# The Interplay Between Smallholder Farmers and Fragile Tropical Agroecosystems in the Kenyan Highlands

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## 1. Introduction

That farmers rely on the land for their livelihoods is obvious. The converse, that ecosystem services depend on farmers' behaviors, must also be recognized if agricultural productivity is to be improved. In sub Saharan Africa, the 70% of the population employed in the agricultural sector (Sanchez 2002) is engaged in an on-going 'dialogue' with the agricultural natural resource base. Recently, this conversation has not been going well: per capita food production has remained stagnant for the last 40 years so now 180 million on the continent lack adequate food, a number that has increased by 100% since 1970 (Sanchez 2002). To provide adequate diets to the African population, increases in crop yields of 3.0 to 3.5% $y^{-1}$ are needed (Reardon *et al.* 2001), but such increases have not been realized as average maize yields have remained static at 1200 kg $ha^{-1}$.

Annual nutrient losses of 22 kg of nitrogen, 2.5 kg of phosphorus and 15 kg of potassium per hectare of arable land across sub Saharan Africa illustrate the severity of soil depletion which contributes to low crop yields (Smaling *et al.* 1997). In the highlands of western Kenya, the situation is worse: annual losses of 112 kg N, 2.5 kg P and 70 kg K have been observed (Smaling *et al.* 1993). Annual fertilizer applications on African agricultural soils are only 9 kg $ha^{-1}$ compared to 83 kg $ha^{-1}$ elsewhere in the developing world (Reardon *et al.* 2001). The combination of high fertilizer costs and low incomes explains this low level of fertilizer use. Fertilizer costs 1.4 to 2 times more in sub Saharan Africa than it does in other parts of the developing world (Jayne *et al.* 2003a) and more than half of the African population earns less than $1 per day. In Kenya, fertilizer use has increased since 1996 to 31.6 kg $ha^{-1}$ arable land in 2000 (Jayne *et al.* 2003b) with the highest application rates on cash crops such as wheat, sugar cane and tea (Jayne *et al.* 2003a). However, the total fertilizer application of the farmers in our study was only 8.8 kg ha$^{-1}$, far below the average of 31.6 kg cited by Jayne et al. ( 2003b). In our study areas where 53-56% of the population falls below the Kenyan poverty line of \$.55 day$^{-1}$, a 50 kg bag of diammonium phosphate fertilizer costs about a month's wages for those at the poverty line (Central Bureau of Statistics & International Livestock Research Centre 2003). This amount of fertilizer can provide sufficient fertilizer for only half a hectare of maize using current fertilizer recommendations in western Kenya.

Poverty reduction depends on understanding why people fall into poverty and how they escape. More important in this discussion of poverty dynamics than arbitrary poverty lines is understanding whether people are mired in chronic poverty or whether poverty represents a transitional state from which they are likely to emerge (Barrett 2003). Development of appropriate policy hinges on our understanding of where ladders are needed to allow people to climb out of poverty and what chutes must be blocked to avoid transitory or long-term descents into poverty. Depletion and repletion of soil nutrients and other natural resource assets are contingent on poverty dynamics as the farmers' abilities to invest in their environment is determined by their economic status.

Poverty dynamics in the Kenyan highlands depend on the interplay of human and natural systems on the smallholder farms common in this area. These farms operate at the margin: small changes in the natural resource base often have large effects on people's lives. Conversely, modest changes in human activity may significantly affect ecosystem functioning. To capture the complexity of these Kenyan agroecosystems, we will develop a dynamic, bioeconomic model. Our goal is to model the linkages between biophysical and economic processes and calibrate the model to identify threshold levels of ecosystem services. Our organizing concept for the economic drivers is the poverty trap.

Poverty traps are an old idea in economics (Young 1928, Rosenstein-Rodan 1943). Most conventional economic growth models assume that aggregate economic performance is the simple sum of the performance of independent or loosely-coupled economic agents. These models either converge to a globally asymptotically steady state, grow without bound or collapse. In contrast, models with strong feedbacks from aggregate performance back to the individuals can exhibit more complicated dynamic behavior, with multiple stable steady states and basins of attraction. The low-end basins of attraction are poverty traps. System forces tend to push those in the basin to remain therein, but an economic agent who climbs over the wall will be pushed to higher levels of income. The usual source of poverty traps in the contemporary literature has to do with positive feedback effects across individuals (Diamond 1982). In our model, the source of poverty traps is the shift in ecosystem services that result from the different agricultural techniques practiced by wealthy and poor farmers.

The purpose of the National Science Foundation’s Biocomplexity Initiative is to foster study of complex ecosystems and encourage the development of integrated frameworks to provide synthesis across societal, spatial and temporal scales (NSF Advisory Committee for Environmental Research and Education 2003). To capture the many interactions between physical, biological and decision-making processes in bioeconomic systems, new ways of doing ecosystem science are needed. Common languages that permit discussion among people in diverse academic fields without losing the subtleties inherent in disciplinary lingo are needed. New approaches to handling and analyzing data are required: dynamic modeling techniques will largely supplant analyses of variance in determining how natural and human systems respond to shocks such as illness, drought, and pests. Likewise, spatial and temporal heterogeneity pose formidable challenges: soil processes mediated by bacteria happen on spatial scales of $10^{-6}$ m within seconds, crop rotations occur at scales of $10m^2$ to 100 $m^2$ over months to years and soil formation requires eons.

Small farms experiencing soil degradation provide an ideal context in which to investigate interactions between human behavior, natural capital stocks, and the flow of ecosystem services. Farmers make decisions about land use and improvements, such as selection of crop varieties, livestock management strategies, soil input applications and labor allocations. These decisions fundamentally affect the growth of plants, production of livestock and functioning of soil micro- and macrofauna, which in turn affect soil structure and chemistry. By improving the productivity of smallholder farmers across the developing world, it should be possible to come closer to meeting two of the United Nations’ Millennium Goals: by 2015 both the number of people living on less than \$1 $day^{-1}$ and those who are hungry should be reduced by 50% (United Nations General Assembly 2000).

