# A method for evaluating climate change adaptation strategies for small-scale farmers using survey, experimental and modeled data

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**Research Highlights**

- We propose a parsimonious method for *ex ante* evaluation of adaptation to climate change based on the Tradeoff Analysis model for Multi-Dimensional Impact Assessment (TOA-MD).
- TOA-MD simulates economic and social outcomes in a heterogeneous farm population that can be aggregated for regional impact assessment.
- TOA-MD is applied to assess impacts of climate change and adaptation under different socio-economic scenarios to 2030 for two mixed crop-livestock systems in Kenya.
- Considerable negative effects of climate change to 2030 are projected but several adaptation strategies are simulated to be able to overcome these effects.

# A method for evaluating climate change adaptation strategies for small-scale farmers using survey, experimental and modeled data

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**ABSTRACT**

Sub-Saharan Africa (SSA) is predicted to experience considerable negative impacts of climate change. The IPCC Fourth Assessment emphasizes that adaptation strategies are essential. Addressing adaptation in the context of small-scale, semi-subsistence agriculture raises special challenges. High data demands including site-specific bio-physical and economic data are an important constraint. This paper applies a new approach to impact assessment, the Tradeoff Analysis model for Multi-Dimensional impact assessment (TOA-MD), which simulates technology adoption and associated economic, environmental and social outcomes in a heterogeneous farm population for a regional impact assessment. The methodology uses the kinds of survey, experimental and modeled data that are typically available in countries where semi-subsistence systems are important, combined with future socio-economic scenarios based on new scenario pathway concepts being developed by the climate change and impact assessment modeling communities. Characteristics of current and future agricultural systems, including land use, output, output price, cost of production, and farm and household size are analyzed and compared for both current and projected future climate (2030), with and without adaptation, and for different socio-economic scenarios. The methodology is applied to two study areas in Kenya. These case studies show the potential of this approach to provide a flexible, generic framework that can use available and modeled data to evaluate climate impact and adaptation strategies under a range of socio-economic scenarios.

**Keywords:** adaptation; climate change; East Africa; impact assessment; socio-economic scenarios; TOA-MD model

## 1. INTRODUCTION

The changing climate is exacerbating existing vulnerabilities of the poorest people who depend on semi-subsistence agriculture for their survival (Slingo et al., 2005; IPCC, 2007; Nelson et al., 2009). Sub-Saharan Africa (SSA) in particular is predicted to experience considerable negative impacts of climate change (e.g., Thornton et al., 2006). The IPCC Fourth Assessment emphasizes that adaptation strategies are essential and these must be developed within the broader economic development policy context (IPCC, 2007). Addressing adaptation in the context of small-scale, semi-subsistence agriculture in SSA raises special challenges that cannot be addressed adequately by the approaches taken thus far in most studies (Adger et al., 2003). Most of the existing research has focused on impacts of climate change and adaptation to climate change in the agricultures of industrialized countries. In the relatively few studies conducted in Africa, agricultural research has either focused on individual crops (e.g., Hijmans, 2003; Jones and Thornton, 2003), has used aggregated data and models (e.g., Winters et al., 1998; Mendelsohn et al., 2000), or used statistical analysis that does not allow for site-specific adaptation strategies (e.g., Kurukulasuriya and Mendelsohn, 2006). IPCC and some recent studies at the sub-continental scale for Africa indicate the importance of assessing the effects of climate change and possible adaptation strategies at the agricultural system and/or household level, rather than focusing on aggregated results that hide a large amount of variability (Burke et al., 2009; Nelson et al., 2009; Thornton et al., 2009a, 2010; Baethgen, 2010). High data demands are one of the important constraints for this type of analysis because site-specific bio-physical and economic data are required, typically obtained from costly multi-year farm-level surveys. At the spatial resolution required, another drawback is that projections of climate change and simulations of the effects on crop and livestock productivity come with a high degree of variability and associated uncertainties depending on the climate models and methodologies used. The development and application of relatively simple and reliable methods for *ex ante* evaluation of adaptation strategies at the household and agricultural system levels are needed to provide timely assessments of the potential impacts in the context of climate change.

This paper describes and applies a new approach to regional technology and environmental impact assessment using a novel simulation approach to impact assessment, implemented with the Tradeoff Analysis for Multi-Dimensional Impact Assessment model (TOA-MD). The methodology is applied to two study areas in Kenya. It makes use of the kinds of data – survey, experimental, modeled, and expert – that are typically available to assess future environmental changes and prospective technologies, especially in countries where complex, semi-subsistence systems predominate. The approach integrates socio-economic and bio-physical data on farmers' land allocation, outputs and cost of production and characterizes the spatial heterogeneity in economic returns to baseline and alternative systems under current and possible future climate. Productivity characteristics of alternative systems that may be better adapted to future climates are characterized using available data which may include laboratory and field experiments, simulation model data, and expert data. Using these data, the model simulates the adoption of alternative systems and their economic and social impacts among farms that may lose or gain from climate change. A variety of possible management strategies is then assessed for their capability to facilitate adaptation to climate change under different socio-economic scenarios.

## 2. STUDY AREAS

### 2.1. Vihiga

Vihiga district in western Kenya lies between 1,300 and 1,500 m above sea level and covers an area of 563 $km^2$ of which 419 $km^2$ is arable land (CBS, 2003) (Fig. 1). Vihiga district is broadly representative of other areas of the East African highlands found in Uganda, Ethiopia, and Madagascar in terms of soils, climate, technology, and production potential (Soule and Shepherd, 2000). The district's high potential agricultural area is characterized by well drained nitisols that support the growing of various cash and food crops (Waithaka et al., 2006). Soil fertility is low due to leaching and continuous cropping without sufficient replenishment (AFRENA, 1998; Salasya et al., 1998). Nitrogen and phosphorus are the main limiting nutrients for food crops (Soule and Shepherd, 2000). Currently the area receives adequate bimodal rainfall that ranges between 1,800 – 2,000 mm per year with heavier long rains from March to June and short rains between September and December. Temperatures are moderate and range from 14 to $32^o$ C with limited diurnal variations.

In 1999 Vihiga district had a total population of 500,000 with a population growth rate of 2.2% (CBS, 2001). According to the latest census in 2009, the population has increased to 550,000 (KNBS, 2010). Poverty mapping in Kenya places Vihiga among the poorest districts in the country (CBS, 2003). Most farm households in Vihiga show a maize deficit of 200-400 kg per year, which is equivalent to shortage in six to ten months each year (Waithaka et al., 2005). The shortage is aggravated by the increasing conflicts among food, cash and fodder crops as farm sizes continue to decline due to growing population pressure and dividing farm land among family members. This has greatly reduced available fodder with hardly enough to feed livestock all year round. With high poverty levels, farmers do not use high-return inputs such as certified seeds, fertilizers, disease and pest control measures, and rotations, but are limited to low-input, low-return enterprises (Waithaka et al., 2006). The average farm household has 4.7 persons living on a 0.5 ha farm creating a greater need for intensified agricultural production.

