Exploring future changes in smallholder farming systems by linking socio-economic scenarios with regional and household models

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Abstract

We explore how smallholder agricultural systems in the Kenyan highlands might intensify and/or diversify in the future under a range of socio-economic scenarios. Data from approximately 3000 households were analysed and farming systems characterized. Plausible socio-economic scenarios of how Kenya might evolve, and their potential impacts on the agricultural sector, were developed with a range of stakeholders. We study how different types of farming systems might increase or diminish in importance under different scenarios using a land-use model sensitive to prices, opportunity cost of land and labour, and other variables. We then use a household model to determine the types of enterprises in which different types of households might engage under different socio-economic conditions. Trajectories of intensification, diversification, and stagnation for different farming systems are identified. Diversification with cash crops is found to be a key intensification strategy as farm size decreases and labour costs increase. Dairy expansion, while important for some trajectories, is mostly viable when land available is not a constraint, mainly due to the need for planting fodders at the expense of cropland areas. We discuss the results in relation to induced innovation theories of intensification. We outline how the methodology employed could be used for integrating global and regional change assessments with local-level studies on farming options, adaptation to global change, and upscaling of social, environmental and economic impacts of agricultural development investments and interventions.

Keywords

Scenarios, smallholders, household modeling, land use modeling, sustainable intensification, agriculture, dairy

1. Introduction

The role that smallholder agricultural producers are likely to play in global food production and food security in the coming decades is highly uncertain. In many parts of the tropics, particularly sub-Saharan Africa, smallholder production is critical to the food security of the poor. Industrialisation of agricultural production is occurring in many places, largely in response to burgeoning demand for food. Some smallholders may be able to seize the opportunities that exist and develop, and operate as sustainable and profitable smallholder agricultural production systems (Herrero et al., 2010; Thornton, 2010). Whether large numbers of smallholders will be able to do this in a carbon-constrained global economy and in an environment characterised by a changing climate and by increased climatic variability, will depend on many things such as increasing regulation, building social protection and strengthening links to urban areas, and substantial investment in agriculture (Wiggins, 2009; World Bank, 2009). Understanding how smallholder systems may evolve in the future is critical if poverty alleviation and food security goals are to be achieved.

In many parts of the tropics, particularly Africa and Asia, smallholders operate mixed crop-livestock systems, which integrate different enterprises on the farm; crops provide food for consumption and for cash sales, as well as residues to feed livestock, and livestock provide draft power to cultivate the land and manure to fertilise the soil. These systems are often highly diversified, and the synergies between cropping and livestock keeping offer real opportunities for raising productivity and increasing resource use efficiency (Herrero et al., 2010). Whether these systems can increase household incomes and enhance the availability of and access to food for rapidly increasing urban populations in the coming years, while at the same time maintaining environmental services, is a question of considerable importance.

Studying this question requires some consideration of theories of change. A general model of agricultural intensification originated with Boserup (1965), who described it as an endogenous process responding to increased population pressure. As the ratio of land to population decreases, farmers are induced to adopt technologies that raise returns to land at the expense of a higher input of labour. The direct causal factor is relative factor price changes, in accordance with the theory of induced innovation. At low human population densities, production systems are extensive, with high availability of land and few direct crop-livestock interactions. Population increases lead to increases in demand for crop and livestock products, which in turn increases the value of manure and feed resources and other inputs, leading to increased crop and livestock productivity. As population increases yet further, systems intensify through specialisation or diversification in production as relative values of land, labour and capital continue to change: fertilizer replaces manure, tractors replace draft animals, concentrate feeds replace crop residues, and cash crops replace food crops (Baltenweck et al., 2003).

Other factors can also play a significant role in determining the nature and evolution of crop-livestock systems (McIntire et al., 1992). In humid areas with a high disease challenge for large ruminants, crop-livestock interactions are likely to be limited owing to lower livestock densities. Other factors include economic opportunities, cultural preferences, climatic variability (e.g., droughts that lead to livestock losses), lack of capital to purchase animals, and labour bottlenecks at some periods of the year that may prevent farmers from adopting technologies such as draft power (Powell and Williams, 1993). Nevertheless, common patterns of both the drivers and the outcomes of intensification of tropical crop-livestock systems can be identified. Choice of crops and livestock interventions have been shown to be at least partly dependent on relative labour and land costs and on market access, at a wide range of sites throughout the tropics (Baltenweck et al., 2003). Furthermore, in the same study education level, market access and human population densities were shown to be major drivers of crop-livestock systems intensification (Baltenweck et al., 2003).

At the same time, alongside these larger scale drivers of farm development, the ability of smallholders to implement new practices is further determined by intrinsic system properties that may act as modifiers to their adoption. Farmers' objectives and the rules governing labour allocation and gender differentiation in the household are examples (Thornton and Herrero, 2001; Waithaka et al., 2006). Such factors are not necessarily related to spatial or macro-economic drivers; they therefore need to be studied at the farm household level.

To understand the evolution of smallholder crop-livestock systems, we propose that.

these systems should be examined at multiple levels by analysing and linking macro-level socio-economic drivers, regional-level land-use patterns, and micro-level household dynamics and strategies. Complementary methods should be used that appropriately reflect the key dynamics of each of these levels (Cash et al., 2006). The significant complexity and uncertainty associated with the interacting biophysical and socio-economic dimensions of agricultural systems should be taken into account by using a multiple scenarios approach, informed by relevant stakeholder perspectives (Biggs et al., 2007). Interactions of smallholder systems with changing contexts should be simulated and discussed iteratively with key stakeholders to explore longer-term evolutionary pathways (Kinzig, 2006).

In this paper we provide an example of this multi-level, multi-scenario, evolutionary framework for the analysis of smallholder systems, using complementary modeling approaches and harnessing relevant stakeholder perspectives. We build on the work of Baltenweck et al. (2003) and Herrero et al. (2007a) by studying the potential household-level impacts of crop-livestock intensification using crop-dairy systems data obtained from longitudinal monitoring of representative case studies and key informants (extension officers and policy makers) from Kenya. The objective of the study was to generate socio-economic development scenarios as to how crop-livestock systems in the highlands of Kenya might evolve in the next two decades and evaluate these plausible, alternative futures through a multi-level modeling framework that includes a) the development of scenarios providing different socio-economic conditions at the country level and above; b) a regional land-use change analysis projecting the spatial distribution of farming systems into the future; and c) the use of a household model to evaluate the results of the spatial analysis at the farm level, allowing for a deeper understanding of internal farm dynamics. We conclude with a discussion of the value of multi-scale, stakeholder-generated, iterative analyses in evaluating synergies and trade-offs in farming systems, particularly related to the dynamics of global change in tropical smallholder systems.

2. Materials and methods

2.1 Area of Study

The study area, which covers the highlands of Kenya is, approximately 65,000 km^2 spread over 34 districts (figure 1). The human population in the area has increased from approximately 21 to 26 million people in the last several years (Kenya Government, 2002; Kenya National Bureau of Statistics, 2010), representing about 68% of the Kenyan human population. Most people in the study area live in the rural areas. The region in Kenya is representative of many regions in sub-Saharan Africa with a similar climate and with similar scenarios for their socio-economic development, e.g. potentially increased economic growth in the rural areas with connections to the rapidly developing urban centers while still uncertainty remains about the supportiveness of the political and policy environment for these developments (e.g. southern Uganda). As such results of this analysis in terms of the driving factors behind changes and the constraints limiting economic growth in the smallholder farming sector can be seen as representative for large areas in the east African highlands.

Figure 1 about here

The soils are predominantly deep, well-drained strongly weathered tropical soils (Nitosols and Andosols) and suited for growing tea, coffee, and wheat as cash crops. Maize and beans are the predominant staple food crops. Compared with the lowlands, the highlands of Kenya have a more favorable agro-ecology for dairy and crop production and better market opportunities because of the high population numbers with a tradition for consuming milk (Staal et al., 2001; Waithaka et al., 2000).

The area has a diversity of farming systems, varying from subsistence farmers, farmers with major dairy activities, intensified farmers with limited dairy activities, and export cash crop farmers with limited or major dairy activities. Production in the Kenyan Highlands is often based on the close integration of dairy cattle into the crop production (Bebe et al., 2003). In the study area, production is typically conducted on a few acres, with a herd of crossbred cows ranging from 1 to 5 in size (usually Friesian or Ayrshire crossed with local Zebu). Crops (for food and cash) are often integrated with dairy production to diversify risks from dependency on a single crop or livestock enterprise. Dairy production is part of the farming system to produce milk for subsistence and for sale, to produce manure for supporting crop production, to provide dairy animals for savings and for social status (Waithaka et al., 2006). Mixed farming derives complementarities in resource use: crop residues and by-products from crop production constitute feeds for cattle, which return manure to maintain soil fertility and crop production, allowing sustained multiple cropping (Giller et al., 2006; Herrero et al., 2010).

2.2 Overview of Methodological Framework

The methodological framework of the research is represented in Figure 2. This framework combines complementary analytical perspectives: socio-economic conditions at the country level through scenarios, a regional/sub-national level simulating spatial land use changes, and a representation of choices and strategies at the household level. The various approaches are linked through the scenario analysis, so that both the spatial dynamics of farming systems and patterns of system evolution at the household level can be studied under similar scenario assumptions.

Figure 2 about here

Based on surveys of 2866 households, farming systems were characterized into six groups. These farming systems were used as input for both spatial and household modeling. These household data were obtained from three surveys conducted in central and western Kenya between 1996 and 2000, as part of a collaborative effort to characterize smallholder dairy systems from the Kenyan Ministry of Livestock Development & Fisheries, the Kenya Agricultural Research Institute (KARI), and the International Livestock Research Institute (ILRI) (http://www.smallholderdairy.org/).

A household questionnaire was completed through single interviews with the household head or in his/her absence, the most senior member available or the household member responsible for the farm. The questionnaires were divided into sections covering household composition, labour availability and use; farm activities and facilities; livestock inventory; cattle feeding, dairying with emphasis on milk production and milk marketing; livestock management and health services; household income and sources; and cooperative membership and milk consumption. Along with the survey data, each surveyed household was geo-referenced.

The households were grouped using an expert-based classification using the following criteria: i) cultivation of only food crops or cash crops for the local market or cultivation of cash crops for export; ii) level of external inputs, captured by the extent of inorganic fertilizer used and an area with fertilizer below or higher than 25% of the cropped area; and iii) level of milk production, captured by cattle milk density, below or above 1000 l milk per ha per year. Figure 3 presents the rationale behind the classification.

