"Modeling Feedback between Economic and Biophysical Systems in Smallholder Agriculture in Kenya: The Crops, Livestock and Soils in Smallholder Economic Systems (CLASSES) model."

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Abstract

We investigate natural resource-based poverty traps using a simulation model of smallholder farms in highland Kenya. Simulation modeling allows for detailed examination of the complex interactions and feedback between farm-household economic decision-making and long-term soil dynamics, which may contribute to persistent poverty among smallholders in this region. We examine the effects of changing initial endowments of land, labour and stocks of on-farm soil organic matter on the long-term welfare of these households. We find that larger farms are better able to cope with both labour shocks and deteriorating natural capital than smaller farms, with smaller farms remaining poor and unable to invest into more diversified agricultural activities, like livestock. This suggests locally increasing returns to various combinations of economic and biophysical assets. Information obtained through such simulation model experiments may lead to better targeting of poverty alleviation programs as well as suggest a broader array of strategies that play off of the complex interactions between economic and biophysical assets.

Introduction

Recent empirical studies using longitudinal data find that a disturbingly large share of the world's poor suffer chronic rather than transitory poverty (Barrett, Little and Carter 2007, Baulch and Hoddinott 2000, Chronic Poverty Research Centre 2004). They appear trapped in a state of perpetual food insecurity and vulnerability due to poor asset endowments and factor market failures that preclude their efficient investment in or use of productive assets. Moreover, those caught in a poverty trap have strong incentives to deplete natural capital in order to sustain human capital (Perrings 1989). Partly as a consequence, nearly two-fifths of the world's agricultural land is seriously degraded and the figure is highest and growing in the poorest areas of Central America and Sub-Saharan Africa (World Bank 2000, WRI 2000). Such degradation can aggravate pre-existing poverty traps, by discouraging capital-poor smallholders from investing in maintaining, much less improving, the natural resource base on which their future livelihoods depend (Barrett 1996, Carter and May 1999, Cleaver and Schreiber 1994, McPeak and Barrett 2001, Reardon and Vosti 1995). The resulting degradation of the local ecosystem further lowers agricultural labour and land productivity, aggravating the structural poverty trap from which smallholders cannot easily escape.

In this paper we describe a simulation model of the feedback between the key economic and biophysical systems that affect the overall welfare trajectory for a typical small farming household in highland Kenya. The model structure and parameterization is informed both by the theoretical literature on agricultural household modeling and recently collected economic and biophysical data from this area. The data include longitudinal information on household characteristics, behaviours and welfare, soil nutrient dynamics under a variety of farming systems, crop growth response to a range of different (experimental) interventions, and key livestock variables, such as animal health and nutrition indicators, productivity and herd size dynamics. Conventional econometric methods would not permit ready integration of these rich data sources across different agro ecological subsystems, nor would it be possible to explicitly model the linkages and feedback effects between components of the system being modelled. We have thus opted for a modular simulation model that allows the biophysical and economic subsystems to interact more explicitly across time periods.

Our modeling strategy is neither a biological process model with an economics component, nor simply an economic optimization model with biophysical features, as typify the extant literature on bio-economic modeling (Brown, 2000). Rather it is a truly integrated bio-economic model that captures critical (but necessarily selective) details of human decision-making and biological processes and feedback within and between sub-systems. Unlike most bio-economic models, the Crops, Livestock and Soils in Smallholder Economic Systems (CLASSES) model is a ‘closely coupled’ model (Antle and Stoorvogel 2006) wherein biological processes and economic decisions are dynamically and recursively linked. The CLASSES model is also distinct from other existing bio-economic household models in that it is non-separable and household consumption and production decisions are explicitly tied together. This framework better explains dynamic decision-making in our research setting, where market imperfections may play a large role in household allocation decisions (Brown 2008). We use the model to examine how interdependency between human behaviour and natural resource dynamics may give rise to poverty traps for small farming households who begin with different initial asset endowments and thereby experience different path dynamics in both their natural resource endowments (e.g., soil nutrient dynamics) and behavioural and well-being indicators. We also use the CLASSES model to identify possible leverage points that may lead to better welfare outcomes with a minimum of unintended consequences on either the economic or biophysical side. This approach provides a novel method for exploring the coupled dynamics of smallholders and the natural resource base on which they depend, in an environment where resource degradation and persistent poverty are first-order concerns for both researchers and policymakers.

Analyzing Poverty Traps

Characterizing and empirically testing the precise dynamics of poverty traps, such as those based on a deteriorating agricultural land resource, has proven difficult. A poverty trap is broadly defined as "any self-reinforcing mechanism, which causes poverty to persist" (Azariadis & Stachurski 2004, p. 33). Under neo-classical assumptions, high but diminishing returns to a relatively small stock of farm assets means that, eventually, the farming household will be able to accumulate assets and increase household income up to some unique equilibrium level, and no trap should exist. Chronic poverty under these assumptions would be due primarily to the fact that the final equilibrium income level falls below a defined minimum income poverty line (which might be the case if the overall land base was so degraded as not to afford the generation of any sort of productive income).