About 60% of the Vihiga population falls below the poverty line of 1 US$/person/day (CBS, 2003) with an average total income of 56 Kenyan Shillings (KSh) per farm household per day (1 US$ was equivalent to KSh 77 in mid-2005). Farm households obtain 65% of their income from off-farm sources in the form of wages and remittances (Waithaka et al., 2006). A high proportion of farm income is obtained from milk sales. In an effort to enhance farm household income and food security, farmers in the district appear to pursue risk management strategies, such as producing much of the household consumed food to avoid market risk, and diversification, and hence grow many crops on their small land holdings.

The main food crops are maize, beans, sorghum, groundnuts, bananas and a variety of vegetables and the main cash crop is tea. The predominant livestock is local Zebu, which is mainly used for dairy production. Most farmers practice zero grazing and grow Napier grass for animal feed, which competes with high value crops in the small holdings. With investments in transportation infrastructure, the area could have improved market opportunities as most farms are within 50 km of the large urban centers of Kakamega and Kisumu with more than 500,000 people each (CBS, 2001).

## 2.2. Machakos

The 13,500 $km^2$ study area is located in the Eastern Province of Kenya and contains both Machakos and Makueni districts. Elevation ranges from 400 to 2,100 meters above sea level (Fig.1). Almost half of the total surface of the study area is under agricultural use (6,615 $km^2$). Most of the soils in the area are deep, friable, with textures ranging from sandy clay loam to sandy clay. Inherent fertility is very poor and soils are generally deficient in nitrogen, phosphorus and soil organic carbon (<1%) (Onduru et al., 2001; Mora-Vallejo et al., 2008). The semi-arid climate in the area has low, highly variable rainfall, distributed in two rainy seasons. Short rains occur from November to January and long rains from March to June. Average annual rainfall ranges from 500 to 1,300 mm and mean annual temperature varies from 15ºC to 25ºC, resulting in a wide range of agro-ecological conditions (MoA, 1987). Drought events do happen in cycles of four or five years, normally in runs of two or more seasons, and they have great impact on food security (Tiffen et al., 1994).

In 1999 Machakos and Makueni had a total population of around 900,000 and 770,000 respectively (CBS, 2001). According to the latest census in 2009, the population has increased to 1,100,000 in Machakos and 880,000 in Makueni (KNBS, 2010). 60% of the population in Machakos and 62% in Makueni fall below the poverty line of 1 US$/person/day (CBS, 2003).

Agriculture is dominated by subsistence-oriented mixed farming systems that include both crop and livestock production, although some coffee and cotton are cultivated in the area as cash crops. Farm households in general own between 1.5 and 6 ha of land, of which 1.5–3.5 ha is cultivated (de Jager et al., 2001). Maize is the most important staple crop, but a wide variety of other food crops are grown (beans, millet and sorghum), vegetables (tomatoes and kales), fruit trees (orange, banana, mango and pawpaw) and tubers (cassava). For all crops, yields are generally low and crop failure is a common problem. Soil nutrient management through application of manure and chemical fertilizer is practiced by farmers. However, due to the relatively high prices of chemical fertilizer, this is only applied on plots that are of good quality and have less risk of crop failure, manure is more often applied on plots with degraded soil fertility and health (de Jager et al., 2004; Mora-Vallejo et al., 2008). On fields with continuous cultivation without external inputs, a sharp yield decline has been observed (Lal, 2010). Soil conservation practices have been implemented in the area since colonial times. While in the 1930s the building of erosion control structures was enforced after severe land degradation took place, nowadays the majority of the farmers (almost 75%) voluntarily maintain these structures and the area is well known for the widespread use of terrace cultivation (de Jager et al., 2004; Tiffen et al., 1994). Irrigation is only available for a minority of farms but some cases exist in locations neighbouring Athi River. Access to simple small-scale irrigation allows the cultivation of vegetables such as chilli peppers, tomatoes, onions and eggplant for commercial production. In such cases, where water and marketing constraints are alleviated, farmers directly respond by applying higher doses of mineral and organic fertilizer. This change in farm management results in higher and more stable yields and higher financial returns (de Jager et al., 2004). In the majority of the households, livestock (cattle, sheep, goats) represents an important component of the farming system. The major functions of livestock are provision of draught power, manure production and capital assets (saving and insurance) (de Jager et al., 2001).

# Figure 1 approx. here#

## 3. MATERIALS AND METHODS

### 3.1. Survey data

The data for Vihiga originate from the project ‘System prototyping and impact assessment for sustainable alternatives in mixed farming systems in high-potential areas of Eastern Africa’

(PROSAM) for which farm survey data were collected in 2000 and 2002 (Waithaka et al., 2005; Salasya, 2005). For this analysis, a selection of 119 farms was extracted from the database for which complete data (quantities and prices) on inputs (such as seeds, labor, fertilizer, and manure), outputs (crop yields, milk production and land areas), and farm management were available (Table 1). For Machakos we used similar farm survey data for 120 households in six villages obtained from studies conducted in the Nutrient Monitoring project (NUTMON) in 2000 (de Jager et al. 2001; Gachimbi et al. 2005). The survey data are used to calculate statistics needed to implement the TOA-MD model for the different activities (crops and milk production) in each study area (Table 1). Annual crops (such as fruits and non-irrigated vegetables), that are grown heterogeneously across farms and occupy very small land units in both study areas are grouped for this analysis under one activity called 'mixed crops'. Crops such as tea, coffee, sugar cane, and woodlots are treated as fixed activities and thus are not included in this analysis.

### 3.2. TOA-MD as a Climate Impact and Adaptation Assessment Tool

For the analysis of climate change impact, adaptation strategies and poverty we use the Tradeoff Analysis model for Multi-Dimensional impact assessment (TOA-MD). The TOA-MD model is a parsimonious, generic model for analysis of technology adoption and impact assessment, and ecosystem services analysis. TOA-MD has been used for the analysis of technology adoption (Claessens et al., 2009, 2010) and payments for environmental services (Antle and Validivia, 2006; Nalukenge et al., 2006; Antle and Stoorvogel, 2006, 2008; Immerzeel et al., 2008; Antle et al. 2010). Antle et al. (2010) present a validation of the TOA-MD approach against more complex, spatially-explicit models of semi-subsistence agricultural systems, including a model for the Machakos case study presented here. Further details on the impact assessment aspects of the model are provided in Antle (2011a). The model software and the data used in this and other studies are available to researchers with documentation and self-guided learning modules at tradeoffs.oregonstate.edu.

