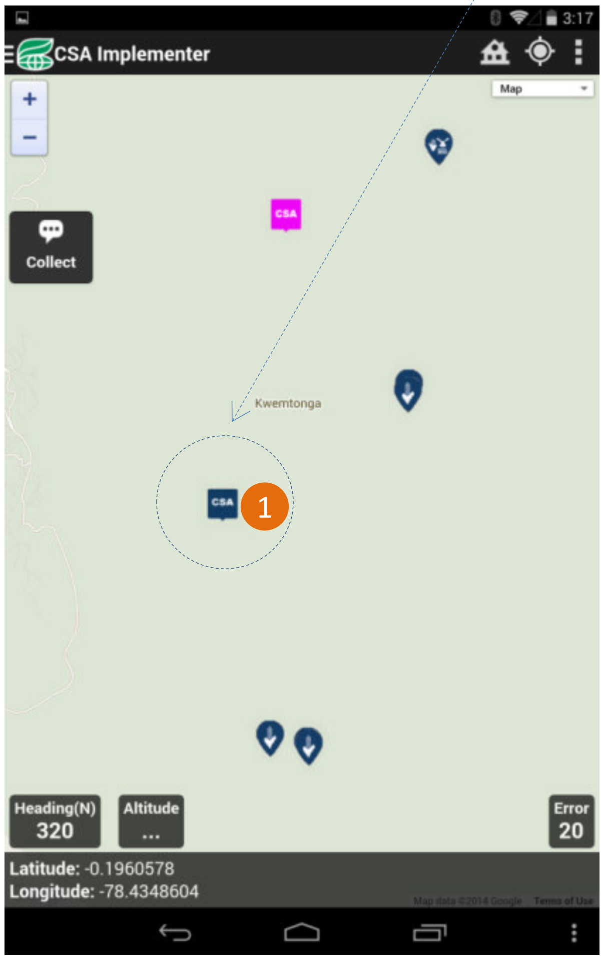
3 Take a picture (or upload a photo)