In contrast, under the poverty trap scenario, initial conditions on the farm matter for long-term outcomes. The dynamics of a natural resource-based poverty trap mean that there likely exists a threshold level of both biophysical and economic assets that defines very different dynamics for households on either side, with asset-poor households unable to accomplish significant biophysical or economic asset accumulation, or generate sufficient income to clear the poverty line. Further, it suggests an inherent non-convexity in the productive capacity of the underlying asset base, so that if households can somehow surmount the threshold, then they will be able to obtain a higher income state. Poverty traps generated by a wide variety of asset dynamics have been proposed as possible candidate explanations for chronic poverty among small farm households (Barrett 2007). Some examples include: herd size dynamics and coping with pastoral shocks (Lybbert, Barrett, Desta and Coppock 2004), and moral hazard and access to credit (Mookerjee and Ray 2002).

Except in cases where exceptionally long data sets are available (as in Lybbert et al 2002), it has historically been difficult to analyze poverty traps and particularly the transition into and out of low-income equilibrium states. This is because very often in practice, outcomes of interest (income, asset levels) are observed most frequently in the neighbourhood of low-level and high-level stable equilibria, but with very few observations of households in transition near an unstable threshold (Barrett 2007).

Livelihood Activity Choice and the CLASSES (Crops, Livestock and Soils in Smallholder Economic Systems) Model

The farming systems of two distinct highland regions in Kenya (Embu and Madzuu districts) that form the basis for the CLASSES model used in this paper present a good opportunity for studying complex economic and biophysical dynamics. The selection of the research sites was driven partly by the observation that soils in both areas are capable of supporting highly productive agricultural systems (Place et al 2005), yet both regions exhibit markedly different socio-economic outcomes. Embu district is relatively close and well connected via paved roads to the major Kenyan produce markets in Nairobi, Kenya's capital city. In contrast, Madzuu district's relative remoteness from a similarly large market and higher population densities result in an income distribution for farmers in the area that is sufficiently inferior that it is first order (stochastically) dominated by those of similar farmers in Embu district (Brown et al, 2006). The relationship between the biophysical assets of a district or household, and its economic outcomes, are thus neither direct nor simple.

Stylized Household Decision-Making in the CLASSES Model

The farming households represented in the CLASSES model face dynamically changing productive capacity on the farm that is partly driven by the degradation of their underlying natural resource base. The underlying motivation for the household decision making structure is presented as follows.

There are four different activities a in which the household may engage each season, t: (1) subsistence food crops, (2) cash crops, (3) fodder crops and (4) milk/livestock production. Output for each of the cropping activities depends upon both the availability of soil nutrients N_{at} in any land allocated to the particular crop, as well as the amount of labour used in production. For simplicity, we have assumed Leontief production functions for each of the crops, so that land and labour resources are used in fixed proportions. Thus, cropping output depends primarily on the amount of land allocated to the crop on the farm, and the associated proportion of nutrients available on the plot of land, represented in reduced form by N_{at}.

The livestock production function (for both milk and off-spring that can be sold or retained) is more complex, but depends primarily on the production of the fodder crop, as well as labour and the level of cash resources for additional feed purchases. The total production of the fodder crop is dependent upon the amount of land optimally allocated to this crop on the farm.

Each activity a therefore has a specific value associated with it $v_a(N_{at},X_{at},W_{at})$ that is dependent upon the proportion of the farm's soil nutrients allocated to the activity, N_{at}, the farm's household characteristics X_{at} (which includes the level of labour and cash available) and a set of exogenous socio-economic variables (like local market prices, transactions costs, wage rates etc.) W_{at}.

The household's problem is to choose how to allocate its productive resources r (which includes its soil nutrients N_t, and its labour and cash resources (included in X_t)) between the four different activities, a. In the allocation problem, the household is essentially deciding upon the fraction of each of these three resources to dedicate to the activity, with the fractions defined by φ_{art} such that $\sum_a \varphi_{art} = 1$ for each resource *r*.

The allocation decision over φ_{art} to maximize the present value of agricultural production to the household is therefore:

$$(1) \qquad \max_{\{\varphi_{art}\}} \mathrm{E}_0 \sum_{t=0}^{\infty} \sum_a \beta^t v(N_{at}, X_{at}, W_{at})$$

with the future value of activity choices discounted by β.[1]

Dynamic optimization problems like equation (1) become computationally infeasible for large simulation models like CLASSES, as the actual state space in the model, which includes several categories of specific soil nutrients, animals of different ages within the household's livestock herd, and several categories of on-farm and hired in labour, becomes too large for typical dynamic optimization techniques. Therefore, in order to operationalize the decision-making structure, we can examine the optimality conditions for a more manageable problem and use this solution to implement a "plausible guess" as to the actual value function at work behind the household's decision-making process (Woodward, Wui and Griffin 2005). We then use this approximate value function in the economics subsystem in the overall simulation model.