The TOA-MD model simulates technology adoption and impact in a population of heterogeneous farms. Farms are assumed to be economically rational and to choose between systems based on expected economic returns. The simulation model uses data on the spatial variability in economic returns to represent heterogeneity in the farm population. When used to analyze technology adoption, an important implication of this model is that incomplete adoption of a new technology can be due simply to heterogeneity in the conditions determining the value of a system to farmers – such as heterogeneity in soils, climate, transportation costs, and the farm household's characteristics – the conditions typical of most technologies and most farm populations. This fact is important to emphasize because much of the literature attributes incomplete adoption to attitudes such as risk aversion or constraints such as access to the technology or financing – constraints that are typically difficult to observe and quantify (for a discussion of relevant literature, see Suri, 2011). While such factors may indeed contribute to low adoption rates in some cases, recent research has shown in important cases that observable heterogeneity in bio-physical and economic characteristics of farms can be sufficient to explain observed – and often low – adoption rates (Antle et al., 2005; Suri, 2011). In climate change assessment, the TOA-MD model implies that not all farms are affected in the same way – in most cases, some farms lose and some farms gain from climate change. Similarly, some farms may be willing to adopt technologies that facilitate adaptation to climate change, while others will not. The TOA-MD model allows researchers to simulate the impacts of the full range of adoption rates from zero to 100 percent.

In the TOA-MD model, farmers are presented with a simple binary choice: they can operate with a current or base production system 1, or they can switch to an alternative system. Under the climate change analysis, it is necessary to distinguish between three factors affecting the expected value of a production system: the production methods used, referred to here as the *technology*, and the physical environment in which the system is operated, i.e., the *climate,* and the economic and social environment in which the system is operated, i.e., the *socio-economic setting* that we shall refer to as a Representative Agricultural Pathway, or RAP. RAPs are qualitative storylines that can be translated into model parameters such as farm and household size, prices and costs of production, and policy. They are being developed by the Agricultural Model Intercomparison and Improvement Project (AgMIP, Rosenzweig et al., 2012; Antle, 2011b) to be consistent with new scenario concepts being developed by the climate modeling and impact assessment communities (further details below, section 3.5). Thus, in the climate change analysis a production system is defined as a particular technology used in a particular climate regime and RAP. These factors combine to determine the productivity and economic value of the system.

A major challenge in scenario design for climate impact assessment is the dimensionality of the analysis, given that there are potentially a large number of technology, climate and RAP combinations. To simplify the presentation, assume for the time being that the analysis is for a given RAP. The logic of the analysis is then summarized as follows: Farmers are initially operating a *base technology* with a *base climate*. This combination is defined as system 1. System 2 is defined as the case where farmers continue using the base technology under a *perturbed* climate. System 3 is defined as an *adapted* technology used with the *perturbed* climate. We can compare the outcomes associated with each system to quantify the impacts of climate change, without adaptation and with adaptation. Using the TOA-MD model, impacts that can be simulated include changes in farm income or poverty rates, as well as other environmental or social outcomes of interest such as changes in greenhouse gas emissions or human health.

It is important to note that in most analyses of climate change adaptation, it is assumed all farms use the adapted technology. However, that assumption is not appropriate in most cases, because the population of farms is heterogeneous (see for example Salasya and Stoorvogel, 2010). Farms will be impacted differently by climate change, and all farms are not necessarily adversely impacted. In this study we use the TOA-MD model, which simulates technology adoption together with impact to simulate the following alternative scenarios:

- the impact of climate change without adaptation, i.e., assuming all farmers use the base technology (compare systems 1 and 2).
- the impact of the adapted technology, when farmers choose whether to adopt the adapted technology under the perturbed climate (compare systems 2 and 3 with economically rational adoption).

In the TOA-MD model, a farmer at a site $s$ using a production system $h$ (defined as a combination of technology, climate and RAP) earns per-hectare returns each period equal to $v_t = v_t(s,h)$. Over T time periods, system $h$ provides a discounted net return of

(1) $$V(s,h) = \sum_{t=1}^{T} \delta_t \, v_t(s,h),$$

where $\delta_t$ is the relevant discount factor. When the production system changes, because of a change in technology or climate or both, expected returns at each site also change. The effect on a farm's returns of changing from system $j$ to system $k$ is $\omega(s,j,k) = V(s,j) - V(s,k)$. Thus, if $\omega(s,j,k)$ is positive it represents the loss, or opportunity cost, associated with switching from system $j$ to system $k$, and if negative it represents the gain from switching from system $j$ to $k$. Define the density $\varphi(\omega|\ j,k)$ as the spatial distribution of gains or losses in the population of farms indexed by $s$. The percentage of farms with $\omega(s,j,k) < a$ (with $a$ an amount in e.g. dollars per hectare) is

(2) $$r(a,j,k) = 100 \int_{-\infty}^{a} \varphi(\omega|\ j,k)\, d\omega.$$

Two interpretations of (2) are possible in the context of the TOA-MD model.

*Technology Adoption*

In the standard *technology adoption* analysis, farms may be able to choose to continue using system $j$ which embodies one type of technology (say, the base technology defined above), or to switch to system $k$ which embodies a different technology (say, the adapted technology). In this case of voluntary technology adoption, note that a farm will switch if $\omega(s,j,k) = V(s,j) - V(s,k) < a$, which implies $V(s,j) < V(s,k) + a$. Thus $r(a,j,k)$ can be interpreted as the proportion of adopters of system $k$ when they experience the gain or loss $\omega(s,j,k)$ from switching, and are also given a payment (if positive) or made to pay a penalty or tax (if negative) of $a$ dollars per hectare to switch. If $\omega(s,j,k) < 0$, the farmer will switch from $j$ to $k$ without any positive incentive payment, and $r(0,j,k)$ is interpreted as the adoption rate that would occur without any incentive payment or penalty. If a government or other entity wants to encourage additional adoption, a positive incentive can be offered to adopters, in which case the adoption rate is $r(a,j,k) > r(0,j,k)$ for $a > 0$. Conversely, to discourage adoption, a negative incentive (i.e., a penalty or tax) can be imposed on adopters (say, a tax on the decrease in environmental services associated with the use of system $k$). This type of adoption analysis can be used to assess the rate of adoption of an adapted technology under climate change by setting $a = 0$, $j = 2$ and $k = 3$, i.e., by comparing systems 2 and 3 as defined above.

*Climate Impact Assessment and Adaptation*

In a *climate impact assessment*, farmers are initially using system 1 as defined above, and if no adaptation is possible, their only option is to use the same technology when the climate changes (system 2 as defined above). In this type of analysis, equation (2) can be interpreted as showing the proportion of farms with losses less than $a$, i.e., with $\omega(s,1,2) < a$. Thus, $r(0,1,2)$ is interpreted as the proportion of farms that are positively impacted, and $1 - r(0,1,2)$ is interpreted as the proportion of farms that is negatively impacted. For $a > 0$, $r(\text{a},1,2) - r(0,1,2)$ can be interpreted as the proportion of farms that have losses between zero and $a$, for $a < 0$, $r(0,1,2) - r(a,p1,2)$ can be interpreted as the proportion of farms with gains between zero and $-a$.

When farmers are confronted with an environmental change such as climate change, they may choose a different technology that performs better in the new environment, if one is available. This *adaptation* to climate change can be evaluated by considering an adapted technology (e.g., the system 3 described above) under the perturbed climate. Following the system definitions presented above, 1-*r*(0,1,2) is the proportion of farms whose net returns are impacted negatively by climate change, and we expect that with adaptation this proportion would decrease so that 1-*r*(0,1,2) > 1-*r*(0,1,3). Antle (2011a) shows that in an economic adaptation analysis, accurate measurement of the economic, environmental and social impacts of technology adoption must take into account the statistical correlation between factors affecting adoption (e.g., economic returns) and the other outcomes of interest. The TOA-MD model is designed to incorporate these correlations into the simulation of impacts on farm income and income-based poverty. In the analysis presented below, we use these relationships to assess the distributional impacts of technology adoption.