Figure 3 about here

2.3 Socio-economic scenarios developed with regional experts

Different socio-economic environments modulate how farming systems may evolve in the future under different sets of policy and demographic conditions. These conditions are complex, uncertain, and linked across global, (sub)continental and national levels. To adequately capture the notion that smallholder farmers might face significantly different futures, we developed scenarios. Scenarios are a set of alternate narratives in words and/or numbers that describe plausible ways in which the future might unfold (van Notten et al., 2003; Kok et al., 2007). Scenarios can be viewed as a linking tool that integrates qualitative narratives or stories about the future and quantitative formulations based on formal modeling (Alcamo, 2008; Volkery et al., 2008) . As such, scenarios enhance our understanding of how systems work, behave and evolve, and so can help in the assessment of future developments under alternative policy directions (Kok et al., 2011). In this case study, scenarios were also used to connected different levels of analysis by exploring smallholder developments under similar assumptions and socio-economic conditions.

The recognition that socio-economic systems are complex and uncertain and may offer widely diverse challenges to smallholders prompts the need for the involvement of stakeholders with long expertise from different sectors, such as policy or the private sector, in the focus region (Wilkinson and Eidinow, 2008). The involvement of such stakeholders also makes it more likely that researchers ask appropriate and locally relevant questions (Xiang and Clarke, 2003). In the case of our study, three scenarios were adapted based on the inputs from planners, policy makers, researchers and organizations interested in Kenya's future agricultural development during several meetings and stakeholders' workshops. More details can be found in Van de Steeg et al. (2007).

Prompted by these stakeholders, we used Kenya's Economic Recovery Strategy for Wealth and Employment Creation (ERSP) scenario (Kenyan Government, 2003) as an explicitly normative, desired scenario for the region that focuses on equitable rural development. However, the stakeholder engagement also yielded two less optimistic scenarios: a scenario where development largely fails, and a scenario where inequitable growth dominates. We refer to these scenarios as the "equitable growth", "baseline " (= low growth) and "inequitable growth" scenarios, respectively.

The projected growth trends for the coming 20 year assumed under the different scenarios, described in Table 1, were translated into new spatial data layers for the drivers of the spatial analysis; for the farm level analysis, scenarios were translated via modifying different parameters and restrictions in the household model. Table 1 describes the various assumptions made for these scenarios. The resulting temporal data layers are called dynamic data layers here, as opposed to static data layers which are assumed not to be affected by the different scenarios.

Table 1 about here

The equitable growth storyline describes the future of Kenya with both political and economic reform, and represents the outcomes planned under the Economic Recovery Strategy for Wealth and Employment Creation. The policy and institutional environments are characterized by functioning institutions and policies, and strong capable oversight institutions to address issues to support economic growth. There is a strong commitment to market-based solutions in order to obtain an optimum balance between demand and supply of goods, services and environmental quality at national and international levels. Under this scenario the Economic Recovery Strategy for Wealth and Employment Creation is fully and successfully implemented. Efficient policy institutions contribute to the enhancement of the agricultural sector. Expected rates of growth and investment as presented in the Economic Recovery Strategy for Wealth and Employment Creation official documents are used to quantify the changes in the spatial data layers over time.

The baseline (= low growth) scenario describes the future of Kenya with inefficient institutions, and a failure to address slow economic growth, unemployment and poverty. The political dilemma is characterized by poor policy formulation and weakness of oversight institutions, such as parliament, to create a favorable policy environment. In this scenario, Kenya continues to slide into 'the abyss of underdevelopment and hopelessness' (Kenya Government, 2003) as no attempts are undertaken for economic recovery. The political environment contributes to the deterioration or at best stagnation of the agricultural sector. Past trends are used to quantify the dynamic spatial data layers under consideration.

The inequitable growth storyline describes the future of Kenya with inefficient institutions and inequitable economic growth. Economic growth is localized, brought about by initiatives of individuals and the private sector, with limited facilitation by the government. Market development and infrastructure are relatively good only in areas with export-led agriculture. In these areas agriculture technology development is also strong, mostly focused on cost reductions and yield increases. There is an increase in agricultural productivity in the large-scale production of cash crops for the international market. In these areas there are local off-farm income opportunities available for rural people via wage labour in commercial farming, with some rural development and income multiplier effects. Under this scenario the Economic Recovery Strategy for Wealth and

Employment Creation is only partly implemented and not all Kenyans benefit, particularly not smallholders.

2.4 Spatial Analysis Model

A specific farming system is expected to occur at locations with conditions that best fit that type of farming system at that moment in time. Logit models were used to predict the relative probability for the different farming systems at a certain location and at a certain time, with the farming systems as dependent variable and location characteristics as explanatory variables (Van de Steeg et al, 2010). The explanatory variables considered in the analysis are chosen based on the analysis described in Staal et al. (2002), by linking spatial measures to the perceived real decision-makers, thus matching the spatial and behavioural units.

The mapping of the spatial distribution of farming systems is described in Van de Steeg et al (2010). Linking farming system choice and drivers of change is a key element of this research effort. Based on the biophysical and socio-economic conditions of a location, the fitted logit models were used to calculate the probabilities of finding different farming systems across the study area. The individual probability maps for the different farming systems were combined into an overall map indicating the spatial distribution of farming systems given the relative probabilities and the region-wide prevalence, by means of an iterative procedure (Verburg et al., 2002). A simple classification by assigning the location to the farming system with the highest probabilities is not appropriate, as this would reflect the prevalence of farming systems in the original sampling which is not representative for the entire study area. Instead, the allocated area of each farming system is determined by an estimate of the surface area of each farming system type occurring in the study area. The distribution of farming systems, at the base year, is derived from an external database (CBS, 1997) that was considered to contain a representative sample for determining the prevalence of the different farming systems.

Over time, the surface area of different farming systems is determined by the demand for certain agricultural commodities, i.e. how much of each agricultural commodity is required to satisfy the needs of the changing population. We considered the four most important commodities for the study area; maize, beans, tea and milk. Using the initial estimate of the surface area and the total demand for the commodities based on FAOSTAT, the percentage of production of each commodity supplied by each farming system is estimated.

Next, using average consumption data, growth in gross domestic product (GDP) per capita under the different scenarios, and income elasticity of the demand for four commodities, the evolution of the demand for the different commodities by year and by scenario is predicted. Consumption data were derived from FAOSTAT. Income elasticity demands were derived from USDA (2013); we used 0.58, 0.81, 0.9 and 1.6 for maize, beans, milk and tea respectively. We assumed a growth in gross domestic product per capita of 0.7%, 4.7%, and 2.7% for the low, equitable and inequitable growth scenario respectively (Kenya Government, 2002; Kenya Government, 2003).

Based on the evolution in the demand for commodities, it is possible to predict the change in farming systems, using the contribution of each farming system to the production of the different commodities (under the assumption of similar productivity by cluster). The map with farming systems distribution at the base year, the set of static and dynamic spatial data layers, and the logit models that relate the probability of occurrence of farming systems to location characteristics were used as input to a spatial and temporal model of farming systems dynamics. Scenario analyses were performed with the CLUE-S (the Conversion of Land Use and its Effects at Small regional extent) modelling framework. CLUE-S is specifically developed for the spatially explicit simulation of land-use and farming system change based on an empirical analysis of location suitability combined with the dynamic simulation of competition and interactions between the spatial and temporal dynamics of land-use systems (Verburg et al., 2002).

Based on the demand for certain commodities, i.e. an estimate of the prevalence of the different farming systems, the predicted probabilities are corrected in an iterative procedure to obtain a classification that reflects the prevalence correctly as well as the relative probabilities calculated for the different locations. For farming system types

where the allocated area is smaller than the demanded area the value of the iteration variable is increased. For land use types for which too much is allocated the value is decreased. Through this procedure it is possible that the local suitability based on the location factors is overruled by the iteration variable due to the differences in regional demand. The procedure followed balances the bottom-up allocation based on location suitability and the top-down allocation based on regional demand.
For each scenario a sequence of maps with the spatial distribution of farming systems over time was generated following the method described above. From this we were able to simulate the trajectories of farming systems change for each scenario.

2.5 Household Modelling

Clustering Procedure for Household Characterization

In order to identify case studies that could have diverse pathways of evolution inside each predetermined class (see Figure 3), a further classification of farms was performed and each class was further divided into three sub-groups representing the variability within each class.
From the variables of the initial dataset, those that could change over time included land size, cropped area, level of education of farmer, milk production, herd size, and family size. Rather than grouping the farms using a cluster analysis on these variables, a Principal Component Analysis was first performed by class in order to observe if there were relationships between these variables and to check that the same factors could be identified in each of the six classes, i.e. the importance of variables when explaining heterogeneity was similar between classes.

Factor 1 in the Principal Component Analysis was *Farm Size* (a combination of land and herd size) for all classes. Other factors were defined by only one variable (*Family Size, Milk Production* and *Education Level*) and changed relative positions depending on the class. With these factors obtained from the Principal Component Analysis, a hierarchical cluster analysis (by predetermined class) was performed using Ward's method of aggregation. Non-hierarchical clustering and other methods of aggregation were also tested but results were less satisfactory as resulting sub-clusters were unbalanced. To improve clustering performance and avoid distortion from outliers, these were eliminated from the analysis using the TRIM option of Statistical Analysis System (SAS, 2001). The final clustering process resulted in the definition of the same 6 classes as in the expert opinion exercise (Figure 3), but now with three sub-groups in each of these classes systematically representing the diversity within each class. .

Description of Case Study Households

From the final 18 household groups (six classes and three sub-groups in each), a representative case study farm was selected. The IMPACT household characterization tool (Herrero et al., 2007b) was used to collect detailed information from each case study household on general system characteristics (location, system type, agro-climatology, for example); land management (crops and fodders planted, growing seasons, for example); livestock and their management (species, animal numbers, feeding systems); household composition and farm labour; and inputs and outputs (cash, labour, food, nutrients, stock and other assets).

IMPACT analysis and subsequent household model analysis were performed for each of the 18 case studies. Here, because of the large quantity of results produced (18 case studies by three scenarios by four periods of time), only three contrasting case study households will be presented.. These are heterogeneous in terms of size, structure and orientation of production. The three case studies correspond to the following: 1. *Subsistence farm with dairy* (class 2: food crops or cash crops for domestic market only, no or low external inputs and high dairy); 2. *Intensified farm with dairy* (class 4: food crops or cash crops for domestic market only, high external inputs and high dairy); 3. *Export oriented farm with dairy* (class 6: cash crops for export, high dairy).

IMPACT also computed a range of simple indicators of farming systems in terms of monthly cash flows, the family's monthly nutritional status, annual soil nutrient balance, and labour use efficiency (Herrero et al., 2007b). The main characteristics of the three case studies are shown in Table 2.

1. *Subsistence farm with dairy*.