A variety of smallholder agricultural systems models with varying purposes have been developed (Shepherd & Soule 1998, De Jager *et al.* 1998, Barbier 1998, Van Noordwijk & Lusiana 1999, Ruben *et al.* 2001, Okumu *et al.* 2002, Van Noordwijk 2002, Stoorvogel *et al.* 2004). At one end of the spectrum are models which focus almost entirely on biological process, with only a rudimentary human action component. At the other end are primarily economic models with few biophysical features. Models also differ in their spatial, societal and temporal scales and in the extent to which dynamic feedback loops are included. Antle et al. ( 2001) provide a useful framework for the characterization of these models of managed ecosystems. They differentiate between 1) stylized theoretical models that abstract empirical details to predict ecosystem function, 2) models that rely on linking disciplinary models for an integrated assessment with varying degrees of coupling and 3) models that are "fully integrated" without disciplinary boundaries. The extent of coupling is important because it determines the extent to which feedback within the model is possible. Models that are too loosely coupled are unable to capture the interesting nonlinear behaviors and feedbacks that typify agroecosystems. However, it is not feasible to develop a completely integrated ecosystem model. To capture the behavior of soil microbes, important ecosystem engineers, short time steps are necessary, but larger steps are needed to account for intergenerational poverty dynamics. Because of the difficulties in resolving different spatial and temporal scales, models that are too tightly coupled are fragile and usually are not generalizable to other similar systems.

## 2. Research Approach and Methods

Below is a brief description of our research sites, research methods and modeling approach. During the first phase of the research, our emphasis has been on hypothesis development, model elaboration and collection of field data. Our funding began just a year ago, so we are still working on model development, collecting data and piecing together data from earlier studies in order to develop a panel data set of farmers' socioeconomic status and behavior. The second phase of the project will focus on estimation of the model and simulations of the consequences of different policy regimes.

## A. Research Sites

Our two research sites are Embu, located in central Kenya on the shoulder of Mount Kenya and Madzuu in the Vihiga District in Western Kenya in the Lake Victoria basin. The primary farm enterprises in Embu are tea, coffee, dairy, maize, bananas and home gardens (vegetable gardens primarily for home consumption but with some sales of surplus). In Madzuu, there are limited amounts of tea, dual purpose cattle with a few dairy cows, home gardens and intercropped maize and beans and maize and groundnuts. These sites both are considered to have high agricultural potential due largely to their reliable and adequate rainfall, but they differ in market access. Embu is within two hour's drive of Nairobi on paved roads while Madzuu has more limited access to Kisumu, Kenya's third largest city. Characteristics of the two sites are presented in Table 1.

## B. Empirical Data Collection

How the data on economics, social behavior, soil fertility and crop productivity, and livestock needed to parameterize and evaluate the model will be collected is described below. In each section, we provide a short overview of the types of questions we are posing and then describe how we will obtain the needed information.

## 1. Socio-economic Data

We are exploring within- and between-site variation in assets, income and expenditures to unravel the causes of persistent poverty. Do household-level welfare dynamics support the existence of poverty traps that make escape from poverty difficult? And where are the tipping points? There seems to be a fundamental difference between short-term deprivation or transitory poverty, where the prospects of the poor becoming non-poor in the near term are good, and long-term, persistent poverty. While any poverty is undesirable, persistent poverty is a distinct and pernicious phenomenon. Reduction of persistent poverty requires careful study of its causes and rigorous assessment of how people can avoid or escape it. One view of poverty amelioration is that if people can be given just a little edge, they will be able to get ahead. For people in poverty traps, this is not true.

The boosts required to get onto a wealth accumulation path can be considerable (Barrett 2003). There are many purely economic poverty traps such as inadequate access to capital markets. We are exploring those poverty traps which emerge from soil biology and the economics of farm management. The poor can only afford agricultural practices that rapidly deplete their soil, dropping farm productivity and further reducing returns to farming.

The existence of widespread persistent poverty raises the possibility of “poverty traps,” states into which individuals, households, or even entire communities or nations might fall and from which escape is difficult (Barrett 2003). Nonlinear welfare dynamics with multiple equilibria (different steady states toward which households naturally gravitate at least one of which is below an appropriately defined poverty line) are characteristic of poverty traps. Capturing the economic aspects of poverty traps is complicated enough but we also must link poverty dynamics with human responses and the impact that these have on the biophysical environment.

In order to capture poverty dynamics, measurements over time are required. To this end, we have used panel questionnaires to obtain data on household structure, agricultural assets, expenses and production, and off-farm income. We are relying on previously collected panel data from Madzuu and Embu collected under the auspices of the BASIS CRSP project funded by the United States Agency for International Development (USAID)[1] for the initial time points. Each site’s baseline survey was designed for a somewhat different purpose so the data are imperfectly comparable across sites, although we have taken care to ensure consistency across survey periods within each site. In the Embu site, we resurveyed 113 households that had been surveyed previously. However, data from the initial survey were suspect so the Embu data set includes panels from 2002 and 2003 which have been only partially analyzed. In western Kenya, 89 households in Madzuu location in Vihiga District that had originally been surveyed in 1989 were

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[1] US AID Grant LAG-A-00-96-90016-00 “Rural Markets, Natural Capital and Dynamic Poverty Traps in East Africa”, principal investigator Christopher B. Barrett.

sampled again in 2002. Because the Embu data are not complete, our focus in this paper is on Madzuu.

Finally, we followed up the panel survey data collection with qualitative poverty appraisals in each site. These appraisals involved both community-level focus group meetings and key informant interviews to establish local conceptualizations of poverty and community-level phenomena that have affected household wealth trajectories. In depth case studies were used to construct social-historical profiles of distinct household types characterized by observed welfare transitions. Per capita income transition matrices at the household level have helped to establish which households have moved into or out of poverty from one period to the next. We also identified households that had remained poor or non-poor in both periods. In these household level interviews and subsequent community meetings, we looked at the historical context underpinning local households' strategies to improve their welfare and the pathways by which certain households collapse into or escape from poverty.

A second set of questionnaires, focus groups and key informant interviews are underway to determine how farmers make decisions about allocation of financial and natural resources. These activities are designed to elicit perceptions of soil fertility, to learn the criteria used to decide what crops to plant and where, and to find out how people balance risk and the prospects of greater incomes. During the focus group discussions, the participants were disaggregated by age and gender to capture differences among these groups.