Approximating the value function: The choice between two agricultural crops in CLASSES

Consider the simplified problem of choosing the fraction of fixed farmland φ_t to allocate between a subsistence food crop F and a cash crop, G. The household

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[1] In order to better focus on the feedback mechanisms at play between the biophysical and economic dynamics, the CLASSES model does not currently include stochastic shocks. Thus, the expectations taken at t=0 represent farmer perceptions of changing productivity on the farm.

maximizes the present value of farm profits $\Pi(q_t)$, which includes revenues $R(q_t= p_f Ft, +p_g G_t)$ derived from the market value of each of the two crops, p_f and p_g respectively (with p_f normalized to 1 and $p_g=p$) minus the costs of production for each crop, $c(q_t)=c(F_t) + c(G_t)$. Assume that the production of the two crops depends only upon the level of available nutrients in the farmland resource at time t (N_t). Each crop also extracts nutrients from the farm at a rate of $f(F(N_{1t}))$ and $g(G(N_{2t}))$ respectively. For simplicity, the functions $f(.)$ and $g(.)$ are simply linear in crop production, with constants α_f, α_g and that there are no additions of nutrients to the soil (through fertilizer or soil organic matter, for example). The equation of motion for the soil nutrient stock is then simply:

$$(2) N_{t+1} = N_t - \alpha_f F(N_{1t}) - \alpha_g G(N_{2t})$$

The household's optimization problem is to choose φ_t for every time period:

$$
\begin{aligned}
&(3) \max_{\varphi_t} \sum_{t=0}^{\infty} \beta^t \Pi(q_t) \\
&\quad s.t. \\
&Y_{1t} = F(N_{1t}) \\
&Y_{2t} = G(N_{2t}) \\
&q_t = Y_{1t} + pY_{2t} \\
&c_t = c(F(N_{1t})) + c(G(N_{2t})) \\
&N_t = N_{1t} + N_{2t} = \varphi_t N_t + (1-\varphi_t) N_t \\
&N_{t+1} = N_t - \alpha_f F(N_{1t}) - \alpha_g G(N_{2t})
\end{aligned}
$$

This problem can be examined using the Bellman method, for a one period choice over φ_t. The state variable is reduced to the level of soil nutrients, and the control variable is φ:

$$(4) v(N) = \max_{\varphi} F(\varphi N) + pG((1-\varphi)N) - c(N) + \beta v(N - \alpha_f F(\varphi N) - \alpha_g G((1-\varphi)N))$$

The first order conditions provide the following relationship:

$$(5) F_N\left(1-c_F-\beta\nu_{N'}\alpha_f\right)=G_N\left(p-c_G-\beta\nu_{N'}\alpha_g\right)$$

where the subscripts refer to the partial derivatives with respect to the production functions *F* and *G* and the nutrient stock, *N*, and *N'* refers to the available nutrient stock in the next season *(t+1)*. The first order condition basically states that, if acting optimally, the household allocates land between the two crops until the additional marginal profit gain above the future value of nutrients lost in crop uptake is the same for each crop.

Combining the first order conditions with envelope theorem results provides the following relationship:

$$(6) \frac{F_N(1-c_F)-G_N(p-c_G)}{\alpha_f F_N-\alpha_g G_N}=\beta\left(\frac{F_{N'}(1-c_f)(1-\alpha_g G_{N'})-G_{N'}(p-c_G)(1-\alpha_f F_{N'})}{\alpha_f F_{N'}-\alpha_g G_{N'}}\right)$$

or

$$\frac{F_N(1-c_F)}{\alpha_f F_N-\alpha_g G_N}-\beta\left(\frac{F_{N'}(1-c_f)(1-\alpha_g G_{N'})}{\alpha_f F_{N'}-\alpha_g G_{N'}}\right)=\frac{G_N(p-c_G)}{\alpha_f F_N-\alpha_g G_N}-\beta\left(\frac{G_{N'}(p-c_G)(1-\alpha_f F_{N'})}{\alpha_f F_{N'}-\alpha_g G_{N'}}\right)$$

This relationship indicates that the household will allocate land to each crop until the point that the present additional marginal profit from the nutrients in the crop over the opportunity cost incurred allocating nutrients to it rather than the other crop is equal across crops. Households will therefore allocate resources on the farm until the point where the additional present value of the activity over the cost in terms of asset availability in the next period is the same across activities.