### 3.3. Climate change projections

For climate change projections to 2030, we used data from the IPCC Fourth Assessment report (2007, TYN SC 2.0 dataset (Mitchell et al., 2004)) and spatial and temporal downscaling techniques as described in Thornton et al. (2009a, 2010) and Jones et al. (2009). Data from two Global Circulation Models (GCMs) and two scenarios from the Special Report on Emissions Scenarios (SRES, Nakicenovic et al., 2000) were used. There are considerable differences between different GCMs and SRES scenarios in terms of projected changes in temperatures and rainfall. In this study we used a combination of the HadCM3 (Mitchell et al., 1998) and ECHam4 (Roeckner et al., 1996) GCMs, and SRES A1FI and B1 (very high and low emissions) on the basis of the arguments provided in Thornton et al. (2009a): An analysis by McHugh (2005) on multi-model trends in rainfall for East Africa suggests that certain GCMs are better able to simulate observed rainfall patterns in this region than others. ECHam4 is a ‘‘wet’’ model while HadCM3 is a ‘‘drier’’ model. For emission scenarios, a low-emission scenario (B1) and a high-emission scenario (A1F1) were chosen, which span the range of best estimates of temperature change to 2090–2099 relative to 1980–1999 (IPCC, 2007). While the differences between the SRES scenarios become much more marked by 2100 and beyond, in terms of impacts on temperature, even by 2030 there are differences between the A1FI and B1 scenarios depending on the GCM used. The choices of combination of GCM and emission scenario thus span a wide range of projected temperature and rainfall changes.

### 3.4. Effects of climate change on productivity and simulated adaptation strategies

A summary of model settings for the base, climate change and adaptation scenarios is given in Table 1. To simulate the potential effects of climate change on crop yields, crop growth simulation models as currently implemented in version 4.0 of the Decision Support System for Agrotechnology Transfer (DSSAT, Jones et al., 2003; ICASA, 2007) were used for maize and beans (Thornton et al., 2009a). The yields used are the mean simulated yields of 30 replications (weather years) of four combinations of the two GCMs and SRES scenarios described above. Regarding the impacts of carbon fertilisation on crop yields, there is considerable on-going debate as to the size of the effects on the physiology of crops (Ainsworth et al., 2008; Boote et al., 2011), and there are more uncertainties concerning yield benefits in low-input, rainfed subsistence production systems such as those that prevail in the study region (Thornton et al., 2010). There are also substantial knowledge gaps concerning the impacts of CO2 concentrations and how they may interact with changing ozone concentrations and with other biotic and abiotic stresses (Challinor et al., 2009; Boote et al., 2011). Carbon fertilisation effects are incorporated to some degree in the DSSAT models, but given the uncertainty surrounding this issue, they were not used. Carbon dioxide concentrations were held constant at 330 ppm (Thornton et al., 2009a).

For both crops and both study areas, a declining yield trend is projected, caused by an increased temperature without adequate rainfall (Thornton et al., 2010). A range of feasible adaptation strategies was simulated based on stakeholder consultations (farmers, extension agents, policy makers) in the region. The introduction and adoption of an improved (heat/drought tolerant) maize variety, bringing yields back to 95% of the base level, is tested as an adaptation strategy, 'imz' in Table 1). For sweet potato, Napier grass and the 'mixed crops', no crop growth simulation models are currently available. For Napier grass and 'mixed crops', a 20% yield decline was estimated. The vegetables in Machakos are irrigated and no yield reduction was assumed under climate change. Drought and heat tolerant varieties of sweet potato as well as dual-purpose varieties (roots for food and vines for livestock feed) are currently being promoted in Kenya and in general sweet potatoes are known as a reliable food security crop giving good yields in marginal climatic and soil conditions (Diop, 1998; Bovell-Benjamin, 2007; Andrade et al., 2009). For Vihiga, no yield decline was assumed under climate change for (non dual-purpose) sweet potato. Adoption of dual-purpose sweet potato (DPSP) is tested as an adaptation strategy and treated essentially as a new crop in both study areas (as in Claessens et al., 2009). For Vihiga, yield data for DPSP were taken from on farm field trials in nearby locations in western Kenya and eastern Uganda (Ndolo et al., 2007; Mwanga et al., 2006). For Machakos, yield data for DPSP were obtained from on farm field trials in Kibwezi, which is centrally located in the study area. We tested both the lowest quartile and average yields from these datasets ('dpsplw' and 'dpsp' respectively in Table 1). As an example, the option of substituting half of the area under the 'mixed crops' with DPSP was tested for both study areas.

The physiological effects of increased temperatures on animals and their productivity are well known (Blaxter, 1962; SCA, 1990). However, little information is available at the local level to be able to assess impacts on animal productivity in different systems, especially in the tropics. The main effect of increased temperature is a decreased feed intake due to the inability of animals to dissipate the heat associated with digestion and metabolism of feeds (Blaxter, 1962). Above the thermo-neutral zone, intake may decrease to a point where significant reductions in milk yield can be observed (for systems with little control over the exposure of animals to climate typical of Kenya). For the climate change scenario, as a proxy for heat stress, we tested a 20% milk yield reduction for both study areas, caused by a declined intake of fodder and their respective yield declines (less on farm produced fodder available for feed). Introducing DPSP as an adaptation strategy increases both quantity and quality (mainly crude protein content) of on farm produced animal feed and can substantially improve milk yields and farm incomes, even under the current climate (Claessens et al., 2009). In combination with an anticipated genetic improvement of the animals through both natural and artificial selection as adaptation strategy (Seré et al., 2008; Thornton et al., 2009b), we tested bringing the milk yield back to 100% and 120% of the base production for both study areas ('dpsp1' and 'dpsp12' respectively in Table 1).

In order to obtain a more in-depth analysis of different sub-groups of farmers in the two study areas, the data from Table 1 were disaggregated in the TOA-MD model for farmers with and without dairy production. A third category of farmers, those with access to irrigation, was differentiated for Machakos.