The household consists of eight members (five of them working on the farm). Farm size is 2.46 ha (only 18.7% owned), from which 2 ha are pastures, mostly cut-and-carry pastures. The only crops in this farm are maize and beans. Fertilizer and hybrid seeds are used but in very low amounts. Labour is hired to meet additional requirement for feeding cattle, planting, weeding and harvesting. The herd structure consists of three female calves, four cows, one young bull and one reproductive male, which is used for serving farmers' cows in the area, bringing some income to the farm. The breed of cattle kept is Friesian and the major purpose is milk production. The cattle are zero-grazed all year round and are fed on Napier grass, maize stover and concentrates.

The main source of income for the family is the sale of milk; very little surplus of food crops is sold. The household also gets some off-farm income (20.8% of total household income) by doing wage work on other farms. The household's major costs are related to food crop production, with comparatively few livestock costs and other expenses (off-farm food, children, school fees, etc.). Annual income per person and per ha are medium in relation to the other case studies.

Most energy and protein sources come from the food crops and milk produced on the farm, but the family is not able to meet the World Health Organisation energy requirements (deficit of 11.6% of total family requirements).

Table 2 about here

2. *Intensified farm with dairy*.

This household consists of seven members (four working on the farm). Farm size is 1.4 ha (43% owned), from which 0.4 ha is dedicated to crops and the rest to grazing pastures. The major crops are maize, beans, bananas and kales. The main cash crop is kale, although some beans and bananas are also sold. Fertilizer is mostly used on maize and pesticides are applied to kale. One Ayrshire cow and its calf are kept for milk production. They graze on communal land and are also stall-fed with Napier grass, crop residues and concentrates.

Most agricultural income for the household comes from kale and some milk. Some off-farm income is obtained through wages received from work on other farms by the household head and his wife, accounting for 18.8% of total household income. Livestock keeping costs are more important than those due to agriculture, because of little hiring of labour for cropping activities. Economic results are the poorest of the three case studies.

Similar to the previous case study, most energy and protein sources come from the food crops and milk produced on the farm, and the family is nearly able to meet the WHO energy requirements (deficit of 1.3% of total family requirements).

3. *Export-oriented farm with dairy*.

This household consists of six members (four working on the farm). The household head has twelve years of education. Farm size is the biggest of all the case studies with 4.8 ha (all owned), from which 3.7 ha is dedicated to crops and the rest to cut-and-carry pastures. Main crops are for export (tea, coffee and passion fruit) and the other crops (beans, maize and potato) are for family consumption. Casual labour is hired to meet the requirements of land preparation, planting, weeding and harvesting. Fertilizer, pesticides and hybrid seeds are used in substantial quantities. This household keeps highly improved Friesian cattle (two calves, two heifers, one young bull and four milking cows). A long-term labourer has been hire to take care of the cattle. The system of feeding is zero-grazing, with Napier grass, crop residues, concentrates and brewers by-products.

The only household income comes from agriculture and milk, the last being slightly more important than export crops. Livestock keeping costs are comparatively low in relation to the costs of cropping (casual labour and inputs). Economic results - globally, per person and per ha - are the best of the three case studies.

This family is able to meet largely its World Health Organisation energy and protein requirement, and contrary to what was observed in the previous case studies, the main source of food is purchased, although only a low proportion (6.8%) of total income is spent in purchasing food.

Household Modelling

The IMPACT tool was linked to a household linear programming model and used to generate the data files that this model needed to run (Herrero et al., 2007b). The Household model allows the identification of the optimal combination of activities to achieve an objective function subject to the constraints of the system. It is based on a linear programming optimization model developed in Xpress-MP. The household model structure and functioning are presented briefly below; further details can be found in the supplementary information.

The objective function was to maximize farm gross margin: *crop sales + livestock sales + other income – crops inputs – livestock inputs – labour – food purchase – other expenses*.

The decision variables in the household model included the following. Land use (management options for plots). Dairy orientation (optimal number of dairy cows). Feeding strategies for cows and herd structure, these are not optimized and only the observed current situation is considered. Therefore, observed milk production per cow is constant. Use of commodities (eaten by the family, sell, buy, store, feed the animals, leave as fertilizer).

Some key constraints were related to food security (food needs by the family in each month), seasonal labour availability, cost and demand; seasonal prices, market demand, food storage, the range of cropping and livestock activities; and annual cash flows, which are essential for investing in new activities or for dealing with specific cash demands at certain periods during the year.

The household model developed by Herrero and Fawcett (2002) and used in previous modeling studies in smallholder systems (Waithaka et al., 2006; Gonzalez Estrada et al., 2008; Zingore et al., 2009) was further adapted for multi-time period modeling, running in monthly periods in steps of five years from 2005 to 2025 (see supplementary information for the description of the model). Optimization occurs annually, and results from the previous year were used as the starting point for the next year. Additional activities such as new cropping options could be included in the household model, allowing the farming systems to change orientation of production or intensify.

Trajectories of change were defined through a transition matrix (Table 3) to allow one type of system to evolve through time into another, and this could occur after one run of five years – for instance, a farmer could evolve from being a subsistence farmer to become a farmer growing cash crops and/ or having more intensive dairy production. The transition matrix constitutes a logical "roadmap" of how a system might evolve into another as time progresses, and this roadmap is different for the different scenarios defined above. With this approach we add a degree of realism to systems' change.

Table 3 about here

To translate the drivers described in Table 1, which define the trajectories described in Table 3, into the information requirements of the household model, projections of different variables that changed according to scenario, specific location of the case study and period of time were carried out. These related specifically to *land size* and *opportunity cost of labour*, as it was considered that these two variables were most directly affected by the projected demographic and off-farm employment projections in the alternative scenarios (Baltenweck et al., 2003). Real values of land size and cost of labour and projections through time are represented in Figure 4. We assume changes in crop and livestock production due to climate change in the time window up to 2025 are small compared to the socio-economic changes that are represented here, i.e. price changes and changes in land size.

Figure 4 about here

Several assumptions had to be made to run the household model. These are described below.

Assumptions on intensification trajectories: transition from subsistence farming systems to intensified systems was simulated through an increase in the use of fertilizers and expected yield improvement for the major food and cash crops: maize, beans and potato. The DSSAT models (Jones et al., 2003) were used to produce fertilizer response curves for these main crops.

Assumptions on export-oriented trajectories: to simulate transition of cash- and food-oriented farming systems to export oriented farms, a new cropping option was introduced, that of growing passion fruit. According to the stakeholders consulted and the Kenya Agricultural Research Institute, this is a promising cash crop in the Kenyan highlands. For the new cropping option, information on yearly requirements of inputs (fertilizers, pesticides, etc.) and labour on a monthly basis, establishment costs, yields, and prices were obtained from Kenya Agricultural Research Institute scientists and other expert opinion.

The first trajectory considers changes in labour cost and land size, and values of these two driving forces are different by scenarios to mimic the scenarios narratives. The values of these two variables by scenario are presented in Figure 4. Under the first trajectory, the number of cows is also a decision variable. Compared with the first trajectory, the second trajectory considers change in labour costs and land size, and the number of cows is still a decision variable; in addition, the model is set to choose whether to start growing passion fruit and whether to intensify crop production (captured by applying fertilizer on the maize and beans plots).

Figure 4 around here

Assumptions of simulations across 20 years: to run the household model for a period of 20 years, four periods of five years each were considered, and optimisations were done annually. The final output obtained from one period in terms of optimal land use and number of cows was used as the initial conditions for the next period. To do this, non-annual costs (for example, establishment cost of crops or cost of purchasing new cows) were divided by five.

When running the household model for the case study households with observed data, calibration of the model for specific constraints was needed. Although the household model has quite an elaborate set of constraints, they are still somewhat generic and cannot reflect farmer behavior exactly; and they may not reflect specific local conditions, such as limited amounts of inputs being available due to local market restrictions, for example. Therefore, a process of calibration of some model constraints was carried out. This usually involved modifying the market prices of some commodities to reflect the internal transaction costs incurred by the household. When results of the household model came near the observed results in the farm, the specific model (called 'optimal base' in the results shown below) constituted the starting point for subsequent runs.

We did not perform a systematic sensitivity analyses for each of the case studies, but in this study the scenario analyses, with its diverse socio-economic pathways provide substantial parameter variability to understand how farming systems are likely to evolve under different conditions. Similar observations were made recently by Claessens et al. (2012).. Scenarios were analysed for three different farm types, for different input settings and over three periods of time, and the results obtained in this analyses show which drivers, variables and parameters captured in this setup are most important in driving changes in the functioning of the farm households. This methodology also determines whether the household model is sensitive enough for detecting change caused by the socio-economic scenarios (see Figure 4) against this background of substantial variability.

3. Results

3.1 Spatial Modelling

3.1 Spatial Modelling

In order to map the spatial distribution of farming systems over time, first the surface area demanded by certain agricultural commodities of the different farming systems is determined for the base year (Van de Steeg et al., 2010). Table 4 presents the percentage of production of certain agricultural commodities supplied by each farming system. Note that farming system classes two and four were combined, since the number of households in these two categories was very small. The last category represents the non–agricultural households.

Table 4 about here

The evolution of the demand for the different commodities by year and by scenario is predicted. Table 5 summarizes the demand for the different commodities (tons/year/person).

Table 5 about here

The combined annual changes in the demand for different commodities (Table 5) will change the surface area of the different farming systems (Table 4) accordingly. Table 6 provides the estimates of the distribution of farming systems over time, driven by the evolution in the demand for commodities.

Table 6 about here

Based on the evolution in the demand for commodities, it is possible to predict the spatial trajectories in farming systems. Farming systems change is found all over the study area (Figure 5), but especially in the neighbourhood of urban areas where population density is high and where there are many possibilities for off-farm income generation. Besides demand, changes in farming systems are also driven by the variability of the spatial variables (Table 1). As spatial variables are changing over time, the optimal occurrence of a certain farming system for a given location will change (Table 7). Consequently, a reallocation of land takes place between farming systems. Between 15 to 25% of the study area is likely to change for the different scenarios (Figure 5), and this range is used as the basis for defining the three scenario storylines that are the outcomes of the CLUE-S model exercise.

Figure 5 about here

The preference for certain farming systems for a specific location is determined by several household and spatial variables. It is not possible to derive a dominant explanatory factor that leads to the change of one farming systems to another at a regional level. The trajectories of farming systems change constitute a complex system driven by many household and location characteristics, both static and dynamic.

Table 5 about here

Baseline scenario

About 20% of the surface area of the study area was projected to change in this scenario, so the midrange value of the predicted range is shown in Figure 5. Of this, more than 50% of the farming systems change into export-oriented farming systems. Most important trajectories of change were from subsistence and intensified farmers with limited dairy activities to export cash crop farming with limited dairy activities.

Equitable growth scenario

About 25% of the surface area of the study area was projected to change for this scenario, the highest value of the range predicted in Figure 5. Of this, more than 61% of the farming systems changed into export-oriented farming systems. Also for this scenario the most important trajectories of change were from subsistence and intensified farmers with limited dairy activities to export cash crop farming with limited dairy activities.