Optimization in the full model

Extending the relationship in (6) to the full range of activities, we assume that the household follows a similar set of rules. It will allocate all household resources N_t and X_t (taking into account changing exogenous conditions W_t) in proportions that equate the excess present marginal profits of the household's assets in these activities. This decision rule can be summarized as:

$$(7)\frac{\Pi^{a}_{\bar{r}}}{e_a q^{a}_{\bar{r}}}-\beta\frac{\Pi^{a}_{\bar{r}'}}{e_a q^{a}_{\bar{r}'}}=\frac{\Pi^{-a}_{\bar{r}}}{e_{-a} q^{-a}_{\bar{r}}}-\beta\frac{\Pi^{-a}_{\bar{r}'}}{e_{-a} q^{-a}_{\bar{r}'}}$$

for each activity, a and alternative activity, - a.

for the vector of household resources $r_t=\{N_t, X_t\}$, the four productive activities a and the usage of the household's natural resource base in a particular activity, $e_a(r_t)$.

In practice, given the particular production function we have adopted for crops, the land and labour are used in fixed proportions. So, to make decision-making consistent between the crop and livestock activities, we approximate the marginal profit of soil nutrients in all activities with the average net value product for labour (i.e. average revenues minus average costs) for each of the four activities. These simplifications can be justified by the facts that a) the marginal product of labour in a crop is simply the marginal product of land (and thus the marginal product of the underlying nutrient stock) multiplied by the fixed ratio of land to labour in the Leontief production function and b) for Leontief production functions, the marginal and average value products of inputs are equal. We approximate the value function for livestock in a similar manner, as an average net value product of labour for the production of milk and off-spring.

The above optimization procedure assumed that the optimal division of household assets each period φ_{art} is a continuous parameter. However, in the actual model, this is not possible, due to tractability issues. The farm is instead split into ten equally sized patches of land. For the resource allocation decision, φ_{art} is a {0,1} variable, with $\varphi_{art} = 1$ if, for activity a,

$$(8)\,\frac{\Pi^{a}_{\vec{R}}}{e_a q^{a}_{\vec{R}}} - \beta\frac{\Pi^{a}_{\vec{R}'}}{e_a q^{a}_{\vec{R}'}} > \frac{\Pi^{-a}_{\vec{R}}}{e_{-a} q^{-a}_{\vec{R}}} - \beta\frac{\Pi^{-a}_{\vec{R}'}}{e_{-a} q^{-a}_{\vec{R}'}}.$$

Finally, to allow households to evaluate the optimal allocation of farm resources as in (8), we utilize ‘adaptive expectations’ based on observed past profits in each of the four activities in order to evaluate the discounted expected profits in each of the activities in the next period. Use of adaptive expectations means that households can specifically rank each of the four activities in terms of current profits, and also tells the household what the rank of these expected profits will be in the next period. With this formulation, the decision criteria reduces to:

$$(9)\,\frac{\Pi^{a}_{\vec{R}}}{e_a q^{a}_{\vec{R}}} > \frac{\Pi^{-a}_{\vec{R}}}{e_{-a} q^{-a}_{\vec{R}}}$$

Details of the Economic and Biophysical Systems in the CLASSES simulation model

We use the simulation software Vensim$^{\text{TM}}$ to lay out the many complex relationships between biophysical and economic resources embedded in the livelihood activity choices facing farming households in the survey region and to assess whether or not households with limited access to either natural or economic assets may fall into poverty traps.

The CLASSES model describes conditions for an average smallholder farmer in highland Kenya. It has three primary modules that interact with each other over the course of 100 quarters, (or 25 years). First, the soils module describes the dynamics of biomass and nutrients over time as they are cycled between the household’s naturally occurring soil stocks, agricultural crops, and residues. This module also describes the relationship between changing soil nutrient stocks and crop yields, which are harvested and consumed or sold by the household at crop-specific intervals during the simulation. Second, the livestock module describes the size, overall condition, input requirements and productive outputs of the household's stock of dairy cattle (if present), allowing for varying herd sizes and productivity depending upon changing feed availability and financial constraints. These first two modules comprise the model's biophysical system. The economic module describes how the household changes its allocation of labour, land and monetary resources among several important livelihood activities, including food, forage and cash crops, milk production and off-farm labour.

Over the simulation time of the model, households observe deterministically[1] changing returns to agricultural activities on their farms. These returns are characterized by the average value product of labour (AVP_L) and evolve over time due to the dynamics in the underlying biophysical resources that determine agricultural production, as described in the previous section. Using simple economic decision-making rules, the household makes periodic choices over how to best allocate their land, labour and monetary resources over time, based on these changing patterns in the returns to different activities. One of the overall outcomes of this sequence of choices is the household's economic welfare trajectory, which is therefore dependent upon both the underlying dynamics of the resource base as well as the management decisions of the household. A stylized representation of the interaction between the economic decision-making and biophysical systems is shown in Figure 1. The thin arrows relate to the allocation of material assets and related biophysical outcomes, whereas the thicker arrows indicate flows of information that guide the decision-making process. Changes in household welfare generated by changes in the overall composition of agricultural activities and the behaviour of their returns (labelled 'Welfare Dynamics' below) are caused by both the biophysical dynamics as well as factors exogenous to the household (shown as

‘Exogenous Factors’). Economic decision-making responds to this collective information on a period-by-period basis by adjusting the allocation of resources (shown as ‘Resource Allocation Decisions’), which initiates a new round of dynamic changes on the biophysical side of the model and subsequent changes to household welfare.