## 2. Soil Degradation and Repletion

That soil degradation plays an important role in poverty in the Kenyan highlands has been clearly established (Place *et al.* 2003), but the rates at which degradation occurs and at which lost nutrients can be repleted must be established. Critical to our understanding of these dynamics is determining whether irreversible thresholds exist. At what point, does soil become so degraded that rehabilitation is not practical? Our focus is on soil organic matter (SOM) because it is critical in maintaining the fertility of weathered, tropical soils (Craswell & Lefroy 2001). We also are studying N and P dynamics which are strongly related to SOM status in these soils. Organic matter including nitrogen (N) and phosphorus (P) pools can be fractionated by particle size, density and aggregate size (Cambardella & Elliott 1993, Barrios *et al.* 1996, Feller & Beare 1997, Maroko *et al.* 1998, Solomon & Lehmann 2000, Lehmann *et al.* 2001). These fractionation methods describe pools of SOM with different turnover times, those that are labile and those that are stable (Parton *et al.* 1987). Of particular importance for our study is the identification of functional SOM pools (Feller *et al.* 2001), which give information about reversibility and threshold levels of degradation. A loss of SOM from labile pools may occur at very early stages of soil degradation and can be readily detected by the techniques mentioned. Replenishment of these pools is easily achieved by appropriate management interventions such as green manuring (Lehmann *et al.* 1998) or short-term fallows (Barrios *et al.* 1997). On the other hand, depletion of stable SOM pools often protected in aggregates and organo-mineral complexes (Schulten & Leinweber 2000) indicates more severe soil degradation as a result of long-term or intensive cropping without replenishing SOM. This soil degradation may not be readily reversible and more drastic changes in land use practices will have to be introduced to improve soil productivity (Solomon & Lehmann 2000, Solomon *et al.* 2000). The soil submodel describes the extent of soil degradation as a function of (i) time under cultivation, (ii) land management (using an organic matter and nutrient balance on the farm level; comparison between poorer and richer farmers and their respective soil erosion and/or conservation effects), and (iii) market access for purchased fertilizer or manure amendments, which varies by site.

To better understand the dynamics of N, P and organic matter depletion and repletion, we have collected data along a chronosequence in Nandi and Vihiga districts in Western Kenya with sites that were converted from forest to agriculture in 1900, 1930, 1950, 1970, 1985, 1995, and 2000. Samples from the forest provide the zero time points. To establish that these sites actually were converted at the times specified, we investigated local records from district and agricultural offices and spoke with elderly community members. Conversion times were not established until we had congruent data from at least 3 sources. Important local events (i.e. building of a mission hospital or school) were used as benchmarks. Six chronosequence blocks with 8 time conversions each have been established in Western Kenya. When these blocks were selected, care was taken to ensure that the parent material of the soil, slope, and climatic conditions were similar for all conversions within a block. Four of the blocks emanating from the Kakamega and Nandi Forests consist of heavy textured soils while two blocks in the Kibiri-Tiriki area northeast of Madzuu contain sandier soils. Once the conversions had been established, soil samples were collected from 3 farms from each conversion in each block using a radial sampling scheme to obtain one composite sample per farm. Using NIR spectrometry (Shepherd &

Walsh 2002) with appropriate calibrations developed using standard wet chemistry methods, we have data on cation exchange capacity (CEC), organic carbon, texture (clay, silt and sand content), pH, calcium, magnesium and phosphorus from all of the farms included in the chronosequence as well as from the farms in Embu and Madzuu. We also have information on the activities of key enzymes in the carbon, nitrogen and phosphorus cycles of soils (Tabatabai 1994).

The same chronosequence sites are being used for repletion experiments to determine soil and crop responses to the same N, P and OM inputs to compare soils with different levels of degradation. The goal of the chronosequence research is to parameterize the dynamics of long-term soil degradation and to relate the quantity and quality of SOM and soil nutrients in Embu and Madzuu to degradation states obtained from the chronosequence. Because our model includes measurable pools only, full parameterization of the soils model is possible. This approach of “modeling the measurable” contrasts sharply with conventional modeling techniques using the CENTURY model (Elliot *et al.* 1996, Gaunt *et al.* 2000).

As part of our effort to understand the processes of degradation and repletion, we will measure changes in microbial diversity from samples taken from the chronosequence and Madzuu using DGGE and T-RFLP (Dunbar *et al.* 2000, Girvan *et al.* 2003). Once we understand how microbial activity and populations change in response to farmer interventions and how they relate to SOM turnover, the fluxes of C and nutrients between pools in the model will be related to microbial community structures, providing a mechanistic understanding of SOM dynamics.

### 3. Livestock

Livestock play multiple roles in smallholder farming systems in the Kenyan highlands: 1) provision of milk, meat and fiber, 2) supplying manure, an important soil amendment, 3) transportation and animal traction, and 4) a form of savings account (Pell 1999). How do changes in both the intestinal and soil biota affect digestion and decomposition of plant cell walls in their respective habitats? The salient issue is to determine at what points humans and their animals can and do perturb the system, deliberately or unintentionally. Research on the effects of livestock and their manure on soil fertility and nutrient cycling and on their predicted productivity and economic contribution to household welfare is underway. The Cornell Net Carbohydrate and Protein System (Fox *et al.* 2003) will form the basis of the livestock modeling effort.

## C. Model Development

At the household level, we couple models of human and natural systems to identify emergent properties[2] of the integrated system. Events that occur beyond the farm boundaries that affect what happens to people, soils, crops and livestock are captured as exogenous variables. The general structure of our model is described in Figure 1. We have a biophysical model of soil dynamics which has the obvious state variables

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[2] Phenomena that occur at different spatial and temporal scales than the system's driving equations (Holland 1995).

describing the soil. The dynamics are driven not just by the state variables, but also by external variables describing farmer decisions. Similarly, the state of the soil is an input into the crop and livestock production functions which, along with farmer decisions, determine the evolution of farmer wealth. For example, using the terminology in Figure 1, Farmer's Choices result in both Biophysical and Economic Actions which in turn feed back onto Farmer's Perceptions of their biophysical and economic status in the next time period (T+1). An intriguing aspect of this structure is that it permits us to examine discrepancies between the farmers' perceived realities and the conditions measured by the scientists involved in the project. Bearing in mind that both farmers and scientists filter out much of what is happening on the farm as they develop their perceptions, it will be interesting to see how much agreement there is between the two.