Inequitable growth scenario

About 15% of the surface area of the study area was projected to change for this scenario, the lowest value of the range predicted in Figure 5. Of this, more than 40% of the farming systems changed into export-oriented farming systems in the zone without large-scale farming, and about 25% in the zone with large-scale farming. For this scenario the most important trajectories of change were intensified farmers with limited dairy activities to export cash crop farming with limited dairy activities, and from export cash crop farmers with limited dairy activities to intensified farming or non-agricultural activities.

3.2 Household Modelling

Results are presented for three case studies (Figures 6, 7 and 8) under the different scenarios, for a time horizon of 20 years (in five-year periods, results of 2005-2010 and 2020-2025 are presented) and for one or two trajectories of change, as described in Table 4. Observed data, the optimal solution "optimal base scenario" after the fine tuning process, under the current circumstances in terms of input/ output prices, land area and labour availability, and the results of the scenarios are also presented in Figures 6, 7 and 8.

Evolution of the Case Studies

Subsistence with dairy (Figure 6): This case study is defined by a medium size family with intermediate land area (2.46 ha) and relatively large herd size. The "optimal base scenario" indicates maintenance of milk production and concentration on production of maize and beans.

In the baseline scenario, in combination with Trajectory 1, dairy declines gradually from period 1 through 4 from eight cows in the first period to five cows in the last period, due to decreasing land size that reduces land availability for food crops and cut-and-carry forage. Hired labour decreases drastically and there is a higher dependency of the household on basic off-farm staple food and forages.

In Trajectory 2, dairy declines drastically in the first five years and then remains constant as from the second period; this occurs because the farmer starts to grow passion fruits that are more profitable than dairy. With decreasing land size over time, however, the farmer has to decrease the land allocated to this enterprise in the subsequent periods.

In this scenario, the farmer increases the land under maize intercropped with beans, which suggests a move towards increased farming for subsistence food crops (the farmer intensifies the crop activities by applying fertilizer on the maize-beans plot) and at the same time starts to export crops to improve economic output. Hired labour evolves following the requirements of the passion fruit crop. Other results of the model, not shown here, were that the dependency on off-farm staple food decreases, and the dependency on purchased forages increases.

Under the "equitable growth" scenario, the farmer maintains the dairy herd due to land consolidation (the farmer can allocate more land to fodder), despite the increase in labour costs that could have potentially negatively influenced the decision to keep cattle. The biggest change in land use is the proportion of land dedicated to maize and beans, with the aim of improving food security in the household and selling the surplus. Hired labour increases due to the larger cropping area.

In Trajectory 2, the number of cows on the farm decreases in the first period (due to substitution of forage area for passion fruit), but the number increases again afterwards when land area enlarges. It is important to notice that the farmer only starts growing passion fruit if cash is available to start this activity, which has high initial costs. Cash is also available to use fertilizer on the maize-beans plot. In the first period there is a higher dependency on off-farm staple food and forage, but decreases in the second and third periods. Hired labour use increases largely due to the cultivation of passion fruit.

In the "inequitable growth" scenario, with labour costs and land size values being "intermediate", the results of the household model are also in between those observed in the other two scenarios. Trajectory 1 is stable and similar to the "optimal base" (land remains constant). In Trajectory 2, the number of cows decreases drastically as the farmer chooses to grow passion fruit, taking up land at the expense of planted fodder. More land is also allocated to maize and beans where fertilizer is applied to increase yields.

Figure 6 about here

Intensified with dairy (Figure 7): This case study also refers to a smallholder farmer but now with a high proportion of off-farm income. The "optimal base scenario" slightly increases the amount of land used for food and cash crops (maize and beans) at the expense of the grassland area, but maintains the dairy activity.

Under the baseline scenario and Trajectory 1, the dairy herd is maintained from the first to the fourth period despite the decline in grazing resources due to the decrease in land holdings (through increases in the purchase of Napier grass forage). There is no major change in the cropping patterns under this trajectory, except that the kale cropping area doubles to generate more cash.

In Trajectory 2, when passion fruit is an option, the farmer starts the activity (cash is available from previous periods) and decreases the land for dairy (cut-and-carry forage and natural pastures), thereby reducing herd size in the last period. Fewer food crops are grown (maize intercropped with beans and bananas), together with less area for kale in the final period. No additional fertilizer is applied. Therefore, there is a higher dependency on off-farm staple food and forage. Hired labour needs to be increased to deal with the requirements of passion fruit.

The results obtained in the "equitable growth" scenario are similar to those in the baseline scenario. This can be explained by the fact that land size increases marginally for this farmer. It is worth noting that some land is left unallocated during the last period of the second trajectory, suggesting that high costs of labour under this scenario prevented the farmer from increasing high labour-intensive activities such as dairy or passion fruit production.

The evolution of the trajectories under the "inequitable growth" scenario shows similar results to the previous scenario except that the farmer maintains his dairy herd even when growing passion fruit. This is explained by the fact that under this scenario the cost of labour increases less than in the equitable scenario; and only a marginal part of the land is left unallocated.

Figure 7 about here

Export oriented with dairy: This case study involves the biggest farm (4.8 ha) and the one with the highest diversification of activities (dairy and several export crops). All income comes from the farm and the profit obtained is the largest of all the case studies. The "optimal base simulation" slightly increases the amount of land dedicated to export crops (coffee) at the expense of grassland and planted fodder. A large amount of food is purchased from outside the farm (maize and bananas).

It is important to notice that, due to the peri-urban location of the farm, close to the capital city Nairobi where population densities are higher and where there is a higher demand for land for non-agricultural activities, the evolution of land size is opposite to that observed for the other case studies. This means there are increases in land size in the baseline scenario and decreases in the "equitable growth" scenario. For similar reasons, prices of hired labour increase in all scenarios but at a higher degree than for the other case studies (Figure 8).

Under the baseline scenario, dairy is maintained similar to the "optimal base" results throughout all four periods but there are some differences in land use. In the first period food crops (bananas and maize) disappear completely at the expense of cash crop coffee which continues increasing up to period 3, after which there is a shift to more land being dedicated to passion fruit in the last five years. This is due to the more expensive cropping cost of coffee (due to a higher demand of labour). In the third period, the food crops (potatoes and beans) increase as the available land increases, but declines in the last five years due to the high labour cost in the area. Total labour requirements remain constant through time and there is an increment in the dependency on some staple foods such as maize and bananas and also forages.

In the "equitable growth" scenario, this farm experiences a decrease in land size. All activities (including passion fruit) are reduced except dairy, which is maintained (although the herd size is slightly reduced in the last period); and this despite increased labour costs. This move towards more specialized dairy activities near cities is consistent with previous studies that showed that dairy is profitable near cities despite high farming costs, because of high demand for milk translating into a higher milk price. In this way, labour requirements are decreasing with land size and at the same time, dependency on off-purchases increases.

The "inequitable growth" scenario offers intermediate results between those observed for the previous two scenarios. Land allocated to coffee decreases substantially and becomes zero at the end of the 20-year period. On the other hand, passion fruit and dairy activities are maintained, despite the increased labour costs and slightly decreased land size. In this scenario, more land is allocated to food crops because the decrease in land size is lower than under the equitable scenario.

Figure 8 about here

4. Discussion

Intensification, diversification and plausible change in the Kenyan highlands

Our study attempted to explain trajectories of intensification and diversification in the Kenyan highlands using theoretical concepts of induced innovation. While in general terms the findings of our study confirm the importance of relative factor prices (land, labour) for establishing the trajectories of change, we also found that different farming systems would react differently depending on the choices available and the prevailing socio-economic climate (modeled through different scenarios in this study). These findings are clearly relevant for regions with similar agro-ecological and socio-economic conditions, i.e. for larger areas in the east African Highlands.

Under the conditions studied, dairy is maintained or reduced in the period 2010 - 2025, and never increases in any of the scenarios. Land pressure is very strong and as a result, not much land is available for pastures and forage. Communal pastures are limited and land is preferentially allocated to food or cash crops when population density increases and land size decreases. With the spatial model, a shift towards export-orientated farming of cash crops was projected in all scenarios, with no or little increase in dairy. Especially in the neighbourhood of urban areas where population density is high and where there are many possibilities for off-farm income, changes in the predicted farming systems occur (the household model projected diversification through high value crops). In the household modeling exercise, land size and cost of labour relative to land returns are the determining factors for the evolution of farming systems. These variables, together with commodity prices, determine the economic possibilities within the farm and constrain the development of the farm towards activities that generate cash and are efficient in the use of land (Baltenweck et al., 2003; McIntyre et al., 1992).

Applying the two modeling approaches to the same study area gave valuable additional information because model detail is different between the two and changes in farming systems are described differently. Whereas the spatial model is determined by statistical relationships that are based on current distributions of farms, the household model is an optimization model, which assumes the farmer to be a ‘Homo economicus’. Both approaches have their limitations for exploring future development pathways, but if the two different approaches project similar patterns of evolution, this can give more credibility to the plausibility of the findings from each tool. Both tools quantify a change towards land intensification and cash crop production (diversification). The household model shows that a substantial increase in milk price is needed for a further increase in dairy production.

Whereas the spatial land-use model showed only the potential shift in farm types in space and time, and the results over the scenarios were quite similar, the household model showed smaller changes in the activities within a certain farm type, and showed clear differences between the scenarios. The baseline scenario, meaning low economic growth, unemployment and raising poverty, will mean, in most locations, relatively larger proportions of rural population and therefore higher pressure on land, with average farm size decreasing. In smaller households (case studies 1 and 2) this could lead to a shift towards subsistence farming, with more cultivation of food and food and cash crops at the expense of pastures and forage areas, and therefore probable a reduction in dairy activities. Hired labour would decrease as a consequence of this evolution towards subsistence farming.

In locations where rural migration to cities could expand, as in case study 3 located close to Nairobi, farm sizes could remain the same or even increase. This situation does not necessarily imply an increase in dairy production if milk prices in informal markets remain the same. In addition, the costs of hired labour could make some labour-demanding activities, such as dairy and other cash crops, less profitable.

For some households, those with larger land areas, better market access, marketing infrastructure already in place and better management, export crops could constitute an option for development, but this will depend on international market regulations and prices and the pressure to crop on-farm staple food for the family.

The “equitable growth” scenario, with general economic growth and better infrastructure, could lead to an increase in farm size if population densities in rural areas do not rise, migration to centres with high employment opportunities occurs, and non-farm activities are available. In smaller subsistence farms, such as case studies 1 and 2, there could be a shift towards more cultivation of cash crops, even export crops in some cases. Even so, dairy activities will increase only if land can be dedicated to the cultivation of cut-and-carry forage crops. Hired labour requirements could increase, especially if export crops become an option, but if opportunity costs of labour rise above a certain threshold, some land could be left uncultivated, which could be a positive environmental outcome, as farmers could tap into investments in mitigation of greenhouse gas emissions. For households located in peri-urban areas, this scenario could mean a decrease in farm size and more expensive labour costs. For case study 3, dairy could be maintained if land can be devoted to forage crops. The cost of labour could also constrain the expansion of dairy, as its marginal productivity will depend on the marginal revenue, which will obviously depend on price of milk. But in general, case study 3 under this scenario will reduce those activities that are highly demanding of labour, as this input becomes more expensive.