3.5. Representative Agricultural Pathways and Socio-economic Scenarios

Most agricultural climate impact assessments in the published literature have evaluated the impacts of climate change on current or adapted technologies within historical or present socio-economic conditions. It would be desirable to evaluate potential climate change impacts under plausible future socio-economic scenarios that are consistent with the assumptions that were used to generate climate change simulations. Until now, the most widely used scenarios for climate impact assessment are the ones presented in the Special Report on Emissions Scenarios (SRES, Nakicenovic et al., 2000). However, these scenarios had a number of important methodological limitations; in an attempt to improve the approach, the global climate modeling and impact assessment communities are developing two new concepts, Representative Concentration Pathways or RCPs and Shared Socio-economic Pathways or SSPs (Carter et al., 2011). The concept of Representative Agricultural Pathways (RAPs) has been proposed as a way to extend these scenario concepts to be more relevant to agricultural models (Antle, 2011b). RAPs include global economic conditions, such as rates of growth in aggregate agricultural productivity, as well as region-specific agricultural and economic development conditions that can be used in disaggregate models such as the TOA-MD model. However, as of this writing, a consensus has not been reached on the details of SSPs, and as a result fully developed RAPs are not yet available. In this study, in addition to current conditions we propose two RAPs that are broadly consistent with the types of SSPs that are currently under development. The proposed SSPs correspond to future worlds characterized by different degrees of *adaptation challenges* and *mitigation challenges.* Here we focus on RAPs that correspond to different degrees of adaptation challenges, because we are not going to directly incorporate analysis of greenhouse gas mitigation into the analysis. Thus we consider two RAPs that correspond to low and high degrees of adaptation challenges, based on the following qualitative storylines:

*RAP1: low adaptation challenges*. Kenya follows a more positive economic development trajectory than the past 30 years, with higher rates of economic growth, movement of labor out of agriculture into other sectors, reductions in rural household size, and increases in farm size. Investments in transportation and communication infrastructure, and more open trade and liberalized domestic policies lead to higher real prices for traded agricultural commodities such as maize in Kenya, in part due to the projected higher real prices of maize due to global demand growth and slowing global productivity growth due to climate change and other factors. Policy changes and infrastructure improvements also lead to lower real prices of critical agricultural inputs such as mineral fertilizer and improved seeds.

*RAP2: high adaptation challenges*, even greater than the current situation. Kenya continues to experience a low rate of economic growth. Population growth rates remain high and rural populations increase, farm size declines, rural household sizes increase. Transportation infrastructure deteriorates, trade policy discourages exports so that prices to farmers remain at current levels, but policy imposes high taxes on imports of critical inputs such as fertilizers. Soil fertility and agricultural productivity continue to decline to an even lower level equilibrium than was observed in the early part of the 21$^{st}$ Century.

Corresponding to these RAPs, we develop parametric scenarios for 2030 as shown in Table 1. We translated the qualitative RAPs into quantitative scenarios by making assumptions about compound annual rates of change from the baseline values from 2012 to 2030 for prices, costs of production and farm size in the range of +/- 1% per year. For maize price changes, we followed the results of global modeling studies which indicate that the combined effects of demand growth and climate change are likely to increase real maize prices from the present until at least mid-century (Foresight, 2011). For RAP1, in addition to the socio-economic parameter settings in Table 1, more land was allocated to maize compared to the base system, consistent with the increased expected returns from maize under RAP1 (half of the area under mixed and Napier grass in the base system was converted to maize for both study areas). In order to be consistent with the qualitative storylines of the RAPs, we analyzed the impacts of climate change under both RAP1 and RAP2 scenarios but only simulated adaptation strategies ('imz' and 'dpsp') for RAP1 (low adaptation challenges).

#Table 1 approx. here#

3.6. Effects of climate change, adaptation strategies and socio-economic scenarios

We start our analysis by assessing the impacts of climate change and adaptation, keeping socio-economic parameters of the base and alternative systems constant. Results of the TOA-MD analysis aggregated across farm types for both study areas are shown in Figure 2. The interpretation of the curves representing the farm population is as follows: The point where a curve crosses the x-axis shows the percentage of farms that gain from the scenario (i.e., the value $r(0,j,k)$ discussed in section 3.2). Accordingly, the points on a curve to the left of where it crosses the x-axis show the percentage of farms with *gains* (i.e., negative losses) greater than the amount shown on the vertical axis. Conversely, points to the right of where a curve crosses the x-axis show the percentage of farms with *losses* less than or equal to the amount on the vertical axis. Figure 2 shows that climate change is projected to have a negative economic impact on 76% of the farmers in Vihiga and on 62% in Machakos. By testing different adaptation strategies with the TOA-MD model, we can simulate aggregate economic impacts on the farm population in each of the study areas. Figure 2 shows that, in the aggregate, the different adaptation strategies simulated have a higher impact on the farm population in Vihiga than in Machakos. The 'best' adaptation strategy (dpsp12) can bring back the percentage of farmers loosing from climate change from 76 to 37% in Vihiga, but only from 62 to 50% in Machakos.

As explained in the methodology, the TOA-MD model can also be used to analyze the effects of different adaptation strategies on poverty rates, net losses (calculated here as the percentage loss relative to the base system agricultural income), and can calculate adoption rates (economic feasibility) of these strategies. Both disaggregated and aggregated impacts of climate change and the simulated adaptation strategies are shown in Table 2. The base poverty rate (expressed as % of farm population living on <$1 a day) in Machakos is higher than in Vihiga (73 vs. 62%), but in terms of net losses in percent of mean agricultural income, Vihiga and Machakos are equally negatively impacted (27 to 32% loss). The introduction of an improved maize variety as adaptation strategy (bringing back yields to 95% of the base level), has a profound effect in Machakos, offsetting the negative effects of climate change at the aggregate level (poverty rates are back to the base level of 73% and there is an aggregate net gain of 20%; dairy farmers are still losing tough, as they have less land allocated to maize than non-dairy farmers). In Vihiga this introduction of improved maize brings back the poverty rates from 69 to 65% but farmers are still losing compared to the base system. Substituting half of the mixed system with low yielding DPSP (dpsplw) hardly reduces the percentage of farmers that are negatively affected by climate change in Vihiga but reduces this from 62 to 57% in Machakos (Fig. 2). This strategy has a similar effect than the improved maize option in Machakos. Increasing the average yield of

DPSP to the observed levels but keeping the loss in milk yield at 20% (dpsp), has a positive effect in both study areas (negatively affected farmers to 63% in Vihiga and to 54% in Machakos). On aggregate, Vihiga is still negatively impacted by climate change but non-dairy farmers are already gaining from this strategy (the poverty rate is back to the base level and there is a net revenue gain of 7%). By increasing milk yields to 100 and 120% of the base level, Machakos has limited additional gains, whereas in Vihiga the percentage of negatively affected farmers goes down to 50 and 37% respectively and adoption rates (defined here as the percentage of farmers economically benefiting from an adaptation strategy) go up to 84% in the aggregate and 90% for the dairy farmers. In general, this analysis indicates that introduction of an improved maize variety or a low yielding DPSP in the cropping system of Machakos would be sufficient to offset the negative impacts of climate change. For Vihiga, average yielding DPSP together with improved feed and/or livestock breeds that can produce 100% of the base milk yield under climate change, are needed to fully offset the impacts of climate change. The disaggregated results in Table 2 show that farmers with dairy in Vihiga benefit relatively more from increases in milk yield than dairy farmers in Machakos. Vihiga has a larger percentage of dairy farmers in the population (62 vs. 15% in Machakos) and higher base milk yields and net returns (Table 1). Accordingly, the increased milk yield does not affect the adoption rates in Machakos as much as it does in Vihiga.