Both the human and biophysical components contain phenomena at many temporal scales. The biophysical model includes: 1) a model of soil nutrient depletion that includes the impact of SOM depletion on nutrient availability (i.e. reduced mineralization of N and P) and the indirect impact of OM on P availability, 2) plants that require soil nutrients and in turn affect soil attributes, 3) livestock that feed on plants and return nutrients to the soil via excreta. In keeping with our "modeling the measurable" approach, we will have measures of crop yields, N mineralization and pools of carbon and phosphorus for the soils submodel and intakes and excretion of these nutrients in the livestock component. Some of the drivers are immediately derivative of farmer decisions such as the quantity and type of fertilizer applied, ownership of and management of livestock, and even the effort spent on manure collection.

The human systems component models farmer decision-making, which takes farmer wealth as a state variable. In application, the model is conditioned by human capital and the cultural mores which delimit the range of farmers' responses to their environment (Cheal 1987, Arizpe *et al.* 1996). Human activity also depends upon the flow of ecosystem services from the natural capital contained in the soil, plant and animal systems. Both material flows (e.g. eroding soil) and informational flows (e.g. that the soil is dying, or that plant biomass is insufficient for animal needs) must be modeled. We have assumed that each farm has a series of different enterprises with a common structure. The most important enterprises in Embu and Madzuu are maize, beans, maize and bean intercrop, maize and ground nut (peanut) intercrop, coffee, tea, dairy, dual purpose cattle, bananas, Napier grass (*Pennisetum purpureum*, a common forage also used for erosion control) and home gardens. An important feature of our model is that it explicitly accounts for the fact that a biologist's perception of a farmer's soils and the farmer's view may differ (Gray & Morant 2003). Because we both survey farmers about their fields and directly measure soil characteristics, we can correlate both views.

## C. Results

Although our model is still embryonic, we do have sufficient soils and economic data to see some interesting relationships. First, we will briefly discuss some of the implications of the social science data and then will compare farmers' perceptions of their farms with biological measurements. Finally, we will present data on soil degradation from the chronosequence that will be critical for the development of the soils submodel.

## 1. Socio-economic Data

The per capita income data for 2002 in Madzuu (Figure 2) appears to have two modes, one around the mean of the current wealth distribution and one at a significantly higher level. These dynamic asset equilibria correspond to expected real per capita daily incomes of \$0.51 in the lower equilibrium, just below Kenya's rural poverty line of \$0.53 day$^{-1}$ (Central Bureau of Statistics & International Livestock Research Centre 2003), and \$1.48 in the upper equilibrium (Barrett 2003). More than 75% of the population was distributed around, and presumably converging toward, the lower equilibrium point below the poverty line. When we examine transitions in and out of poverty in Madzuu between 1989 and 2002, we find that about 60% of the population was poor in both periods, approximately 20% of the population that was poor in 1989 was able to escape in 2002, about 10% of the originally wealthy population became poor and a lucky 10% were classified as wealthy in both periods. These figures are comparable to those observed by Krishna et al. ( 2004). Thus, now that we have preliminary evidence that poverty traps do exist in Madzuu, our next task is to establish the linkage of these traps to natural resource degradation.

## 2. Biophysical Results

<u>Village Soils Data</u>: The approximately 2000 soil samples collected from all plots of the participating farmers tell an interesting story about differences in soil fertility between Embu and Madzuu (Figure 3). Using a composite soil fertility index that includes five

important soil attributes (pH, effective cation exchange, exchangeable K, extractable P and mineralizable N; K.D. Shepherd, personal communication), the soils in Embu are more fertile than those in Madzuu. These data agree with farmers’ perceptions. When the participating farmers were asked to evaluate whether their soils had improved or deteriorated over the past ten years using a 1 to 5 scale, the farmers from Embu were justifiably much more positive about the condition of their soils than were those from Madzuu (Figure 4).

Which crops farmers elect to plant and where they are grown is a topic on which we have both biological and social science data. First, we tested whether soil fertility varied by crop for the most common crops grown in each region. All maize systems including those with and without intercropping were grouped together. Similarly, if a plot had coffee plants, it was classified as coffee even if other crops or an over story were present. Using this classification scheme, the nine enterprises included 932 of the 967 fields in Madzuu and 977 of the 1052 fields in Embu.

In Madzuu, soil fertility was highest in plots with home gardens, coffee and pasture while areas with Napier grass, tea and fallow were the least fertile (Figure 5). The many maize fields were of intermediate fertility. These data confirm farmers’ reports that, in Western Kenya, tea is a crop of last resort that is grown only when the soil cannot produce other crops.

Embu is similar to Madzuu in that there are significant differences in soil fertility among enterprises, but in Embu the most fertile fields are those with tea and pasture (Figure 6). The least fertile are those with maize and coffee, while bananas and fallow fields are of medium fertility. In Embu, milk and tea are the most important cash crops and credit is available for fertilizer for tea from the local tea companies. Most of the cattle are improved dairy cattle which represent a significant investment and have the potential to yield a significant return. Embu maize yields are low because of acidic soils. Although people persist in growing maize for home consumption in this unfavorable environment, they do not invest heavily in it. Historically, coffee has been an important cash crop, but marketing problems have meant that farmers have not been paid for the past several years.

One of the underlying hypotheses of this project is that there is a relationship between environmental degradation and poverty. Preliminary data exploration using linear regression with off-farm income and per capita income as indicators of financial wealth, number of livestock and land size as indicators of natural capital, and gender, education level and age of the head of the household as indicators of human capital (Table 2) revealed some interesting trends.  For example, there is a negative relationship between off-farm income and the fertility of maize plots, suggesting perhaps that wealthier people invest less in maize because either they can afford to buy it or they choose to devote their resources to more productive ventures than maize. However, this is speculation; until we better understand the dynamics of soil degradation and poverty traps, it will be difficult to come up with meaningful relationships between the two.