4 Finish collecting a new point site

09 CSA demo plots

If you want to use the new collected site to start a demonstration plot,



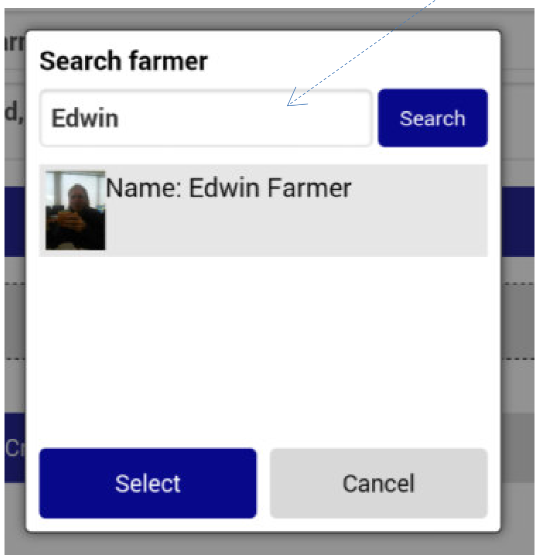
1 click on it on the map

2 click start demo

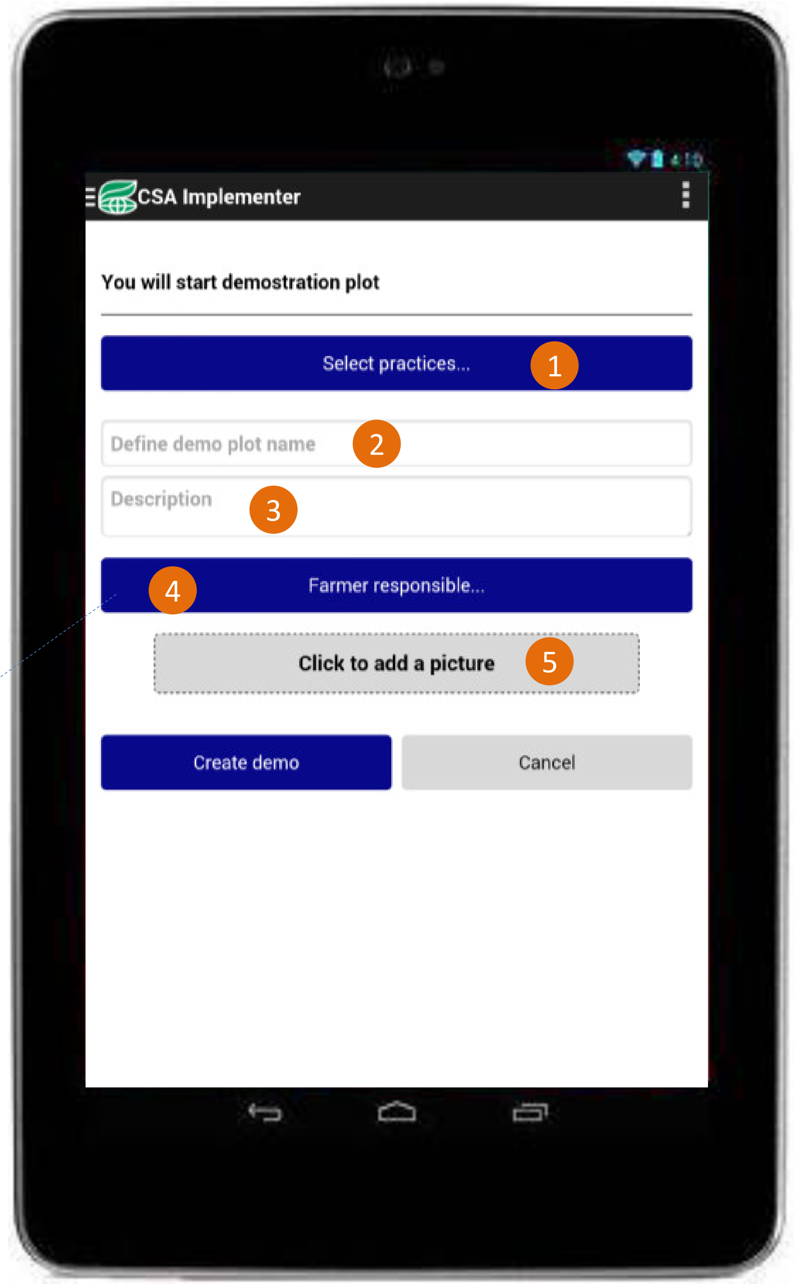
09 CSA demo plots

<u>Start a new CSA demo site:</u>

1. Start by **selecting a CSA practice** you want to implement
2. Define a unique **name** for you demonstration site (demo plot name)
3. Add a short **description** of the site
4. Select a **responsible farmer** to the site