By introducing the socio-economic scenarios (RAPs) in the analysis, we can look at the effect of these scenarios on the impacts of climate change and adaptation strategies ('imz' and 'dpsp' for RAP1 only as explained above). For the optimistic *low adaptation challenges* scenario (RAP1), the base poverty rates are much lower compared to the previous analysis (41 vs. 62% for Vihiga, 60 vs. 73% for Machakos). Climate change is bringing up the poverty rates to 44 and 64% and causes aggregate net losses of 8 and 19%. Both adaptation strategies simulated are able to offset the negative impacts of climate change in both study areas, which is consistent with the low adaptation challenges concept under RAP1. The effect of the adaptation strategies on poverty rates is less important because increased off-farm income in the scenario dominates the effect of increased production under climate change adaptation. For the negative *high adaptation challenges* scenario (RAP2), base poverty rates are higher than for the previous analysis (68 and 79%). Climate change is bringing the poverty rates up to 71 and 81% and causes aggregate net losses of 10 and 16%. No adaptation strategies were simulated, consistent with this scenario.

#Figure 2 approx. here#

#Table 3 approx. here#

## 4. DISCUSSION

In this paper we proposed the TOA-MD model as a methodology to test climate change adaptation strategies with limited data, that is with data that are typically available in countries where small-scale, semi-subsistence agricultural systems predominate. There is however an inherent weakness in using this type of data, which limits the confidence in modelled outcomes. The real issue of course is how much certainty one can gain with expensive and time consuming gathering of additional data or parameterizing more complex models. For both examples, existing datasets (farm surveys) were used to characterize the base systems. Various assumptions had to be made; hence substantial uncertainty is associated with the parameterization of the climate change, adaptation and socio-economic scenarios.

The results in Table 2 for the irrigated system in Machakos provide some insight into the challenges researchers face in making reliable estimates of impact and adaptation with limited data. In the case of the irrigated farms, Table 2 shows a very large positive impact of the adapted technologies. However, this result appears to be due to the fact that the maize and other crop yields are unusually high on these farms, perhaps because the available irrigation is benefitting not only vegetables but other crops as well. As a result, the estimates of climate change impacts on maize, and the potential benefits of an adapted maize variety or the introduction of dual-purpose sweet potato -- based on data representing rainfed systems -- are not appropriate if these crops are also benefitting from the available irrigation. However, estimates of climate change impacts on these crops in irrigated systems are not available, thus illustrating the data challenges that researchers can face when highly heterogeneous conditions are encountered.

As mentioned in the methodology, there is already a high level of variability in climate projections between different GCMs and SRES scenarios and we chose to use a specific combination of GCMs and SRES spanning a wide range of projected temperature and rainfall changes. More uncertainty is added when downscaling GCM data to the appropriate spatial and temporal resolution to be used in the DSSAT crop growth simulation models. And there is the parameterization of the crop growth models itself which is generalizing genetic coefficients for maize and beans. Hence it is worth stressing that the projected yield changes to 2030 should merely be seen as a mean response in relation to all possible combinations of GCMs and SRES scenarios, making use of the best information we can currently obtain from crop growth simulation and downscaled climate projections.

It is also likely that the impacts of climate change on productivity are underestimated because the effects of increasing climate and weather variability have not been included (and this is one of the biggest constraints in rainfed agriculture). Methods are becoming available to evaluate the effects of climate variability at the agricultural system level (Cooper et al., 2008), but there are still challenges to use the relatively coarse data of GCMs at an appropriate spatial and temporal resolution (Baethgen, 2010; Thornton et al., 2010).

CO2 fertilization effects were not included in our analysis based on the many uncertainties associated with it (see methodology and Thornton et al., 2010).

Productivity changes for crops other than maize and beans and for milk were estimated based on the trends for maize and beans and information we obtained from the literature. As our analysis of dual-purpose sweet potato and dairy illustrates, changes in productivity can be subjected to a sensitivity analysis. If the results are found to be sensitive to the inherent uncertainty in the available data, then further analysis is called for. For example, in the case of dairy productivity, it may be possible to improve the quality of estimates using more detailed livestock models that account for the effects of climate and feed quantity and quality on livestock productivity (e.g. Herrero et al., 2008).

The TOA-MD methodology utilized here is based on economic feasibility (expected profitability). Accordingly, the simulated adoption rates can be interpreted as providing an upper bound on likely adoption rates because other factors that have been found to be important in technology adoption, such as financial constraints, risk aversion and cultural considerations are not taken into account (see Sunding and Zilberman 2001; Claessens et al., 2009).

The main reasons why introduction of DPSP as an adaptation strategy is economically viable for a relatively large percentage of farms appear to be the relatively high yields, net returns and the positive effect of increased feed quality on milk production and income. The researchers who collected the DPSP yield data from on farm field trials (Mwanga et al., 2006, Ndolo et al., 2007) suggest that the yields they observed are higher than most farmers would achieve because crop management and soil conditions would be less favorable than in the farm trial sites. A sensitivity analysis was therefore conducted using low yielding DPSP as one of the adaptation strategies.

Both Vihiga and Machakos are broadly representative of agricultural systems in other parts of East Africa. By using an agricultural systems classification like the one by Seré and Steinfeld (1996) or Robinson et al. (2011) e.g., results of the analysis, when interpreted with caution, could be scaled up to the agricultural system and regional scale levels.

## 5. CONCLUSION

The development and application of relatively simple and reliable methods for assessing the impacts of climate change and adaptation strategies at the agricultural system and/or household level are needed to provide timely recommendations on the potential impacts of alternative technologies and policies. In this paper, the TOA-MD model was presented as a method to evaluate the impacts of climate change and the economic viability of adaptation strategies using the kinds of data that are typically available in countries where semi-subsistence systems are important. The method was applied to the mixed crop-livestock systems of the Vihiga and Machakos study areas in Kenya. With a combination of simulated and estimated changes in crop and livestock productivity, the economic impacts of climate change to 2030 were analyzed. Climate change is projected to have a negative economic impact on 76% of the farmers in Vihiga and on 62% in Machakos. Different adaptation strategies were tested by changing crop and livestock productivity under climate change and by introducing socio-economic scenarios based on Representative Agricultural Pathways. The analysis suggests that introducing an improved maize variety or low yielding DPSP in the cropping system of Machakos may be sufficient to offset the negative effects of climate change, whereas improved feed quantity and quality in combination with improved livestock breeds that can perform better under climate change are an additional requirement for adaptation to climate change and improvement of farmers' livelihoods in Vihiga. As in all scenario studies using models, and especially in the context of climate change, various assumptions and uncertainties are associated with using the proposed approach and results should be interpreted with caution. Despite these limitations, the methodology presented in this study shows the potential to yield new insights into the way that realistic adaptation strategies could improve the livelihoods of smallholder farmers operating in the mixed crop-livestock systems in East Africa and other parts of the world.