Chronosequence Data: Figures 7 and 8 show levels of soil organic carbon and soil enzyme activities from one of the blocks in the chronosequence. Both carbon levels and enzyme activity decline very rapidly within 10 years of conversion from forest to agriculture. When we are able to couple these data with additional information on soil degradation, soil repletion, crop productivity and household economic status, we should be in a strong position to explore the complexity of the on-going conversations between farmers and their crops, soils and livestock.

## 4. Summary

Considerable effort has been expended to determine how social and biophysical aspects of the agro-ecosystem might be linked in a dynamic model to explore the relationships between farmers' perceptions of their options and biophysical and economic processes. Preliminary data hint at linkages between poverty traps and soil degradation. Longitudinal data from Madzuu indicate higher rates of farmer-reported and measured soil degradation than found in Embu. Our socio-economic panels have underscored the importance of off-farm earnings to investment in agricultural intensification and soil nutrient amendments in Madzuu. The chronosequence sites are providing useful information on the dynamics of soil depletion and repletion that will be used to parameterize our soils submodel. Most importantly, we have developed a model structure that permits us to monitor the exchanges between farmers and their biophysical environment.

Table 1. Characteristics of Kenyan research sites in upper Embu in Eastern Province and Madzuu in Vihiga Province.

| | Upper Embu | Madzuu | Reference |
|---|---|---|---|
| Rainfall (mm) | 1736 bimodal | 1500-1800 bimodal | (Kenyan Agricultural Research Institute 1994) |
| Soil types | **Nitisols**, andosols, cambisols, arenosols | Acrisols, nitisols, ferralsols | (Shepherd *et al.* 1996, Gitari *et al.* 1999) |
| Population density (people km$^{-2}$)[a] | 619 | 820 | (Central Bureau of Statistics & International Livestock Research Centre 2003) |
| Mean Farm size (ha) | 1.0±0.83 | 0.4±0.41 | This study |
| % of individuals below poverty line [a, b] | 53±3.98 | 56±5.52 | (Central Bureau of Statistics & International Livestock Research Centre 2003) |
| Predominant ethnic group | Embu | Luyha | |

[a] Figures from Manyatta Division, Embu District, Eastern Province and Vihiga Division, Vihiga District, Western Kenya were used.

[b] KSh 1239 month $^{-1}$ is used as the poverty threshold by the Central Bureau of Statistics ( 2003).

Figure 1. Diagram of bioeconomic model. The state variables are Observed Biophysical Characteristics, Farmer's Perceived Biophysical State and Farmer's Economic State. The circles represent equations that drive the two economic and biophysical modules.

Figure 2. Bimodal income distribution in Madzuu, 2002.

Figure 3. Distribution of soil fertility index from soil samples taken from all plots on all participating farms in Embu and Madzuu.

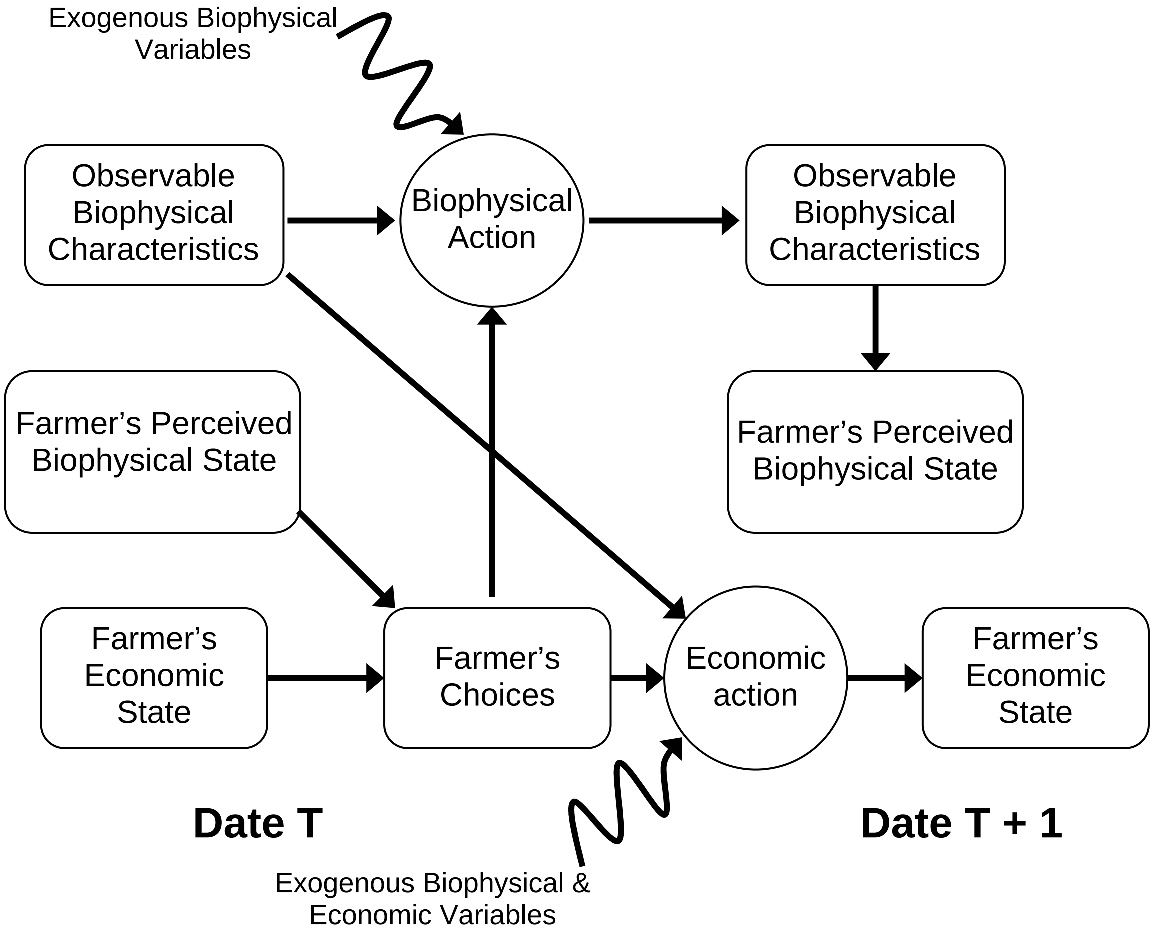
Figure 4. Farmer perceptions of whether soils had improved or deteriorated over the past 10 years. Responses were on a 1 (marked improvement) to 5 (significant deterioration) scale. Data are presented as percentage of respondents within village.