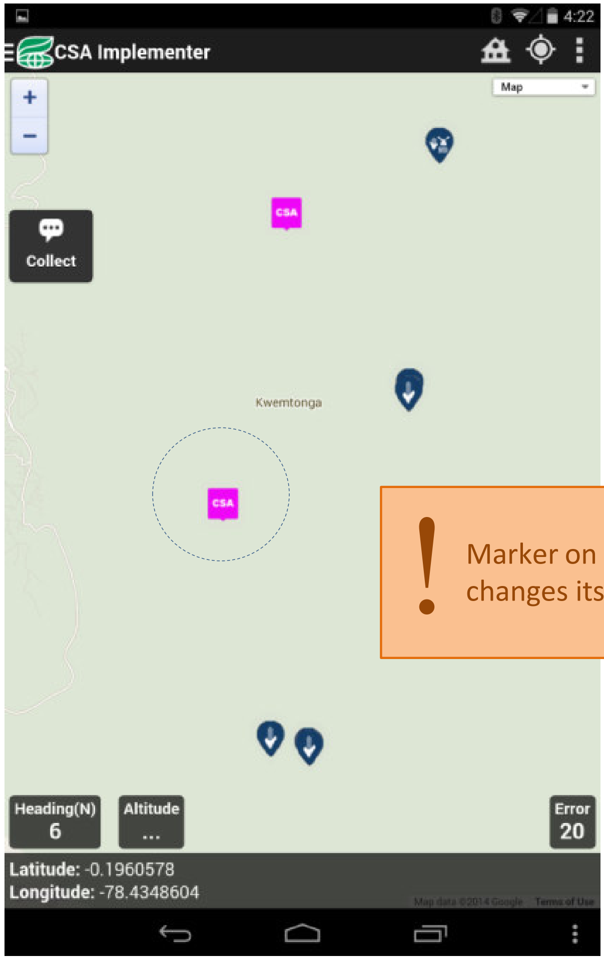


5. Add a first photo

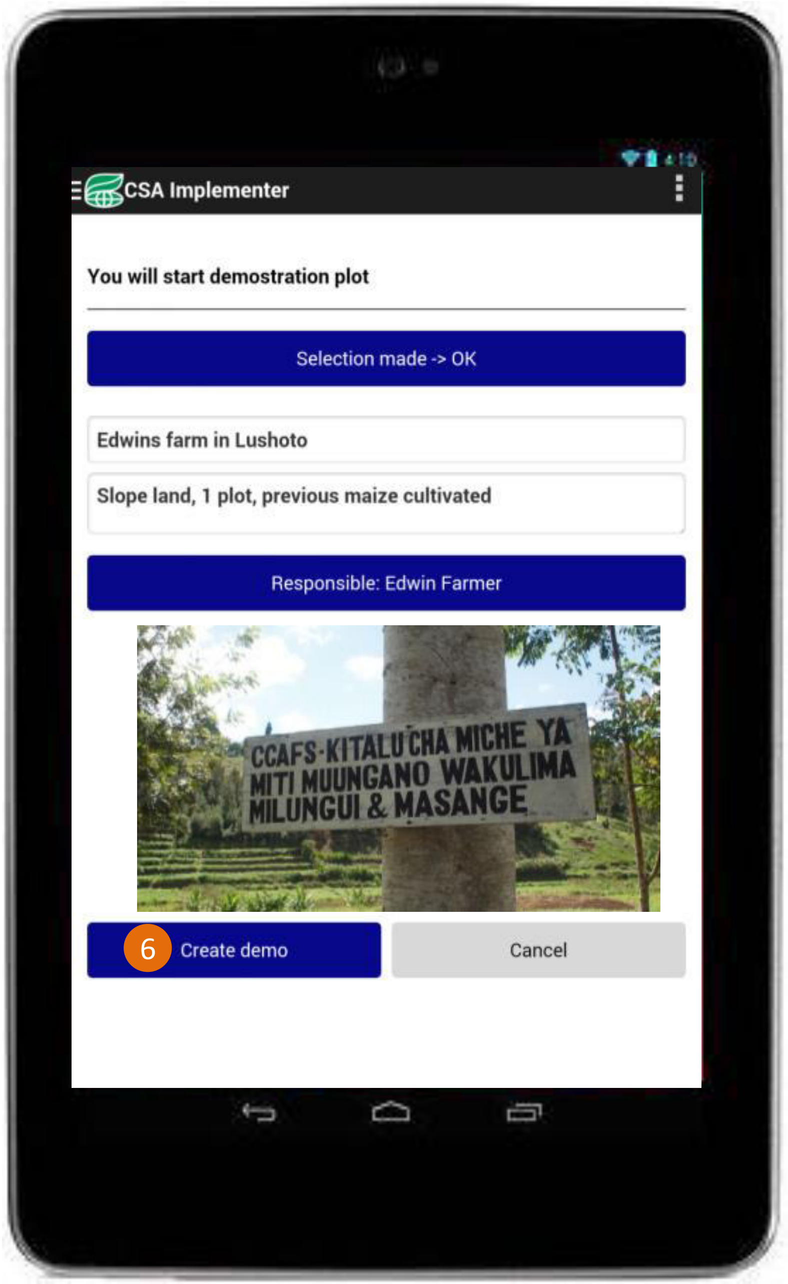


09 CSA demo plots

6 Create demo