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**Table 1.** Summary of data used in the TOA-MD sensitivity and scenario analysis. Characterization of base system from survey data (means with standard deviation between brackets). Alternative systems are expressed as % of base system values for productivity (100%).

| **Vihiga** | **Base System** | | | **Alternative Systems*** | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | *System 1* | | | *System 2* | *System 3* | | | | | | |
| | Area | Crop Yield | Net Returns | CC 2030 | imz | dpsplw | dpsp | dpsp1 | dpsp12 | RAP1 | RAP2 |
| | Ha/season/farm | Kg/ha/season | KSh/ha | ---------------------------% of base system----------------------------------------------- | | | | | | | |
| Maize-Beans | 0.24 (0.21) | 1512 (1319) | 15360 (16726) | 70 | 95 | 70 | 70 | 70 | 70 | | |
| Napier Grass | 0.16 (0.19) | 34450 (23643) | 22366 (23545) | 80 | 80 | 80 | 80 | 80 | 80 | | |
| Mixed | 0.23 (0.21) | 4031 (1701) | 27551 (15971) | 80 | 80 | 80 | 80 | 80 | 80 | | |
| Sweet potato | 0.05 (0.04) | 4006 (2092) | 11587 (8352) | 100 | 100 | 100 | 100 | 100 | 100 | | |
| Dpsp roots | - | 8000 (3676) | 27618 (13233) | - | - | 38 | 100 | 100 | 100 | | |
| Dpsp vines | - | 14800 (8036) | 21018 (12054) | - | - | 70 | 100 | 100 | 100 | | |
| | | Liters/season/farm | | | | | | | | | |
| Milk | - | 3211 (2473) | 52317 (51723) | 80 | 80 | 80 | 80 | 100 | 120 | 120 | 80 |
| Maize price | | | | | | | | | | 130 | 100 |
| Maize cost | | | | | | | | | | 90 | 110 |
| Milk price | | | | | | | | | | 140 | 100 |
| Farm size | | | | | | | | | | 120 | 80 |
| Off farm income | | | | | | | | | | 150 | 100 |
| **Machakos** | **Base System** | | | **Alternative Systems*** | | | | | | | |
| | *System 1* | | | *System 2* | *System 3* | | | | | | |
| | Area | Crop Yield | Net Returns | CC 2030 | imz | dpsplw | dpsp | dpsp1 | dpsp12 | RAP1 | RAP2 |
| | Ha/season/farm | Kg/ha/season | KSh/ha | --------------------------% of base system------------------------------------------------ | | | | | | | |
| Mixed | 0.95 (1.39) | 1187 (1631) | 7085 (13313) | 80 | 80 | 80 | 80 | 80 | 80 | | |
| Maize | 0.78 (0.79) | 1597 (1624) | 12704 (16996) | 74 | 95 | 74 | 74 | 74 | 74 | | |
| Beans | 0.44 (0.59) | 1390 (1374) | 24658 (17942) | 74 | 74 | 74 | 74 | 74 | 74 | | |
| Vegetables | 0.75 (1.00) | 4121 (3369) | 40718 (139490) | 100 | 100 | 100 | 100 | 100 | 100 | | |
| Napier Grass | 1.49 (3.10) | 12318 (14435) | 11310 (18146) | 80 | 80 | 80 | 80 | 80 | 80 | | |
| Dpsp roots | - | 7100 (4501) | 24475 (16204) | - | - | 42 | 100 | 100 | 100 | | |

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Dpsp vines | - | 12600 (9013) | 18900 (13520) | - | - | 83 | 100 | 100 | 100 | | |
| | | Liters/season/farm | | | | | | | | | |
| Milk | - | 1784 (1992) | 39238 (48208) | 80 | 80 | 80 | 80 | 100 | 120 | 120 | 80 |
| Maize price | | | | | | | | | | 130 | 100 |
| Maize cost | | | | | | | | | | 90 | 110 |
| Milk price | | | | | | | | | | 140 | 100 |
| Farm size | | | | | | | | | | 120 | 80 |
| Off farm income | | | | | | | | | | 150 | 100 |

* CC = climate change, imz = improved maize, dpsp = dual purpose sweet potato, dpsplw = low yielding dpsp, dpsp1 = dpsp with 100% of base milk yield under CC, dpsp12 = dpsp with 120% of base milk yield under CC, RAP = Representative Agricultural Pathway (as explained in the text).

**Table 2.** Impacts of climate change, simulated adaptation strategies and socio-economic scenarios on farmers in Vihiga and Machakos.

| **Vihiga** | | | | **Machakos** | | | |
|---|---|---|---|---|---|---|---|
| **Poverty Rate (% of farm population living on <$1 per day)** | | | | | | | |
| Scenario | No Dairy | Dairy | Total | No Dairy | Dairy | Irrigated | Total |
| base | 85 | 38 | 62 | 85 | 43 | 54 | 73 |
| CC | 89 | 49 | 69 | 89 | 51 | 57 | 78 |
| imz | 87 | 42 | 65 | 85 | 44 | 50 | 73 |
| dpsplw | 88 | 42 | 66 | 85 | 44 | 50 | 73 |
| dpsp | 85 | 41 | 63 | 83 | 43 | 50 | 71 |
| dpsp1 | 85 | 36 | 60 | 83 | 41 | 49 | 71 |
| dpsp12 | 85 | 30 | 58 | 83 | 38 | 48 | 70 |
| | | | | | | | |
| RAP1 base | 65 | 17 | 41 | 72 | 30 | 46 | 60 |
| RAP1 CC | 71 | 18 | 44 | 77 | 33 | 47 | 64 |
| RAP1 imz | 66 | 15 | 41 | 70 | 27 | 40 | 58 |
| RAP1 dpsp | 65 | 15 | 40 | 69 | 27 | 40 | 57 |
| | | | | | | | |
| RAP2 base | 89 | 48 | 68 | 91 | 50 | 57 | 79 |
| RAP2 CC | 91 | 50 | 71 | 93 | 53 | 57 | 81 |
| **Net Loss (percentage of mean agricultural income in base system)** | | | | | | | |
| CC | 26 | 27 | 27 | 32 | 31 | 33 | 32 |
| imz | 8 | 11 | 11 | -16 | 6 | -50 | -20 |
| dpsplw | 13 | 12 | 12 | -23 | 5 | -49 | -23 |
| dpsp | -7 | 9 | 6 | -31 | 3 | -51 | -27 |
| dpsp1 | -7 | -5 | -6 | -31 | -7 | -65 | -34 |
| dpsp12 | -7 | -23 | -21 | -31 | -19 | -80 | -43 |
| | | | | | | | |
| RAP1 CC | 30 | 5 | 8 | 35 | 11 | 12 | 19 |
| RAP1 imz | 4 | -5 | 3 | -23 | -8 | -44 | -27 |
| RAP1 dpsp | 2 | -6 | -5 | -27 | -8 | -42 | -28 |
| | | | | | | | |
| RAP2 CC | 26 | 7 | 10 | 25 | 14 | 8 | 16 |
| **Adoption Rate (percentage of farm population)** | | | | | | | |
| imz | 62 | 52 | 56 | 54 | 51 | 51 | 53 |
| dpsplw | 52 | 51 | 51 | 58 | 53 | 50 | 56 |
| dpsp | 74 | 57 | 64 | 61 | 55 | 51 | 59 |
| dpsp1 | 74 | 77 | 77 | 61 | 65 | 55 | 61 |
| dpsp12 | 74 | 90 | 84 | 61 | 74 | 59 | 63 |
| | | | | | | | |
| RAP1 imz | 71 | 56 | 62 | 57 | 54 | 52 | 56 |
| RAP1 dpsp | 73 | 58 | 64 | 60 | 55 | 51 | 58 |