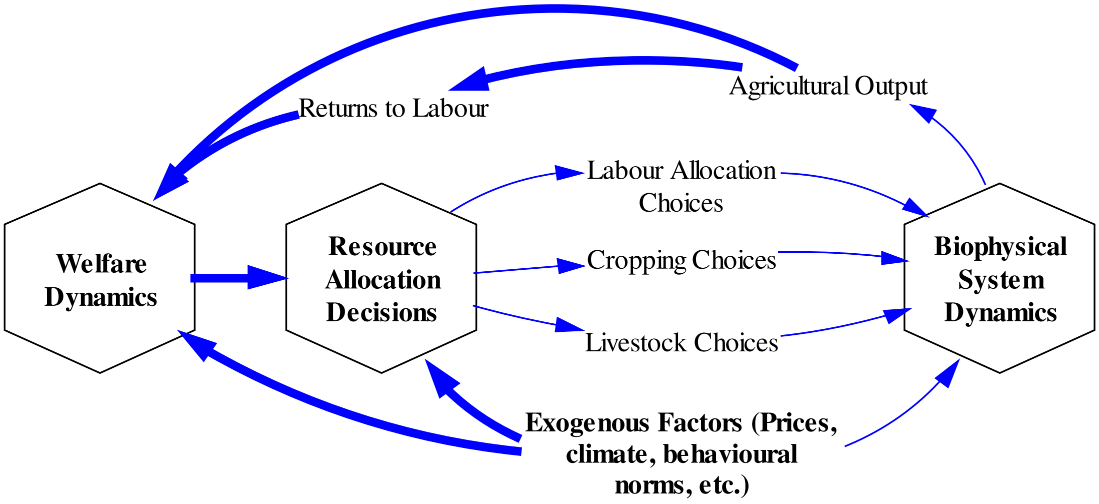

Figure 1. Stylized feedback between smallholder economic choices and biophysical dynamics represented in CLASSES

The interaction of household biophysical and economic assets over the course of the simulation creates instances of locally increasing returns to different asset profiles that may signal the presence of poverty traps, with their source in the biophysical degradation that occurs on farms with limited ability to maintain soil nutrients, given market failures (due perhaps to limited access to credit, for example). Note that there are no specifically stochastic elements in the CLASSES model (like rainfall shocks etc.). Thus, any observed bifurcation dynamics between households with low and high starting levels of assets arises entirely due to locally increasing returns within the deterministic model we have developed, without the influence of environmental shocks or farmer response to risk. If the natural resource base is sufficiently degraded and the household is asset-poor, these two extreme conditions may also be sufficient to generate poverty traps. The next sections describe the soil, livestock and economic modules in more detail.

Soil Dynamics in the CLASSES Model

The soil fertility dynamics of small farms in highland Kenya has been simplified within the CLASSES model to a relatively straight-forward structure where soil organic matter moves back and forth between three different states of aggregation. Parallel structures (termed co flows) track the movement of nitrogen and phosphorus in these organic matter stocks. Figure 2 shows the main stocks (represented by boxes) and flows (represented by pipes) that govern behaviour of organic matter.[2]

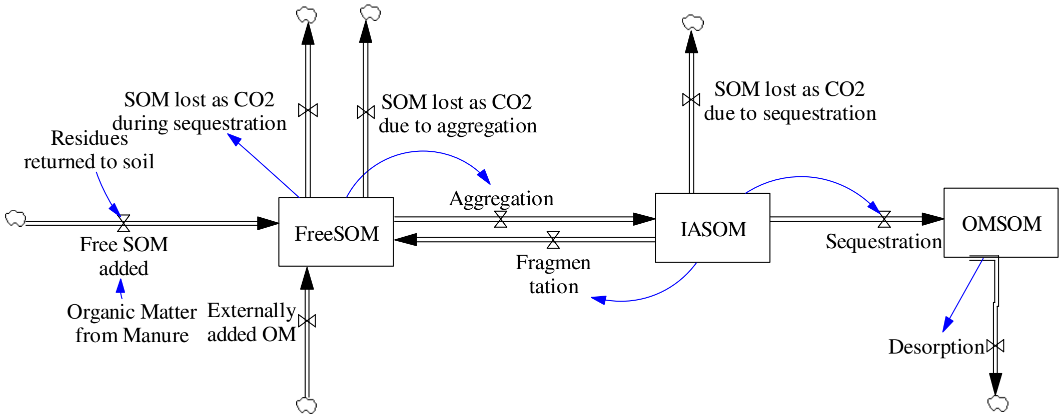

Figure 2. Model representation of the stocks and flows of organic matter between Free, Intra-aggregate and Organo-mineral Soil Organic Matter stocks (FreeSOM, IASOM and OMSOM, respectively).