In the “inequitable growth” scenario, economic growth is localized, benefiting large farmers or companies in the private sector. Market development and infrastructure are improved in areas with export-led agriculture. The results of the household model offers intermediate results between those observed in the other two scenarios. The opportunities for development towards market oriented agriculture or, on the contrary, towards further marginalization and subsistence agriculture, will very much depend on the specific location of the household.

5. Conclusions: multi-scale modeling, scenarios, and understanding change in smallholder systems

We set out to study how agricultural systems in the Kenyan highlands might evolve as a result of drivers of change that could create opportunities for intensification and diversification for different types of farming systems. At the same time, we introduced the notion that it is only under certain political and economic conditions, studied through stakeholder-informed scenarios, that farmers could make the most of these opportunities. Linking these two lines of thought led to the development of an integrated, bottom-up, multi-scale methodology for studying change in agricultural systems, how farmers may be influenced by such changes, and what would the consequences be of upscaling these changes to the regional level.

Often, the results of regional or more aggregated modeling studies are not able to inform what may happen to specific types of farming systems and households, but can only inform general policies and certain types of investments. However, the forces rapidly shaping agriculture and other sectors seem to dictate the need for linking agricultural development with studies of global and regional change. As change occurs, it is essential to have the ability to study what may happen to different types of households, how they might react and adapt or not, what the costs associated with these adaptations could be, who will be the winners and the losers, what kinds of robust interventions may be suitable for different types of farming systems, and what could be the socio-economic and environmental trade-offs if these were to be implemented. Our success in informing future choices for meeting the demands placed on the agricultural sector socially, equitably and environmentally, lies partly in understanding the consequences of different actions at different scales, and how these are interconnected. For this we need more sophisticated, better integrated research methodologies, and better communication between scientists working at different scales.

The research presented in this paper argues for the value of using a multi-level, stakeholder-informed, iterative framework for the analysis of smallholder crop-livestock systems. The combination of complementary models at multiple levels, extensive inputs from policy experts as well as from household-level interviews and a capacity to explore iterative, evolutionary change has generated insights that would not have been possible without this systems-oriented, spatially and temporally dynamic framework. Both the modeling approaches, the spatial land-use model and the household model, project similar changes in the evolution of farming systems, although using very different modeling approaches and working at different levels of integration.

The involvement of regional experts in the development of socio-economic scenarios has enabled us to explore change in smallholder systems under different policy-relevant conditions that incorporate both desired futures as expressed by government strategies as well as less optimistic, more challenging futures. The involvement of policy experts also provides legitimacy to this type of analysis, which increases the likelihood that it will be taken up by relevant user groups (Chaudhury et al., 2012).

This set of plausible scenarios has in turn allowed us to link simulations at different levels and provide consistency in our analysis and comparability of results across these levels (Zurek and Henrichs, 2007). This comparability is due to the transferability of the effects of scenarios' key assumptions across spatial levels. Rather than providing a two-dimensional "low-medium-high investment" set of scenarios, the scenario set included equitable versus inequitable growth as another dimension, one that can be expressed as spatial differentiation. This differentiation can entail highly diverse local conditions for smallholders. The scenarios have furthermore provided a long-term future context beyond present-day conditions in which evolution of smallholder systems can be simulated over multiple iterations. However, in our iterative simulations we have not considered feedbacks from the models to the scenarios which might result in cross-level system shifts (Kinzig, 2006), such as regional land-use change patterns prompting changes in national government policies. Similarly, an extended version of this multi-level, multi-scenarios iterative process could include more iterations between stakeholder consultation and model simulation, whereby experts could comment on the plausibility of the results and ask questions that can guide new research. The Story-And-Simulation approach (Alcamo, 2008) and other examples of mixed qualitative scenarios and quantitative simulations (Volkery et al., 2008) outline a number of benefits of a more iterative interaction between multi-stakeholder scenarios and simulations, and these could inform next steps forward. More generally, there is much potential in using multi-level quantitative scenarios processes directly for policy guidance in multi-stakeholder arenas at different levels of decision making (such as the Millennium Ecosystem Assessment (2005) and IPCC (2007), for instance). We are currently building on the lessons from the study presented here to link regional and household-level models with multi-stakeholder scenarios at regional and local levels through the scenarios activities of the CGIAR

Research Programme on Climate Change, Agriculture and Food Security (CCAFS; Chaudhury et al., 2012). These activities share similarities with other participatory scenario activities (Claessens et al. 2012, Rosenzweig et al 2013).