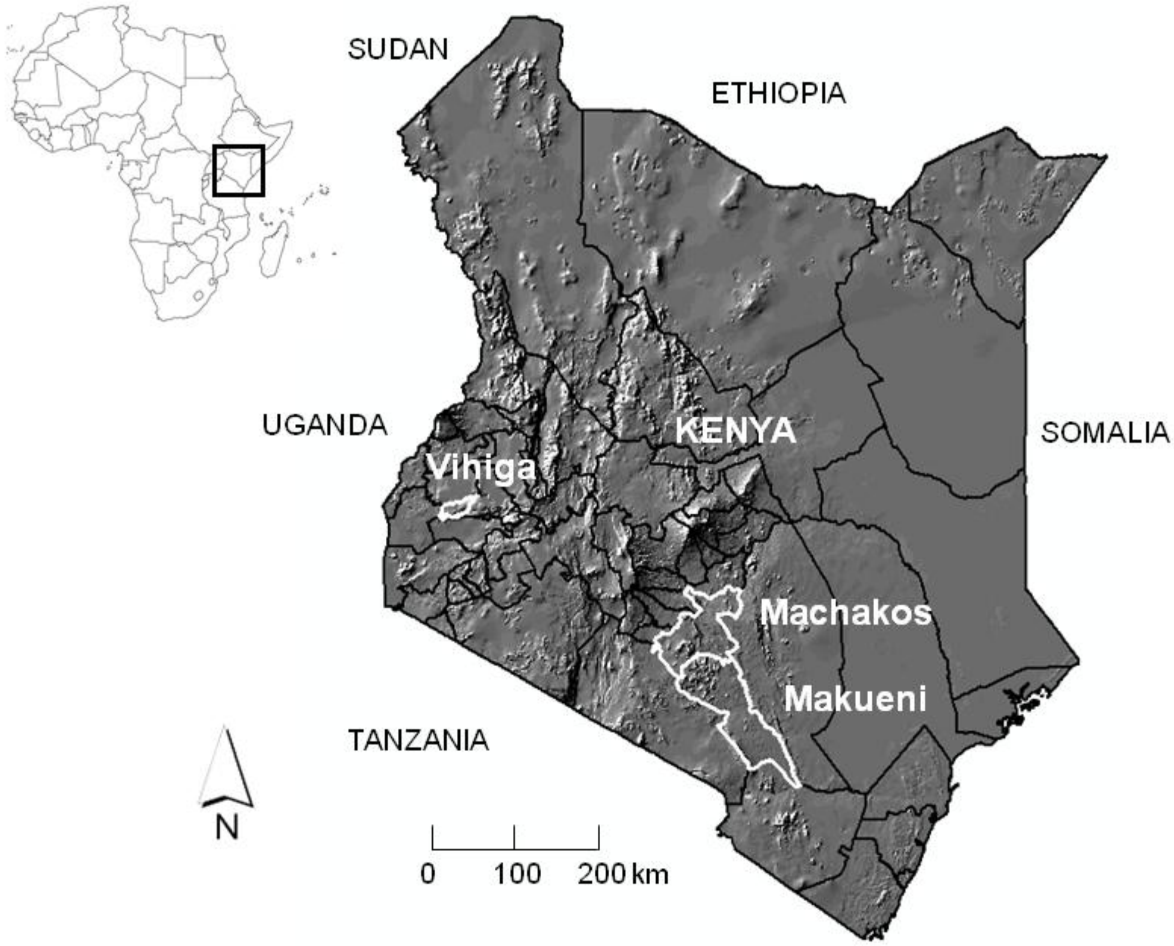


**Figure 1.** Location of the study areas in Kenya. The Machakos study area comprises both Machakos and Makueni districts.

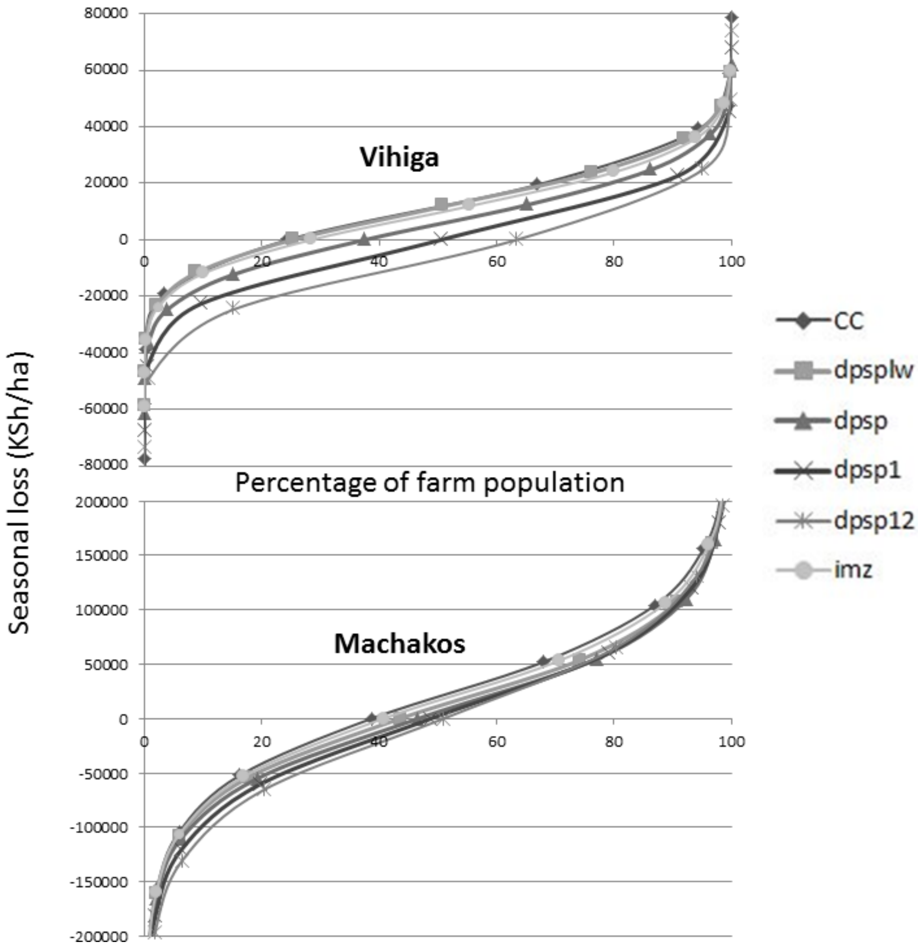


**Figure 2.** Economic impact of climate change and simulated adaptation strategies on farmers in Vihiga and Machakos, Kenya. Notation of legend as in Table 1.