The levels of available nitrogen and phosphorus, largely due to release from soil organic matter, determine crop yields. Crop types include a representative food crop (maize), a representative cash crop (tea) and a representative forage crop (Napier grass; *Pennisetum purpureum*), which are typical in the two highland Kenyan regions. The crop yields are constrained by the most limiting of either nitrogen or phosphorus, and are based on nonlinear functions derived from experimental and observational data from the research sites. Local data also guide the parameterization of flow rates between soil organic matter stocks contained within the soil organic matter pools, as well as the transition of soil nutrient stocks between nutrient pools. Since the CLASSES model does not simulate within-season farm management decision making, the within season dynamics of soil organic matter and nutrient flows are likewise not simulated. This representation has been designed instead to capture seasonal and longer term dynamics of soil organic matter pools in order to facilitate key linkages with the economics and livestock components of the model. The behaviour of this aggregated structure is consistent with expectations based on more disaggregated soil models, based on model evaluation testing.

Livestock Dynamics in the CLASSES Model

Households in the CLASSES model have the option of purchasing and maintaining a stock of dairy cattle as a livelihood activity. For households engaged in livestock production, we employ an aging chain structure, where in-calf heifers purchased by the household give birth and then progress through several calving cycles (involving different physiological states)[3] before they are sold as cull cows at the end of their useful life (Figure 3).

The household feeds livestock with forage (Napier grass) grown on the farm, purchased feeds (e.g. maize bran and meal) and gathered feeds (local grass, banana stems and leaves). The livestock produce milk for sale and home consumption that varies in quantity according to estimated animal nutritional status, which is determined by the availability of feed.

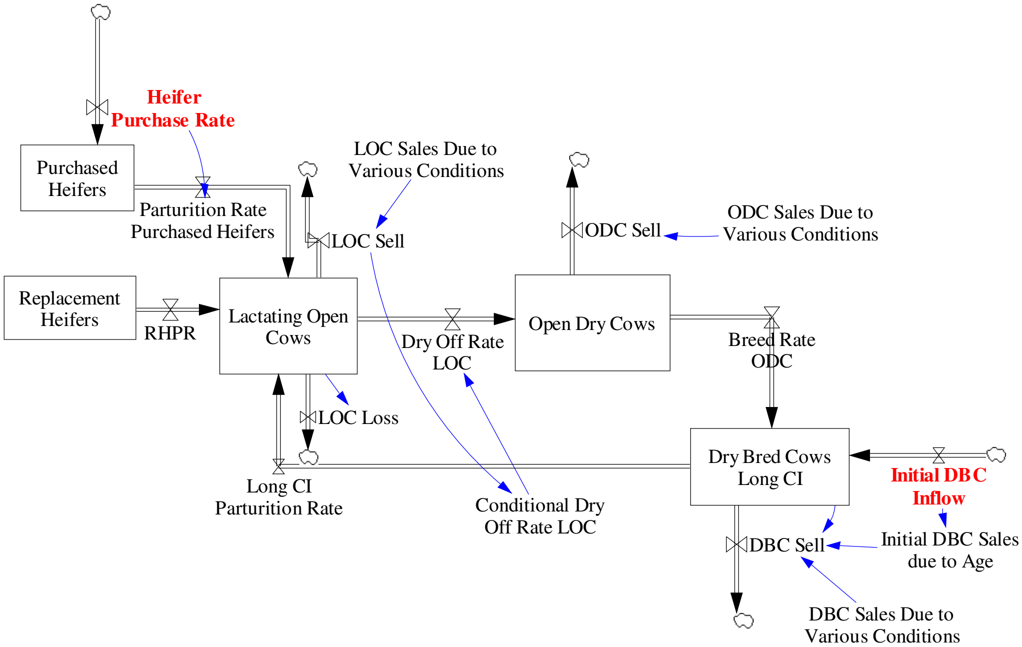

Figure 3. Aging-chain structure for household dairy cattle, showing different growth and physiological states.

The focus on dairy cattle as opposed to other livestock forms is partly due to the fact that dairy cattle ownership influences both household income generation through milk sales and animal sales (Nicholson et al. 2004) as well as soil nutrient dynamics through reincorporation of manure. The dairy cattle in the CLASSES model are intended to be broadly representative of the complex range of livestock activities in highland Kenya.