Figure 5. Distribution of soil fertility index by enterprise from plots in Madzuu.

Figure 6. Distribution of soil fertility index by enterprise from plots in Embu.

Figure 7. Percent of soil organic carbon in samples taken from one block of a chronosequence emanating from the Nandi Forest to Kapsengere. Conversions from forest to agriculture occurred in 1900, 1930, 1950, 1970, 1985, 1995, and 2000.

Figure 8. Soil enzyme activities (acid phosphatase, alkaline phosphatase, urease and ß-glucosidase) from soil samples taken from one block of a chronosequence emanating from the Nandi Forest to Kapsengere. Conversions from forest to agriculture occurred in 1900, 1930, 1950, 1970, 1985, 1995, and 2000.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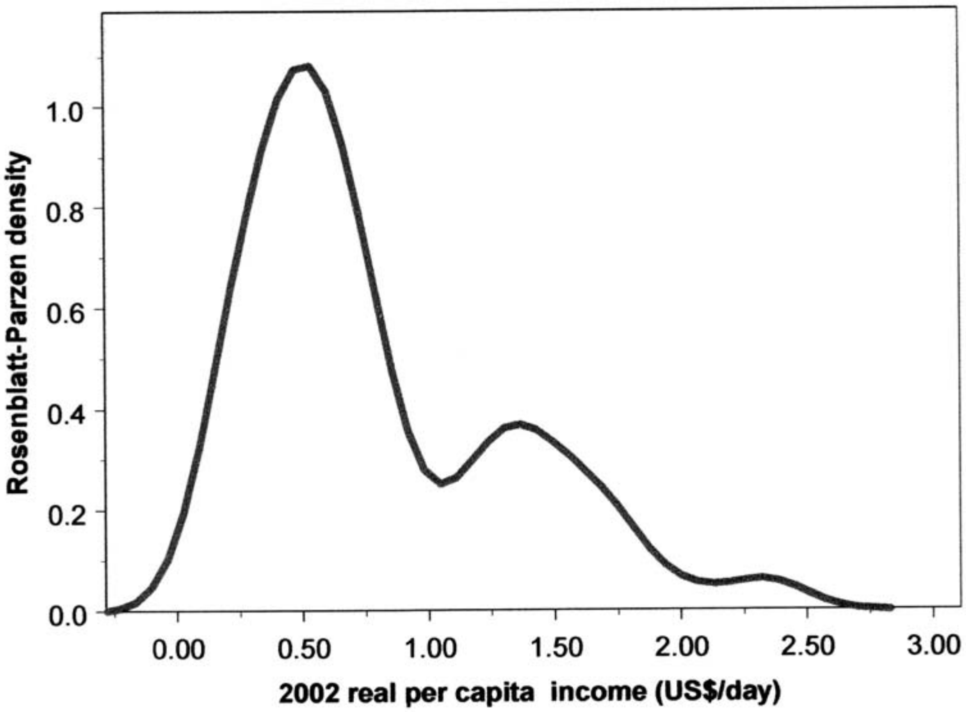
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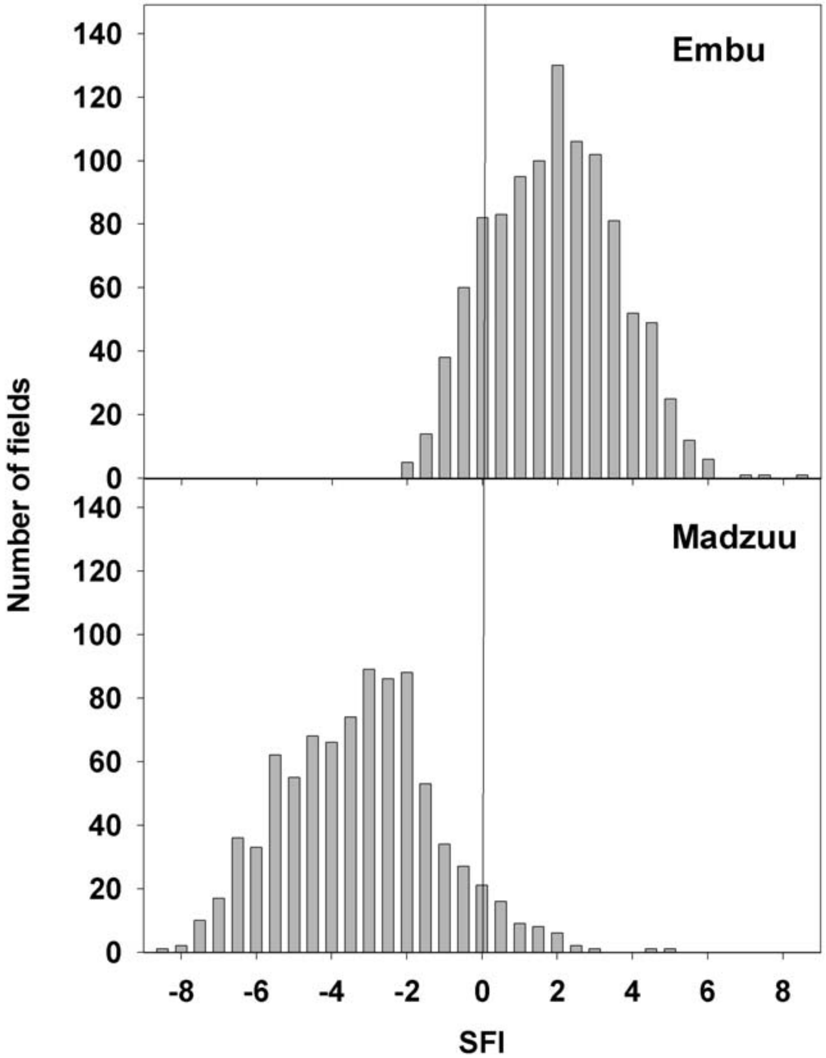
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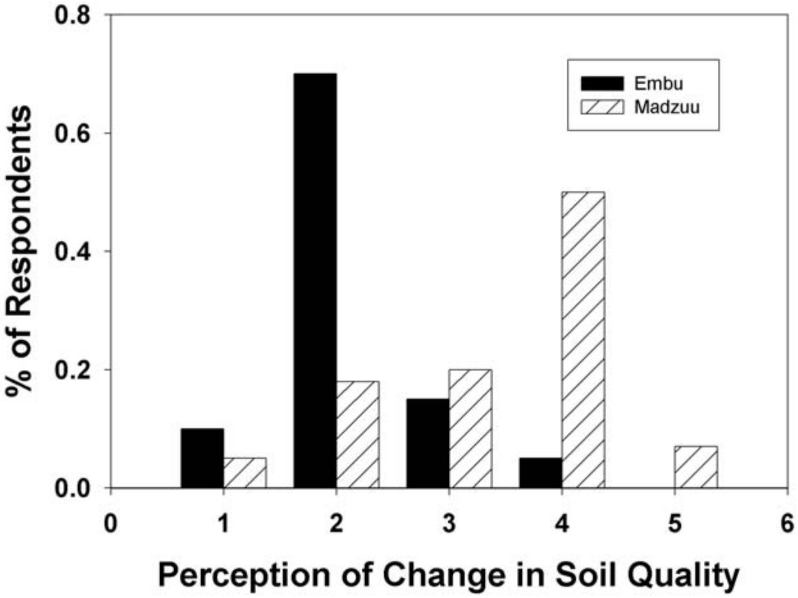