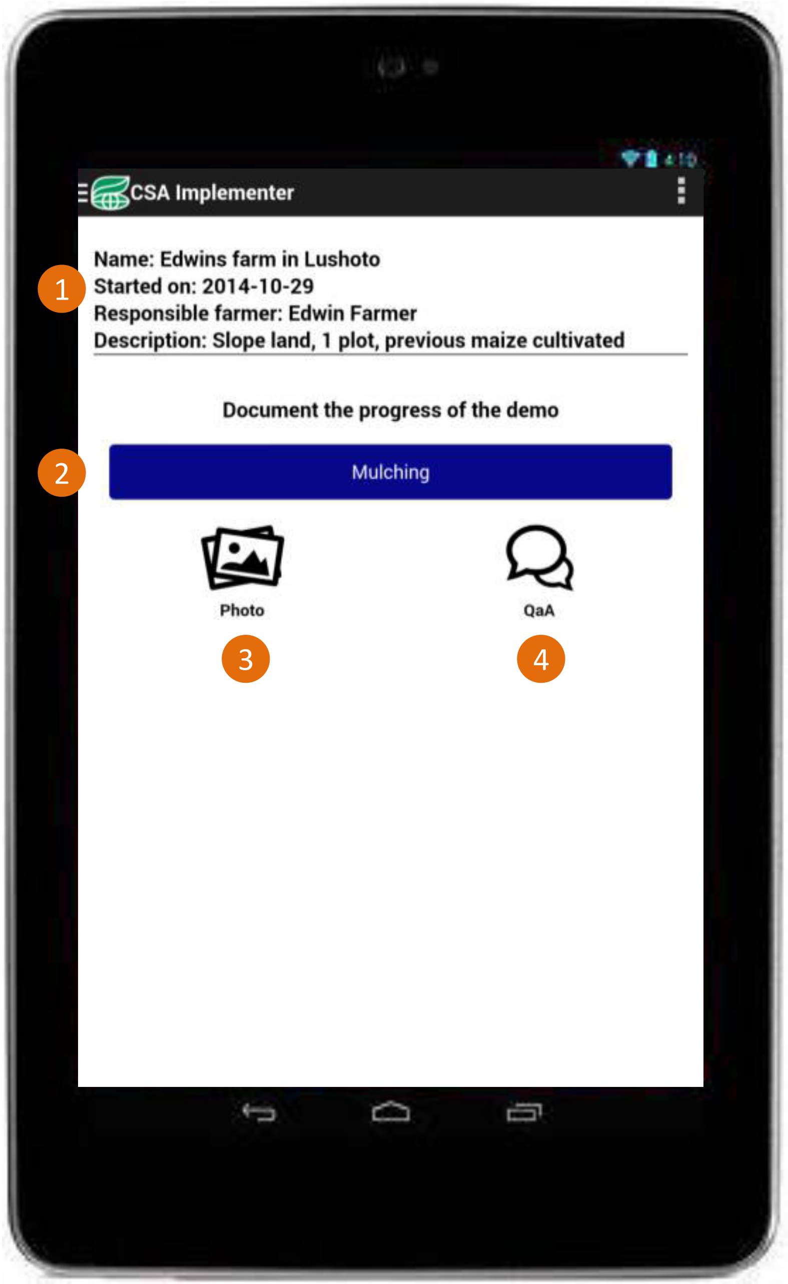
Marker on map view changes its color



10 CSA monitoring

Open demo site on the map:

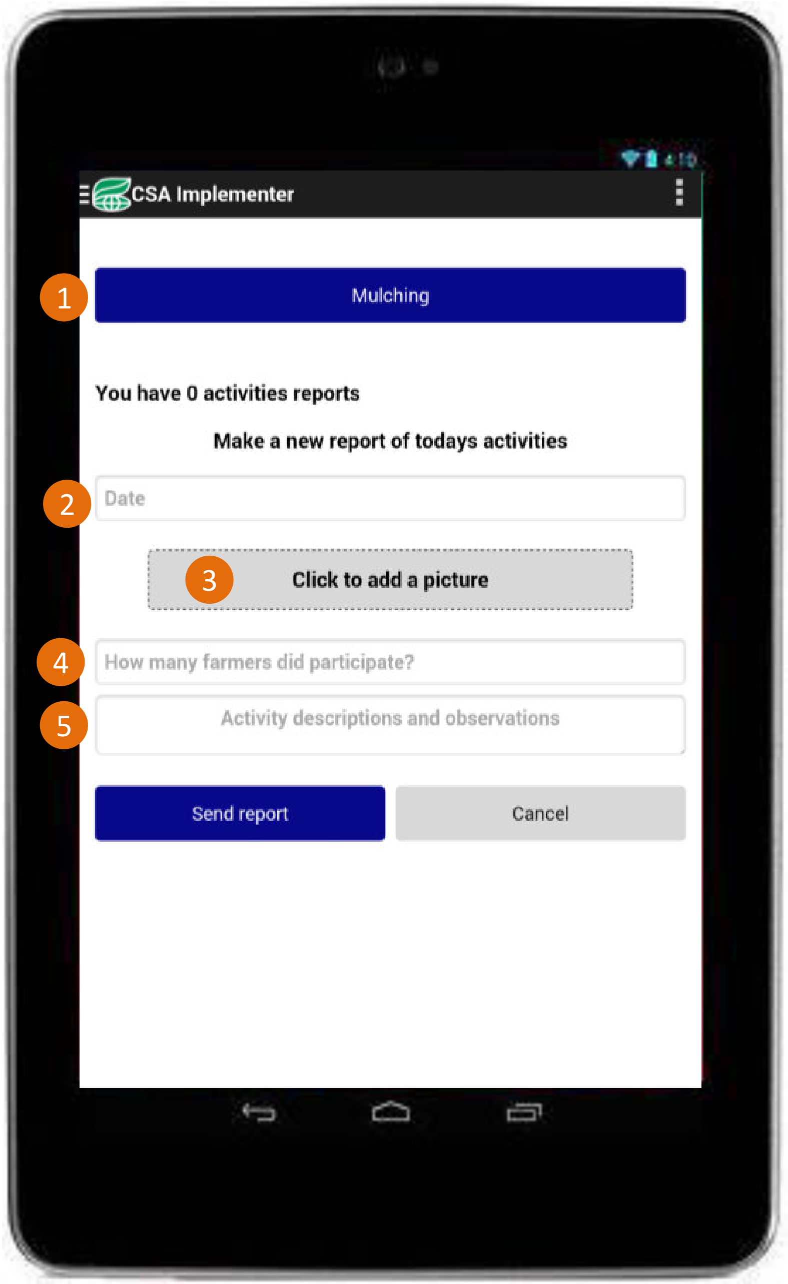
1. See basic information of the demo plot (starting date, responsible farmer, …)
2. See selected CSA practices for implementation on this site
3. Access to photo library
4. Access to Questions and answers related to this site (Q&A)