Implementation of Economic Decision Making in the CLASSES Model

Farm households modeled in CLASSES respond to changing biophysical and economic conditions on their farms by continuously re-evaluating the returns to their labour in the four key on-farm livelihood activities (food crop farming, cash crop farming, forage crop farming and milk production) as described above. In practice, the household examines the average value product (AVP_L)[4] of labour in a given activity by looking at the quarterly net returns (i.e., total value of returns minus its total costs) from the activity versus per labour input used. Actual household resource allocation is then based on the relative ranking of each activity's AVP_L, subject to constraints due to cash resources available for investment (e.g. for livestock). The household also has the option to supply labour off-farm in either a low-skilled or high-skilled occupation. Entry into the latter, which offers higher compensation rates, depends upon a minimal level of educational attainment, which typically sorts workers between low-skilled and high-skilled job opportunities in this area. The daily wages in each of these types of jobs are used to compare off-farm pursuits to the value of the different on-farm enterprises.[5]

For cropping activities, the farm is divided into 10 equally sized patches of land (and simulations of the behaviour of differently sized farms can be achieved by changing the size of these cropping patches). The household chooses the particular crop grown on each patch at the beginning of each planting season, based on the current AVP_L ranking. Households can convert at most one patch every planting season from a lower ranked activity to a higher ranked activity, so immediate farm-wide changes in crops are ruled out, reflecting the binding labour and cash availability constraints faced by Kenyan highland farmers and the non-trivial costs of conversion.

The amount of labour and other inputs required per hectare of crop grown are based on observed labour norms in highland Kenya.[6] This technique thus simplifies decision making sufficiently so that information from the biophysical side can be easily incorporated into the decision making process. The implicit production function for crops is a Leontief function, where land and labour are used in fixed proportions.[7] This structure has been used to examine farmer decision-making in other contexts. It also facilitates modeling activities that the household may stop entirely for periods of time, which may occur in the CLASSES model under certain changes to labour returns (Löfgren and Robinson 1999).

After the production period, the household markets the surplus for each crop. The surplus for maize is determined by the amount harvested that is above the household's minimum consumption requirements, which are also based on locally observed average maize consumption. Households that market surplus grain are thus net maize sellers, while those for whom the total harvest falls short are net buyers. Surplus Napier is determined by the Napier requirements of the household's livestock herd. Households can be either net sellers or buyers of Napier, depending on whether or not there is a surplus or shortfall of Napier that is required to feed the animals. Transactions costs are assumed to exist in the maize market, which affects the effect maize market price, either minus the transactions costs for net sellers or plus the transactions costs for net buyers.

Model Experiments

The CLASSES model can be used to identify possible natural resource-based poverty traps and useful leverage points that would otherwise be difficult to observe empirically over such a long time frame. It also allows more detailed study of potential leverage points than other models that do not have as extensive interaction and feedback between economic and biophysical processes.

A series of experiments with the model demonstrates these features. One of the behaviours that should result if a natural resource degradation poverty trap exists is that different initial household endowments of either biophysical and/or economic assets will lead to divergent long term household welfare dynamics, due to potential non-linearities, complementarities and feedback between the biophysical and economic sub systems in the model. The asset-poor household under this hypothesis is expected to remain poor, due to their inability to generate sufficient income levels on such a limited (and shrinking) asset base.

Experiment 1: The effect of farm size on long-run household welfare [8]

The bulk of the world's rural farming households occupy farms that are less than 2 hectares (World Development Report 2008). In Kenya, limited land markets and increasing population pressure in the highlands are contributing to declining farm sizes. Although small farms are sometimes associated with higher efficiency in terms of crop yields, this increased capacity cannot make up for the low overall level of agricultural output that can be produced within such small farms. It is thus likely that farmers with larger land endowments will be able to generate more income per capita, with which they can achieve higher consumption and the ability to invest in additional high return activities.

To test the effect of land size on long-term household welfare dynamics, we ran two simulations that increased farm size from that of the typical small farm (25th percentile) in the survey area (0.5 hectares) to the median farm size (1 hectare).

In each simulation run, the household starts with all 10 plots in maize and moderately productive soil. Figures 4-8 show the resultant effects of changing farm size on the household's level of cash availability, land allocation, level of available soil nitrogen and the size of the household's herd of livestock.

The household's total cash resources are generated by inflows of agricultural receipts from all enterprise activities minus outflows for subsistence consumption expenditures, hired-in labour requirements and savings, which are used to cover any enterprise investment costs (like the purchase of livestock or to cover perennial establishment costs). Cash availability clearly increases with farm size (Figure 4), although both sized farms generate sufficient cash income to maintain sufficient food consumption and hired-in labour in this experiment.

Soil nitrogen per hectare is generally lower on the smaller farm, although the level is primarily determined by the household's crop choices (Figures 5 and 6). After the 60th quarter (15 years), soil nitrogen has been sufficiently exhausted on the small farm, while the larger farm invests in the 80th quarter in the cash crop, tea (Figure 7). It is assumed that households that grow tea have access to sufficient fertilizer (perhaps via contracting with a tea agency like KTDA), and that farm patches with tea no longer export nutrients off the farm. The larger farm gets extensively involved in tea between the 25th and 60th quarters, as well as after the 80th quarter.