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Figures

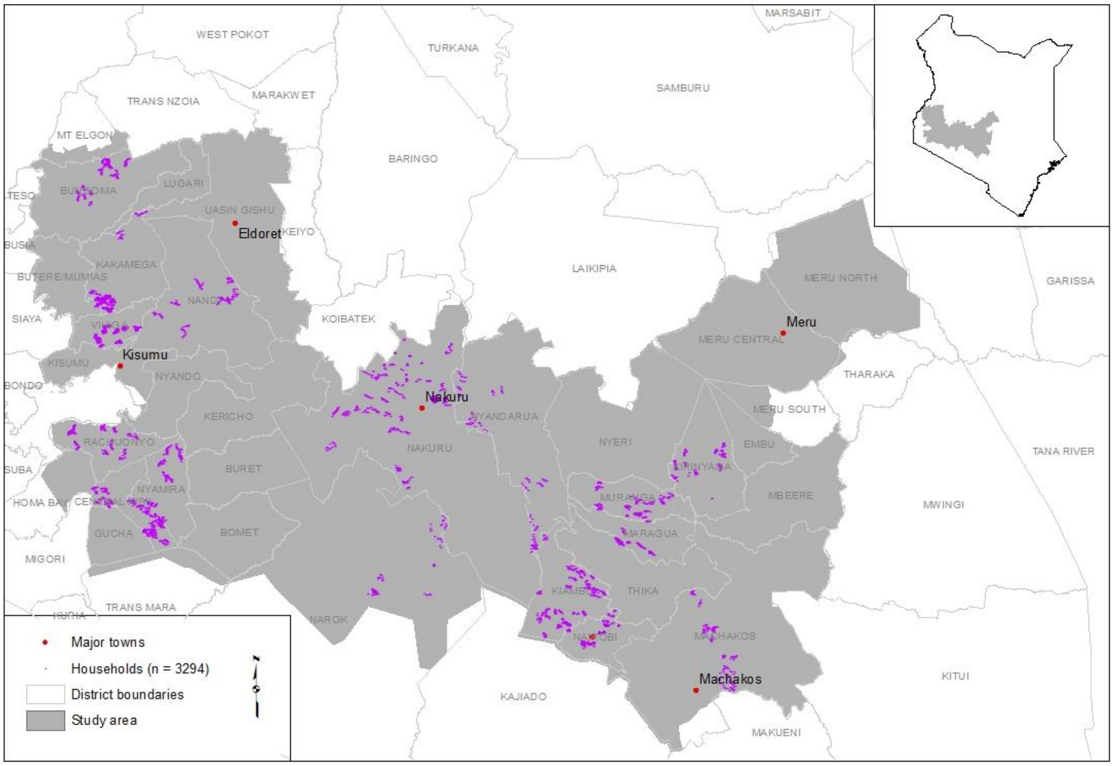


Figure 1: Map of the study area

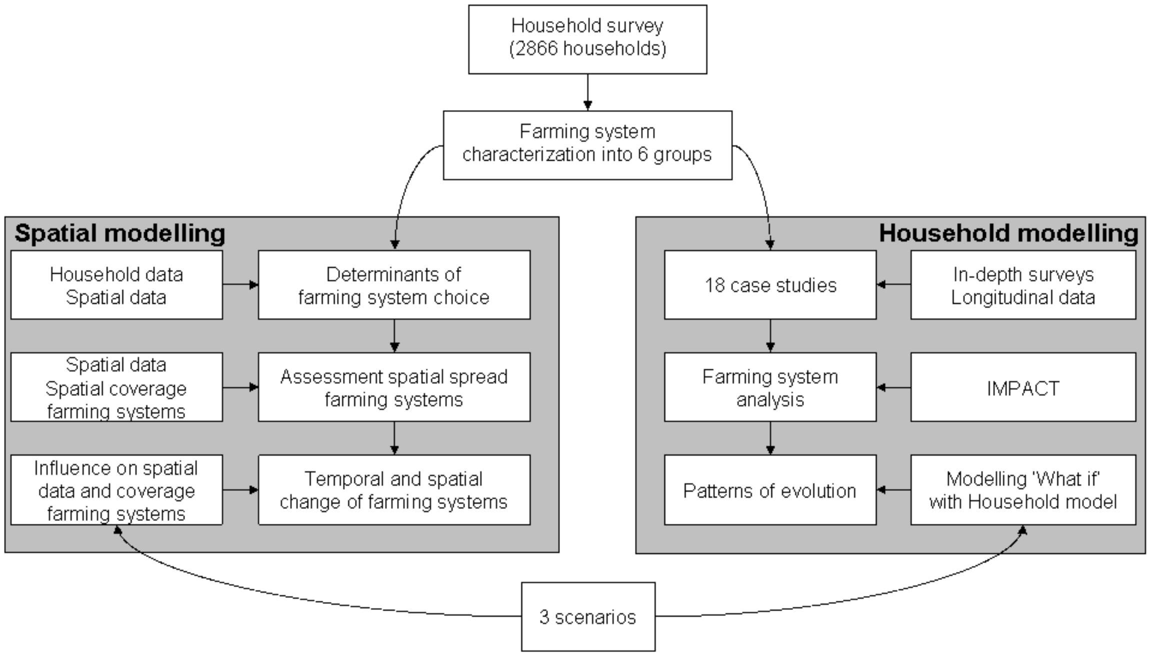


Figure 2: Methodological process at the regional and farm level

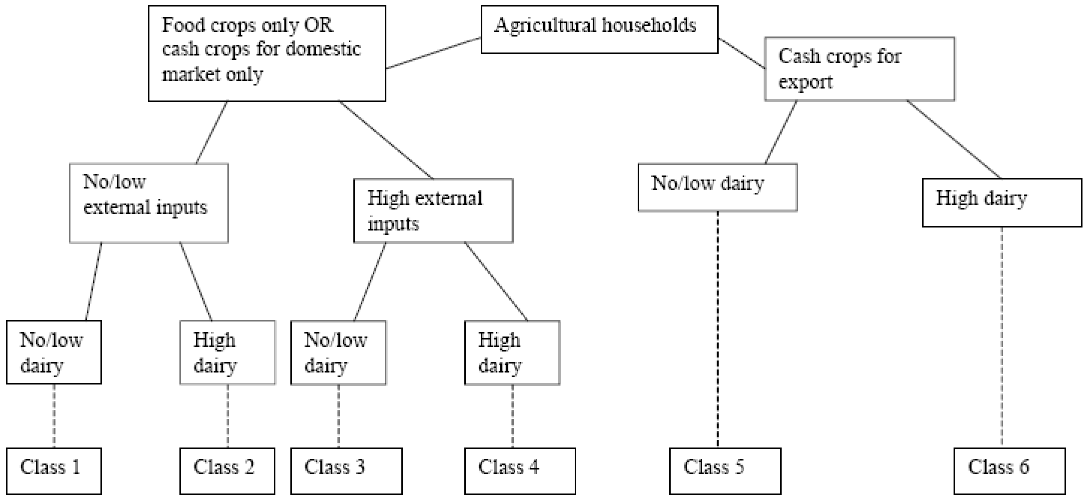


Figure 3: Expert-based classification of farming systems in the Kenyan Highlands

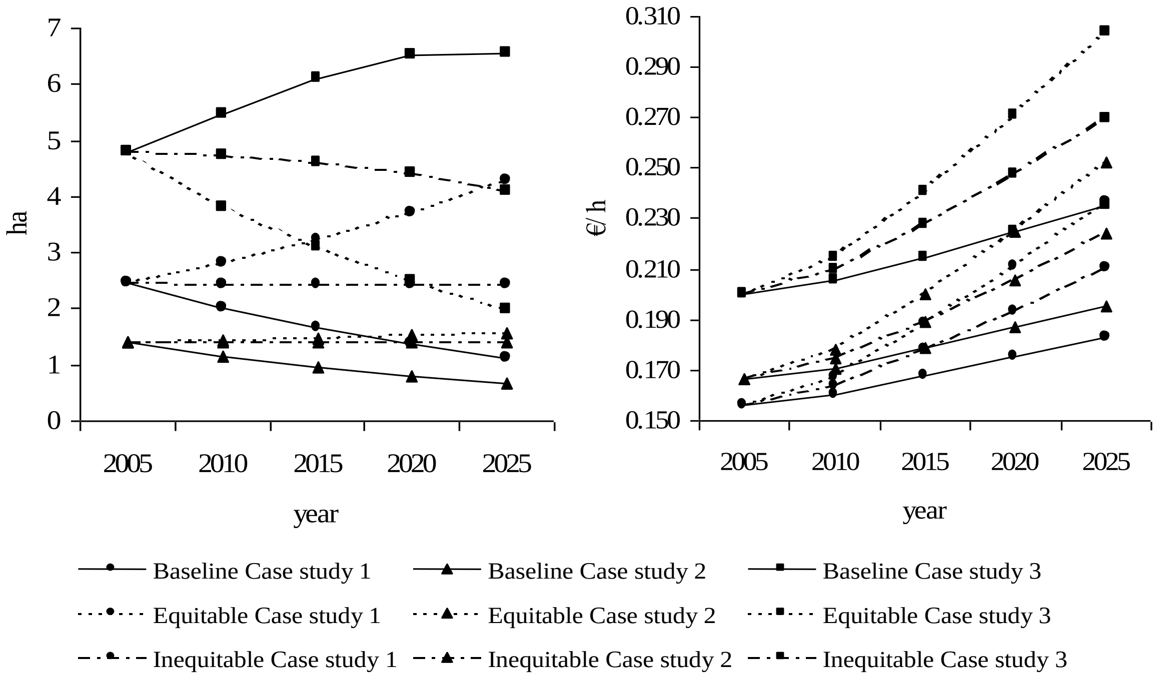


Figure 4: Projections of land size and labour price for the three case studies and scenarios (2005-2025) which serve as inputs for the Household Model analyses

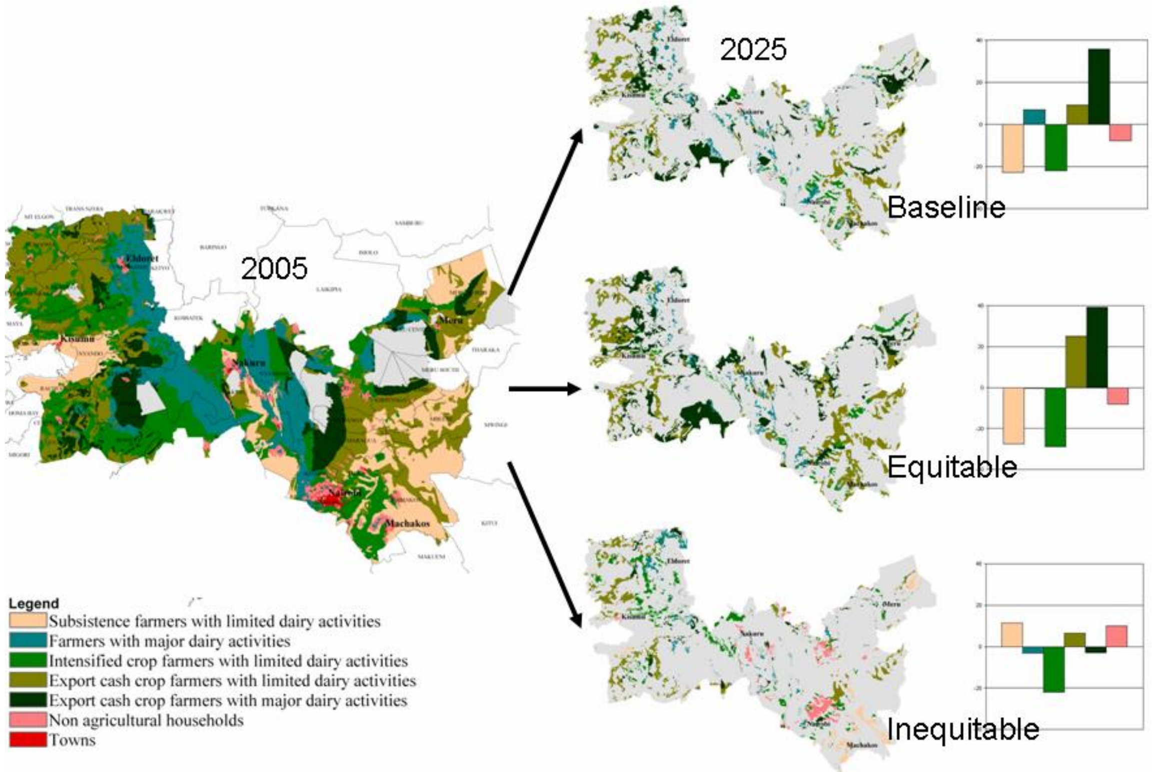


Figure 5: Predicted spatial distribution of farming systems for the year 2005, and spatial and aggregated change in farming systems for different scenarios in 2025 (the grey areas represent areas without change).

Figure 6: Case Study 1: evolution of subsistence farm with dairy; signs above the bar show the trend in the five-year period of simulation (increase, decrease, equal); white bars in milk orientation graph are non-milking cattle

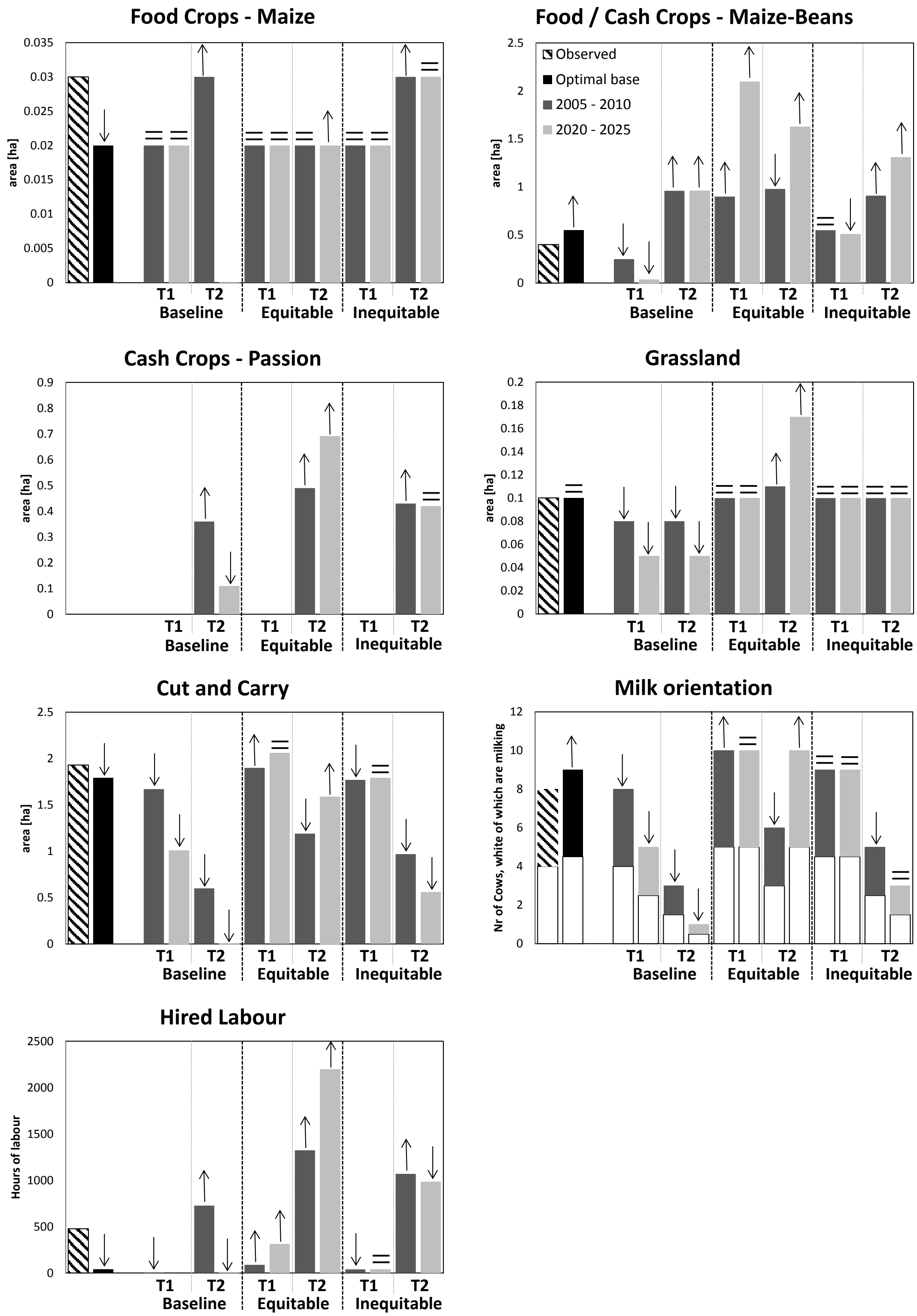


Figure 7: Case Study 2: evolution of intensified farm with dairy; signs above the bar show the trend in the five-year period of simulation (increase, decrease, equal); white bars in milk orientation graph are non-milking cattle