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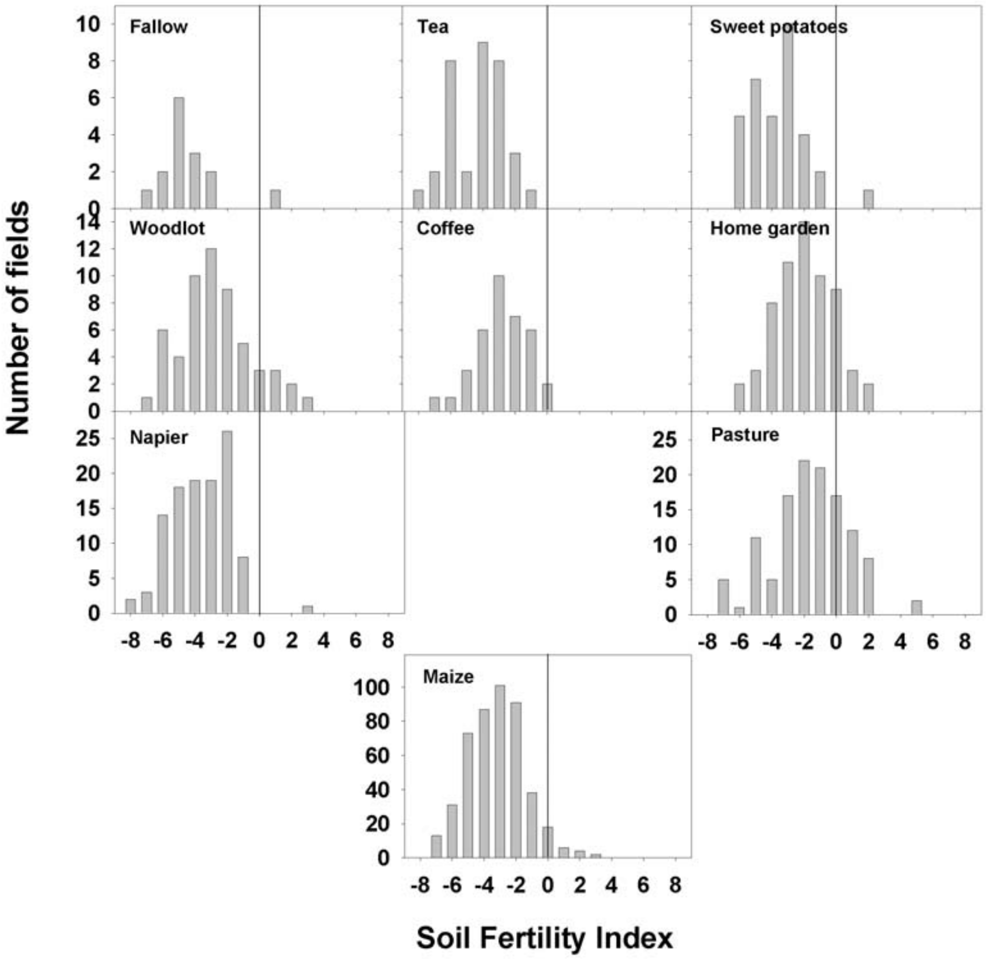
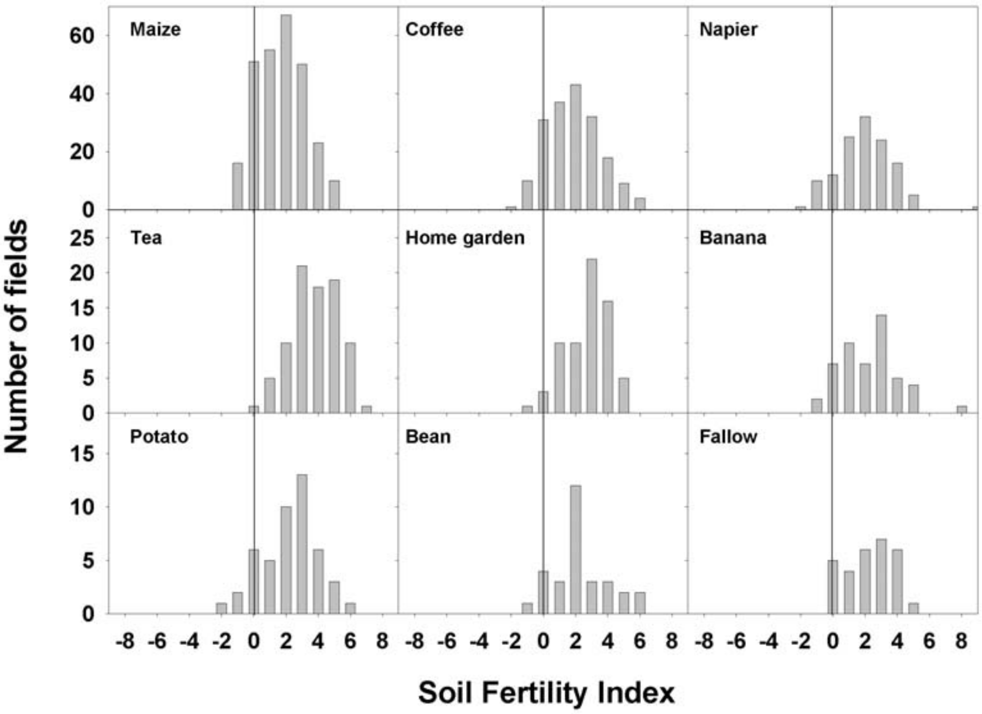
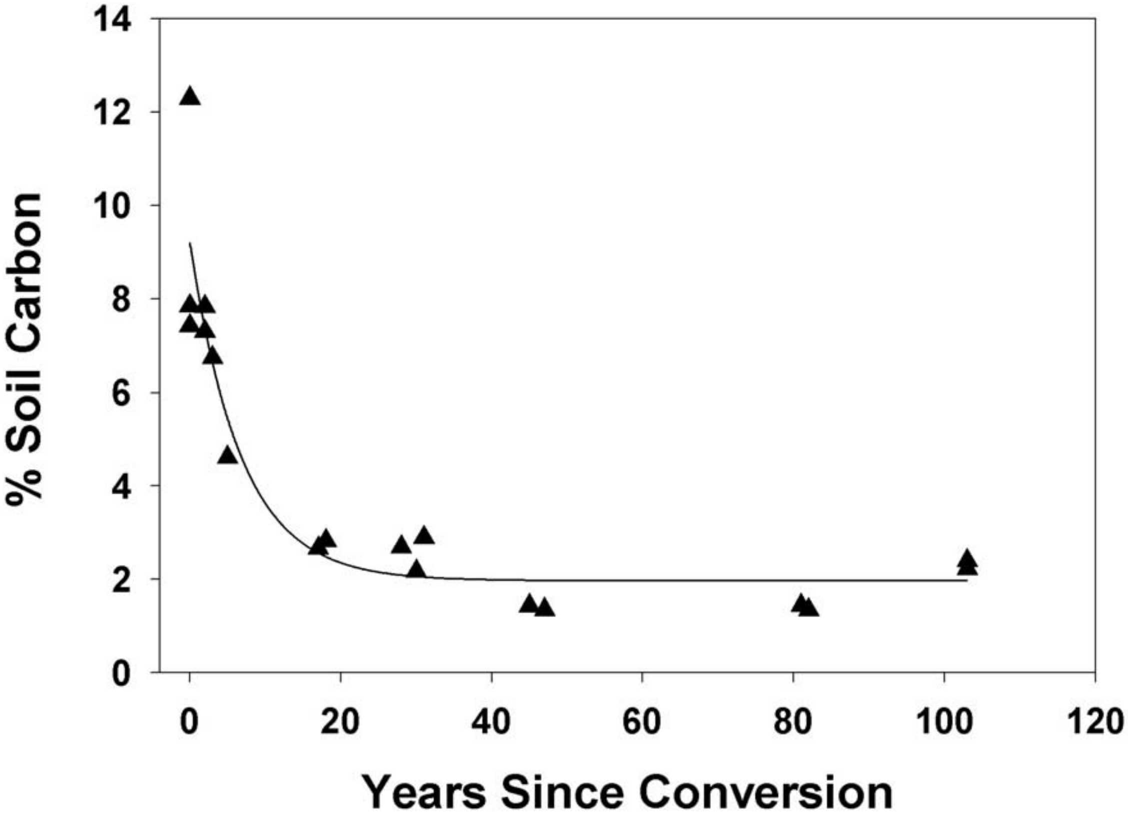
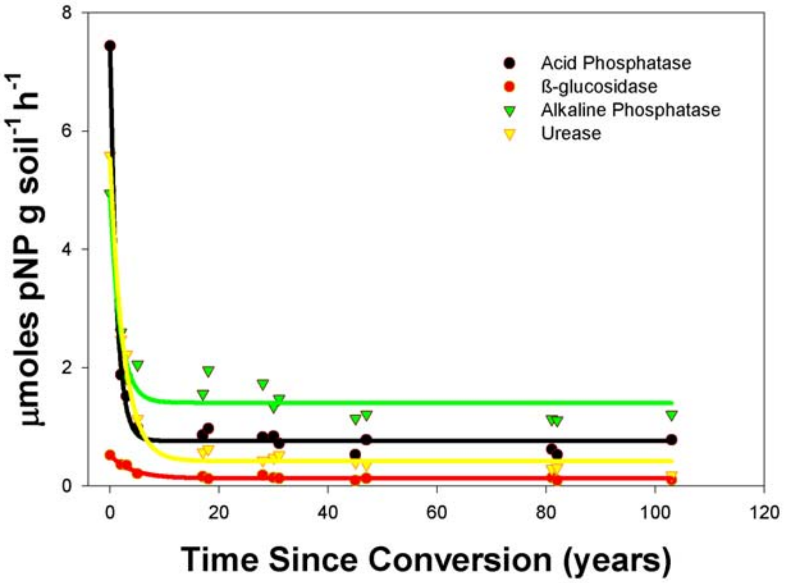
Perception of Change in Soil Quality
Embu
Madzuu


Fallow
Tea
Sweet potatoes
Woodlot
Coffee
Home garden
Napier
Pasture
Maize
Number of fields
Soil Fertility Index
0
2
4
6
8
10
12
14
5
15
20
25
40
60
80
100
-8
-6
-4
-2



Maize
Coffee
Napier
Tea
Home garden
Banana
Potato
Bean
Fallow
Number of fields
Soil Fertility Index
0
20
40
60
0
5
10
15
20
25
0
5
10
15
-8
-6
-4
-2
0
2
4
6
8


% Soil Carbon
0
2
4
6
8
10
12
14
0
20
40
60
80
100
120
Years Since Conversion


8
6
4
2
0
μmoles pNP g soil$^{-1}$ h$^{-1}$
0
20
40
60
80
100
120
Time Since Conversion (years)
● Acid Phosphatase
● ß-glucosidase
▼ Alkaline Phosphatase
▼ Urease

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