10 CSA monitoring

<u>Reporting of implementation activities:</u>

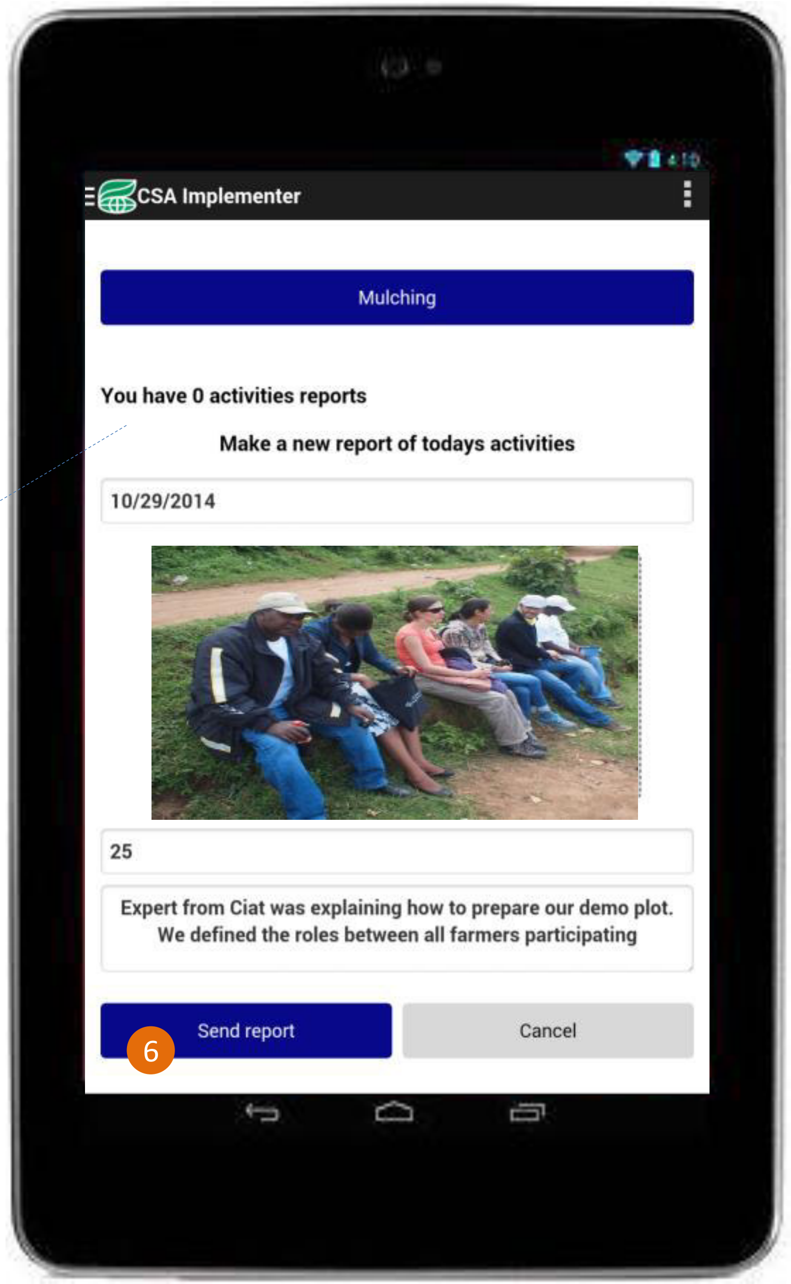
1. Select CSA practice on the main page
2. Add date of report
3. Add a picture
4. How many farmers did participate in this session
5. Make a short description of the carried out activities



Reporting of implementation activities:

6 ***SEND REPORT***

! Main view of demo plot changes to 1 available activity report



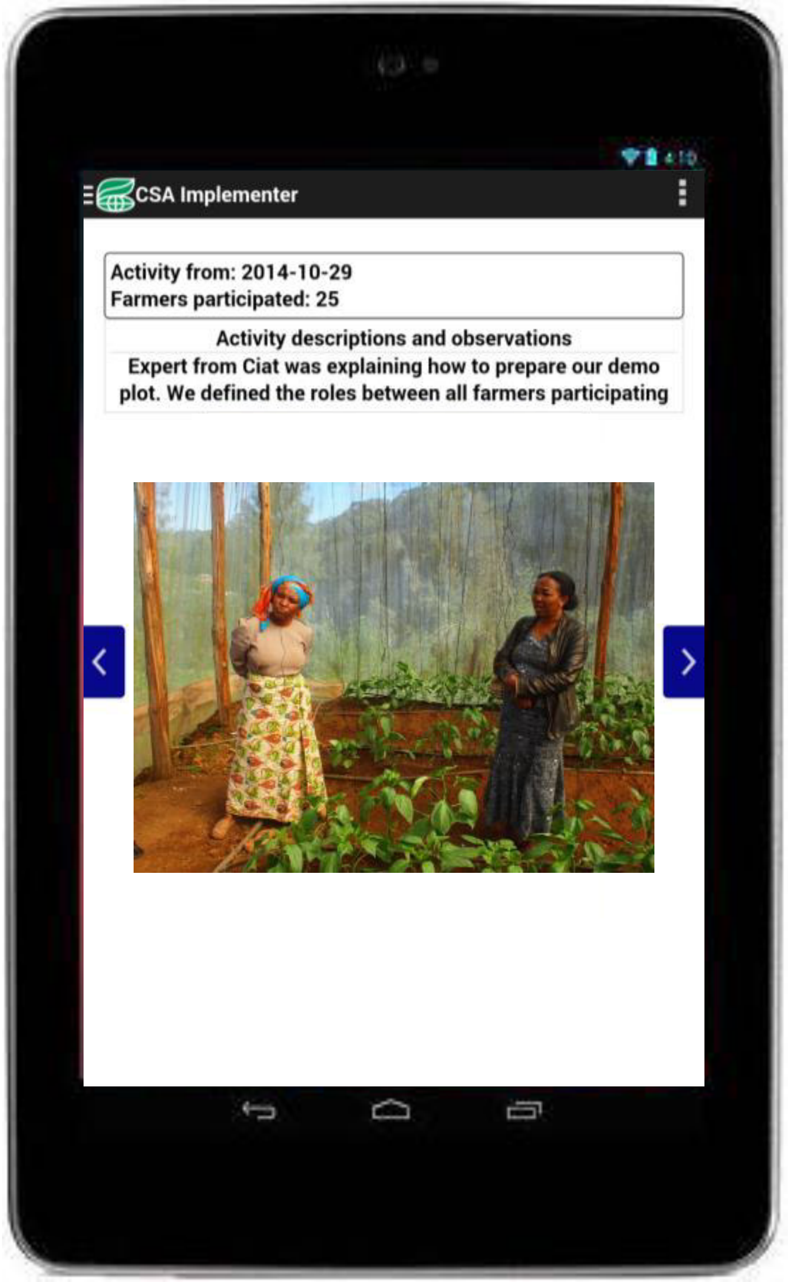
10 CSA monitoring

Photo library:

Browse all photos taken on this site

Photo

Prev Next

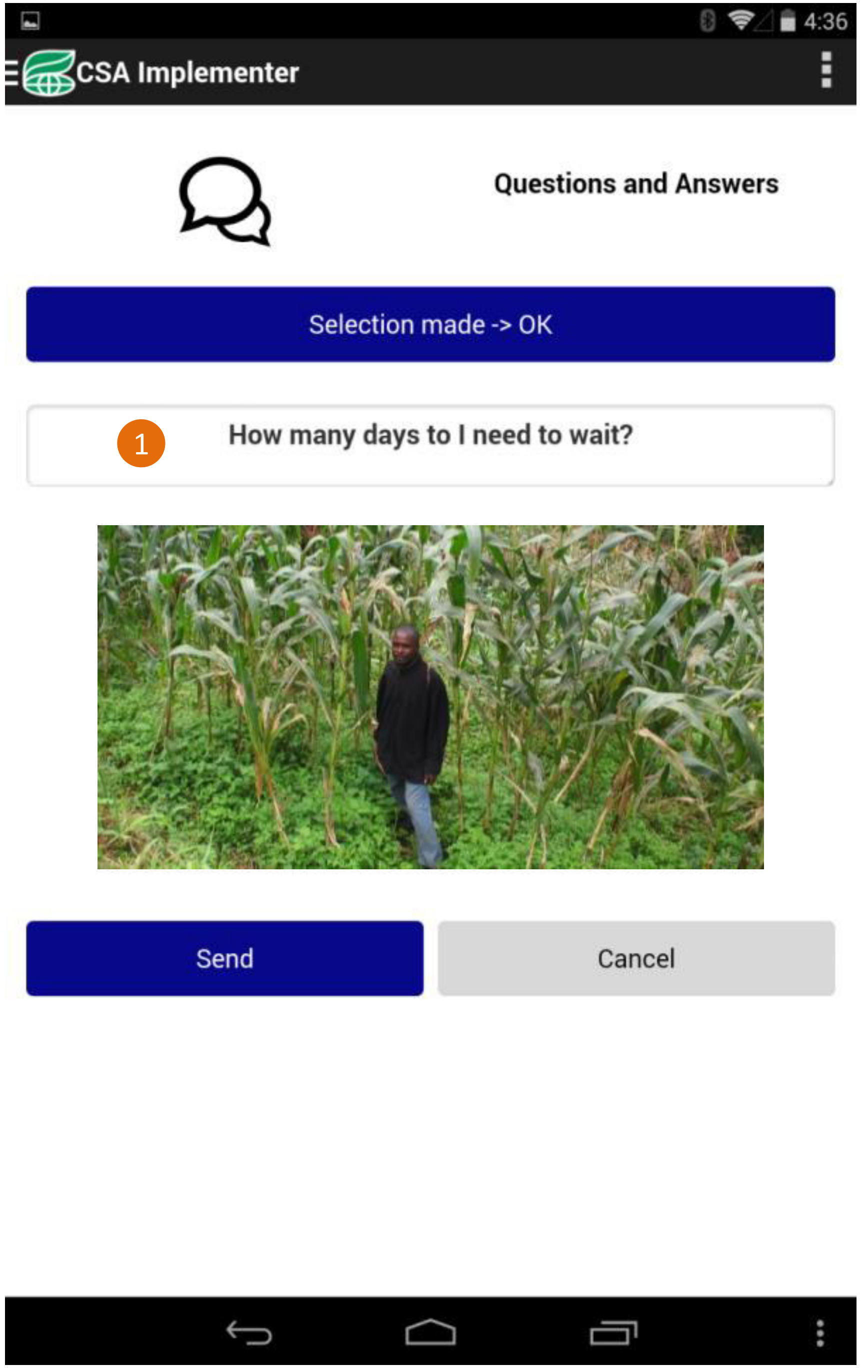


11 CSA questions/answers

<u>Q&A tool:</u>

1. During the demo plot sessions **questions** can be uploaded to the database

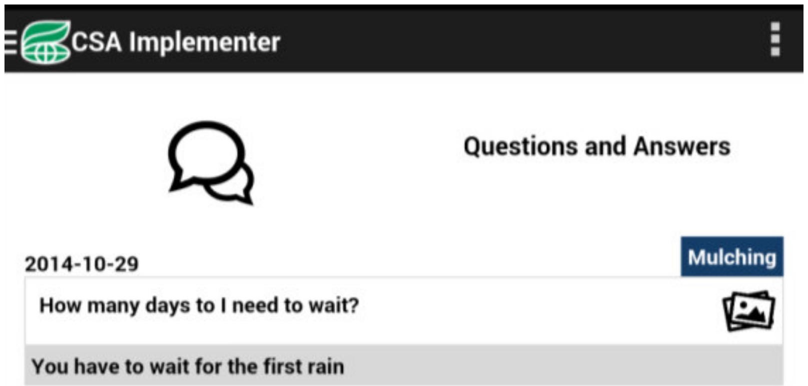
Question will be **answered by experts**



11 CSA questions/answers

Q&A tool:

The CSA web portal can be used by experts to answer questions from demonstration plots



Notification will appear when answer is available

CSA Implementer
user manual mobile app v 1.0

International Center for Tropical Agriculture
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CGIAR

RESEARCH PROGRAM ON
Climate Change, Agriculture and Food Security

CCAFS

Climate Smart Technologies and Practices: Using Science Knowledge and Expert Feedback to Accelerate Local Adoption

Design of question-tree design for Interactive Voice Response (IVR) surveys:

Knowledge, attitudes and skills (KAS) for manure compost CSA option in Lushoto Tanzania.