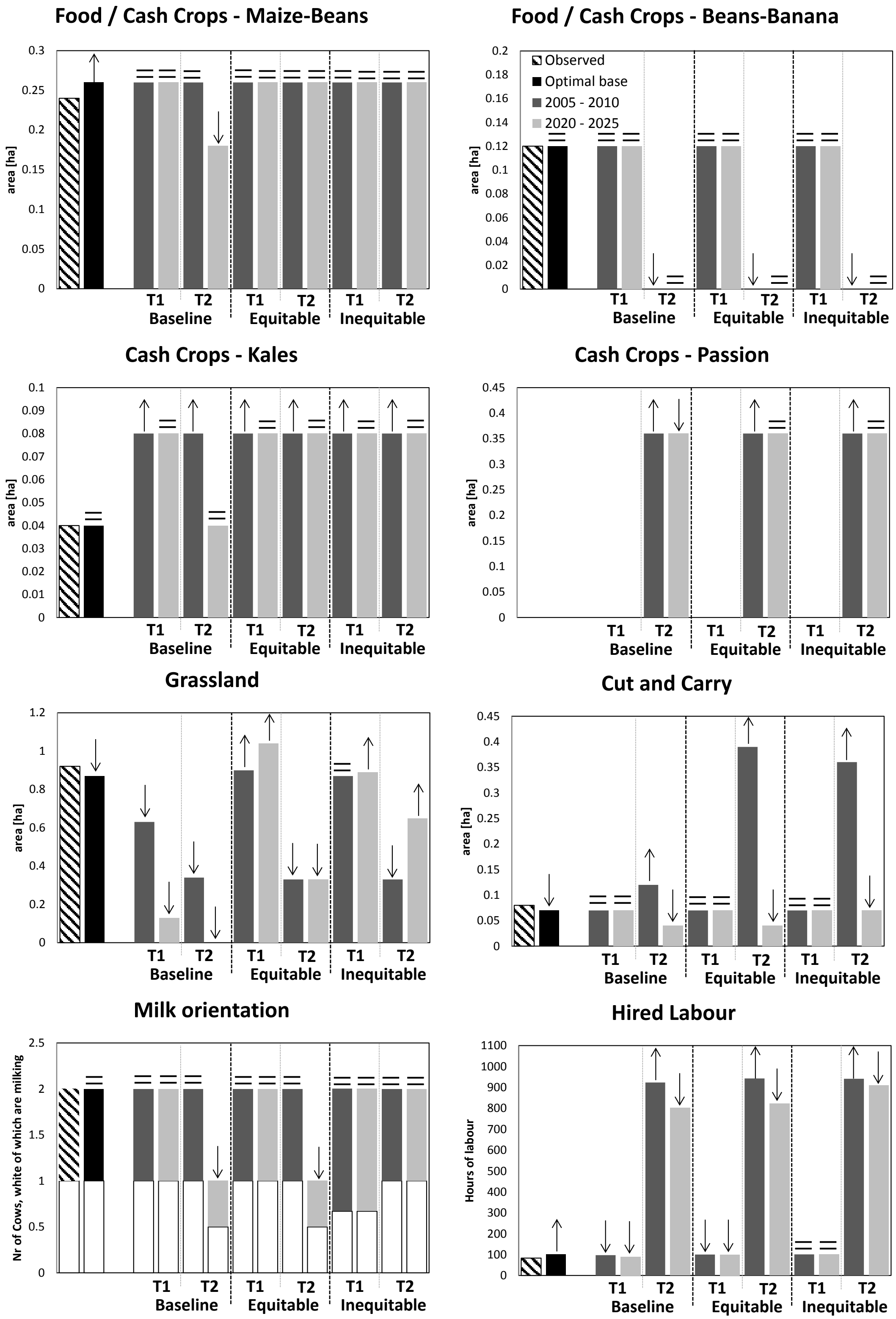
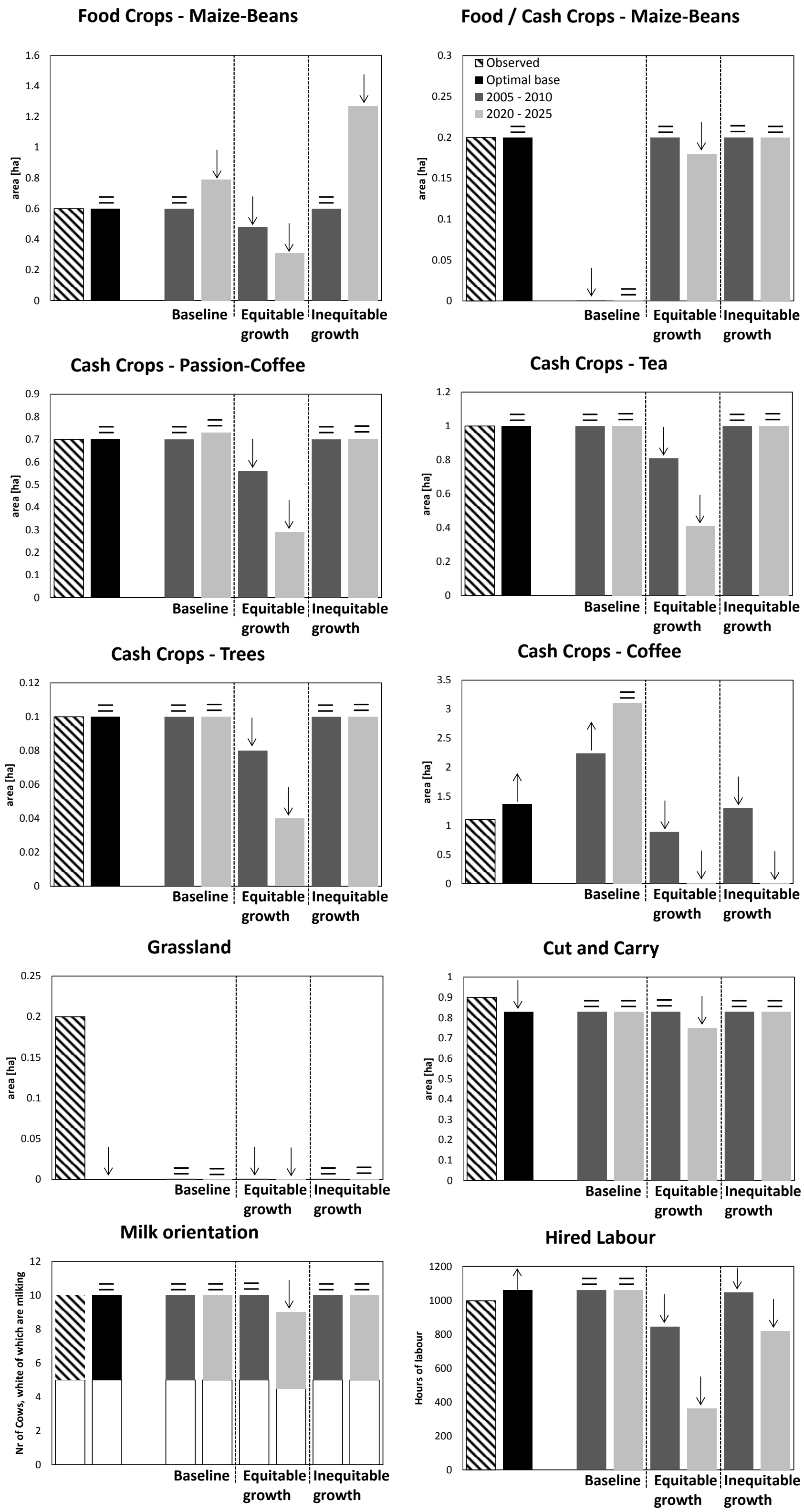


Figure 8: Case Study 3: evolution of export oriented farm with dairy; signs above the bar show the trend in the five-year period of simulation (increase, decrease, equal); white bars in milk orientation graph are non-milking cattle

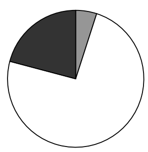
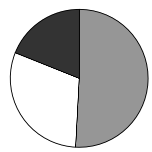
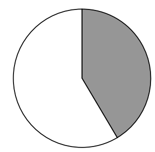
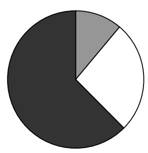
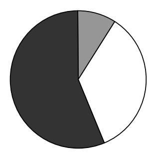
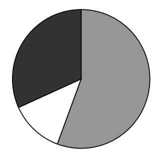
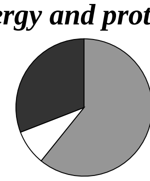
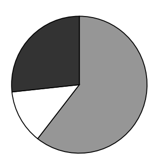
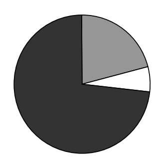


Tables

Table 1: Assumptions for the different scenarios

Drivers	**Baseline scenario**	**Equitable growth scenario**	**Inequitable growth scenario**
Population density	Rural growth rates differ across scenario with a negative growth rate in the equitable scenario in the assumption of out-migration (from rural to urban areas). Rural growth rate in the baseline scenario is calculated as the observed average rural growth rates while for the rural growth rate for the inequitable growth scenario is the average of the rates in the two other scenarios.		
	Rural growth rate=0.7	Rural growth rate=-0.6	Rural growth rate=0.1
Education	The education growth rate for the baseline scenario is the average of past rates while for the equitable growth scenario; it is the rate to achieve universal primary education by 2015. The education growth rate in the inequitable growth scenario assumes two rates: a higher rate in areas near large scale farming compared to the other		
	Growth rate=1%	Growth rate=4.5%	Growth rate=2.25%
Extension services	The baseline scenario assumes a status quo while the equitable scenario assumes a positive growth rate. In the inequitable growth scenario, two rates are used: 2% in areas near large scale farming and 1% in the other areas.		
	Growth rate=0%	Growth rate=2%	Growth rate=1%
Off-farm employment	The baselinescenario assumes a growth rate based on past trends while the equitable growth scenario assumes a higher growth rate. In the inequitable growth scenario, two rates are used: 4.5% in areas near large scale farming and 3.38% in the other areas.		
	Growth rate=2.25%	Growth rate=4.5%	Growth rate= 3.38%
Market access	Dual highway Mombasa- Busia only	Dual highway Mombasa- Busia and all other roads gradually improved	Dual highway Mombasa- Busia. All other roads gradually improved but only in areas with large scale farming

Table 2: Main characteristics of case study households, 2005

Variable	subsistence farm with dairy	intensified farm with dairy	export oriented farm with dairy
General Characteristics			
Location (elevation, m.a.s.l.)	Vihiga (1542)	Nandi (2131)	Kiambu (1954)
Family size (working)	8 (5)	7 (4)	6 (4)
Farm size, ha (no. of plots)	2.46 (6)	1.40 (7)	4.8 (7)
% of crops	17.5%	71.4%	77.1%
Main crops	maize, beans	maize, beans, kales	tea, coffee, passion fruit, beans, maize, potato
Livestock numbers	Cattle (milking): 8 (4)	Cattle (milking): 2 (1)	Cattle (milking): 10 (5)
	Goats: 10, Chicken: 20	Sheep: 3, Chicken: 10	Sheep: 3, Chicken: 13
Economics: income and expenditure			
Annual incomes **agriculture** **livestock** **off-farm**			
Annual expenditure **agriculture** **livestock** **other expenses**			
Net annual income from agricultural activities, €	1610.2	846.2	3083.7
Contribution of off-farm income to total income, %	20.8%	18.8%	0%
Agric. products with highest contribution to income	milk, maize	kales, milk	milk, passion fruit, tea, coffee
Annual agricultural income per person, €	322.4	184.9	1077.3
Annual agricultural income per ha, €	1397.9	1233.0	1795.5
Sources of annual food security (energy and protein)			
Energy sources **On-farm agric. prod.** **on-farm livest. prod.** **purchased products**			

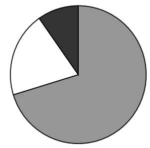
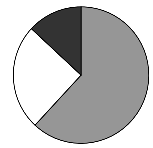
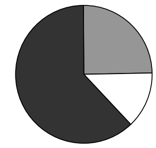
Protein sources **on-farm agric. prod.** **on-farm livest. prod.** **purchased products**			
Family's energy requirements met (deficit)	NO (11.6%)	NO (1.3%)	YES
Family's protein requirements met	YES	YES	YES
Proportion of income spent in purchasing food	11.8%	14.2%	6.8%
On-farm prod. with highest contribution to family's nutrition	maize, milk	maize, milk, beans	maize, milk

Table 3: Trajectories of change between different systems under different scenarios

		Baseline scenario Interval of 5 years				Equitable development Interval of 5 years				Inequitable development Interval of 5 years			
Case study	T	1st	2nd	3rd	4th	1st	2nd	3rd	4th	1st	2nd	3rd	4th
Subsistence & dairy (1)	T1	1	1	1	1	2	2	2	2	1	1	1	1
	T2	2	2	2	2	2	3	3	3	2	2	2	2
Intensified & dairy (2)	T1	2	2	2	2	2	2	3	3	2	2	2	2
	T2	3	3	3	3	3	3	3	3	3	3	3	3
Export crops & dairy (3)	T1	3	3	3	3	3	3	3	3	3	3	3	3

T: Trajectory; 1 subsistence farmers with major dairy activities; 2 intensified crop farmers with major dairy activities; 3 export cash crop farmers with major dairy activities

Table 4: The distribution of farming systems, and their contribution to the total production of certain agricultural commodities, for the year 2005

Class	Farming systems	Land area (%)	Percentage of production			
			Maize	Beans	Tea	Milk
1	Subsistence farmers with limited dairy activities	19.8	24.4	25.1		5.9
2	Farmers with major dairy activities	16.7	16.5	16.9		46.0
3	Intensified crop farmers with limited dairy activities	23.5	32.0	32.2		8.2
5	Export cash crop farmers with limited dairy activities	26.6	18.2	17.8	67.1	7.4
6	Export cash crop farmers with major dairy activities	10.2	8.8	8.0	32.9	32.5
	Non-agricultural households	3.2				

Table 5: Demand for commodities (tons/year/person)

	Baseline scenario				Equitable growth scenario				Inequitable growth scenario			
	Maize	**Beans**	**Milk**	**Tea**	**Maize**	**Beans**	**Milk**	**Tea**	**Maize**	**Beans**	**Milk**	**Tea**
2004	0.103	0.007	0.087	0.777	0.103	0.007	0.087	0.777	0.103	0.007	0.087	0.777
2005	0.103	0.007	0.088	0.786	0.106	0.008	0.091	0.837	0.105	0.008	0.089	0.811
2006	0.104	0.007	0.088	0.795	0.109	0.008	0.095	0.900	0.106	0.008	0.091	0.847
2007	0.104	0.008	0.089	0.804	0.112	0.008	0.099	0.969	0.108	0.008	0.094	0.884
2008	0.105	0.008	0.089	0.813	0.115	0.009	0.103	1.042	0.110	0.008	0.096	0.922
2009	0.105	0.008	0.090	0.822	0.118	0.009	0.107	1.122	0.111	0.008	0.098	0.963
2010	0.105	0.008	0.090	0.832	0.121	0.009	0.112	1.207	0.113	0.008	0.101	1.005
2011	0.106	0.008	0.091	0.841	0.124	0.010	0.117	1.299	0.115	0.009	0.103	1.049
2012	0.106	0.008	0.092	0.851	0.128	0.010	0.122	1.397	0.117	0.009	0.106	1.094
2013	0.107	0.008	0.092	0.860	0.131	0.010	0.127	1.504	0.118	0.009	0.108	1.142
2014	0.107	0.008	0.093	0.870	0.135	0.011	0.132	1.618	0.120	0.009	0.111	1.192
2015	0.108	0.008	0.093	0.880	0.139	0.011	0.138	1.741	0.122	0.009	0.114	1.244
2016	0.108	0.008	0.094	0.890	0.142	0.012	0.144	1.873	0.124	0.010	0.116	1.299
2017	0.108	0.008	0.095	0.900	0.146	0.012	0.150	2.016	0.126	0.010	0.119	1.355
2018	0.109	0.008	0.095	0.910	0.150	0.012	0.156	2.169	0.128	0.010	0.122	1.415
2019	0.109	0.008	0.096	0.920	0.154	0.013	0.163	2.334	0.130	0.010	0.125	1.476
2020	0.110	0.008	0.096	0.931	0.159	0.013	0.170	2.512	0.132	0.010	0.128	1.541
2021	0.110	0.008	0.097	0.941	0.163	0.014	0.177	2.703	0.134	0.011	0.131	1.608
2022	0.111	0.008	0.098	0.952	0.167	0.014	0.185	2.908	0.136	0.011	0.135	1.678
2023	0.111	0.008	0.098	0.963	0.172	0.015	0.192	3.129	0.138	0.011	0.138	1.752
2024	0.112	0.008	0.099	0.974	0.177	0.016	0.201	3.367	0.141	0.011	0.141	1.828

Table 6: The distribution of farming systems over 20 years, driven by the combined changes in the demand for different commodities

Farming System	Scenario	Land area (%)				
		2005	2010	2015	2020	2025
Subsistence farmers with limited dairy activities	Baseline	19.76	19.64	19.51	19.38	19.26
	Equitable growth	19.75	19.59	19.42	19.24	19.08
	Inequitable growth	19.76	19.63	19.50	19.36	19.25
Farmers with major dairy activities	Baseline	16.70	16.65	16.60	16.54	16.49
	Equitable growth	16.70	16.63	16.56	16.49	16.44
	Inequitable growth	16.70	16.65	16.60	16.54	16.51
Intensified crop farmers with limited dairy activities	Baseline	23.44	23.31	23.17	23.01	22.88
	Equitable growth	23.43	23.25	23.06	22.85	22.68
	Inequitable growth	23.44	23.29	23.15	22.99	22.87
Export cash crop farmers with limited dairy activities	Baseline	26.58	26.50	26.41	26.30	26.22
	Equitable growth	26.60	26.58	26.55	26.51	26.48
	Inequitable growth	26.60	26.56	26.51	26.46	26.43
Export cash crop farmers with major dairy activities	Baseline	10.25	10.28	10.31	10.34	10.37
	Equitable growth	10.26	10.34	10.43	10.52	10.61
	Inequitable growth	10.25	10.31	10.36	10.43	10.49
Non-agricultural households	Baseline	3.28	3.62	4.01	4.42	4.79
	Equitable growth	3.27	3.61	3.98	4.38	4.72
	Inequitable growth	3.28	3.62	4.01	4.42	4.79

Table 7: Overview of spatial changes in farming system over 20 years, under different scenarios

Farming system for various years		**Surface area changes (%) by growth scenario**		
2005	**2025**	**Baseline**	**Equitable**	**Inequitable**
Subsistence farmers with limited dairy	Subsistence farmers with limited dairy	0	0	0
	Farmers with major dairy activities	1.2	1.2	1.2
	Intensified crop farmers with limited dairy	5.3	5.4	5.8
	Export cash crop farmers with limited dairy	15.9	21.0	20.6
	Export cash crop farmers with major dairy	0	0	0
	Non-agricultural households	0.4	0	0
Farmers with major dairy activities	Subsistence farmers with limited dairy	0	0	0
	Farmers with major dairy activities	0	0	0
	Intensified crop farmers with limited dairy	0.2	0.5	0.3
	Export cash crop farmers with limited dairy	2.2	3.1	3.1
	Export cash crop farmers with major dairy	3.4	4.1	4.1
	Non-agricultural households	0	0	0
Intensified crop farmers with limited dairy	Subsistence farmers with limited dairy	0.1	0.1	0.2
	Farmers with major dairy activities	5.9	3.4	3.3
	Intensified crop farmers with limited dairy	0.0	0	0
	Export cash crop farmers with limited dairy	16.2	16.9	17.1
	Export cash crop farmers with major dairy	11.7	15.7	15.8
	Non-agricultural households	0	0.0	0.0
Export cash crop farmers with limited dairy	Subsistence farmers with limited dairy	0	0.0	0.0
	Farmers with major dairy activities	2.1	1.1	1.0
	Intensified crop farmers with limited dairy	4.7	0.5	0.5
	Export cash crop farmers with limited dairy	0	0	0
	Export cash crop farmers with major dairy	21.5	18.8	18.7
	Non-agricultural households	0	0.0	0
Export cash crop farmers with major dairy	Subsistence farmers with limited dairy	0	0	0
	Farmers with major dairy activities	0.9	0.1	0.1
	Intensified crop farmers with limited dairy	0.3	0.0	0.1
	Export cash crop farmers with limited dairy	0.0	0	0
	Export cash crop farmers with major dairy	0	0	0

	Non-agricultural households	0	0	0
Non-agricultural households	Subsistence farmers with limited dairy	0.1	0.0	0
	Farmers with major dairy activities	2.7	1.9	1.8
	Intensified crop farmers with limited dairy	1.4	0.7	0.8
	Export cash crop farmers with limited dairy	3.4	4.6	4.5
	Export cash crop farmers with major dairy	0.5	0.8	0.8
	Non-agricultural households	0	0	0