Evidence for a possible natural resource based poverty trap emerges when examining the differences in the livestock investment patterns between small and large farms (Figure 8). Without any change in other parameters for the farms (for example, all three simulations start with an identically sized labour force and the same levels of cash savings and soil stocks), larger households are eventually able to accumulate sufficient cash and savings and invest in livestock once the labour returns to maize and Napier grass fall, whereas smaller households are not able to adopt this strategy.[9] Investing in livestock has the effect of helping to maintain cash stocks, as well as improve crop harvests through the addition of nutrients via the incorporation of manure (Figures 4 and

7). Thus, larger farms have access to a wider set of coping strategies when faced with declining crop harvests brought about by naturally declining soil nutrient stocks.

Experiment 2: The impact of limited on-farm labour availability

Households with higher dependency ratios or those that suffer from a permanent decline in the size of their on-farm labour force (due perhaps to chronic illness or sudden death of a family member) are likely to have more difficulty accumulating income and assets over time, which may limit their long-run welfare. This second experiment examines the results of a permanent shock to a household's labour assets and number of dependents on the long run dynamics for both small and average sized farms (Figures 9-11).

Although both farms suffer the same shock to their household composition, farm size appears to determine to a great extent whether or not the household will be able to sustain and cope with the shock. The shock reduces total cash availability for both farm sizes, although the change is not as drastic for the smaller farm (Figure 9). Soil nitrogen is also reduced for both farms (Figure 10). The larger farm invests in the tea crop between the 20th and 45th quarters, but the smaller farm is unable to shift resources into the cash crop and soil nitrogen gradually declines, with the household growing a mix of subsistence food and fodder crops.

In addition, both farms eventually end up as net buyers of maize towards the end of the simulation, due to the fact that on farm labour for crop production has been reduced, while the number of dependents has increased. The resultant maize consumption shortfall is shown in Figure 11. The smaller farm is a net buyer every season starting around the 70th quarter. Due to seasonal variation in food crop production, the larger household is only a net buyer during the short rains period. The smaller farm starts to seek additional cash income from off-farm work opportunities after about the 15th quarter. This has the advantage that the household has sufficient cash available to pay for food purchases, however it does lead to smaller on-farm yields. The larger household needs to purchase food only during the short rains season, as on-farm food crop yields are sufficient during the long rains to avoid purchasing food in the market.

Experiment 2 suggests another possible poverty trap generated by the interaction between on-farm labour resources and consumption requirements and overall farm size, where larger farms enable the household to maintain food crops and avoid searching for off-farm labour opportunities in order to provide for minimum consumption needs for a large number of dependents.

Experiment 3: The effect of degraded soil organic stocks

Recent research on agricultural livelihood strategies indicates that households that are able to engage in a portfolio of different agricultural activities, particularly those that involve livestock, have higher overall welfare and also earn higher returns for non-livestock activities (Brown et al 2006, Dercon 1998). The main dynamic in much of this research is that of gradual asset accumulation, where households with larger initial asset endowments in terms of land, labour or off-farm income resources are able to make lumpy investments in livestock, while poorly endowed households remain engaged in low-return activities. The CLASSES model allows us to expand the search for such asset thresholds to include natural capital, such as soil nutrients. If initial household biophysical resources are insufficient, then this may also be an important endowment that is often overlooked and one that may also be instrumental in determining farming outcomes.

Figures 12 and 13 compare the outcomes for the 1 hectare household endowed initially with soils typical of those observed after one generation of continuous cultivation after an initial forest conversion, to an identical household that is farming on more degraded soils that would occur after another 40 years, approximately.

The cash availability comparison in Figure 12 indicates the total cash earned from agricultural activities with which households can invest in livestock or other higher return activities. The results suggest that the degraded soil stocks lead to lower overall cash availability, and the household with the poor soils is not able to accumulate any livestock (unlike the accumulation shown in Figure 8).

The median-sized household with the degraded soil is still able to move into a more diversified set of crops, with the increases in soil nitrogen for both scenarios attributable to converting some of the farm into the tea cash crop and applying any provided nitrogen (Figure 13). But it is unable to accumulate sufficient savings to invest in livestock.

Conclusions

By examining smallholder farm households with a fully integrated biophysical and economic model, like the CLASSES model, it is possible to study a wide variety of dynamic interactions between gradually deteriorating natural resources and economic decision making that likely have a long-term impact on welfare for households in highland Kenya. Simulation runs with the model reveal that a variety of initial conditions may determine whether or not such smallholders are able to maintain a sufficient livelihood in the face of shrinking household nutrient stocks. Households that follow a mixed livelihood strategy that includes dairy cattle are able to escape from decreasing incomes from crops by slowing the process of nutrient stock deterioration and generating additional revenue from both crops and the livestock activity.

Further, only sufficiently large farms with healthy soils are able to diversify into livestock by accumulating enough cash from many seasons of larger crop harvests. The smallest farms are cut off from this strategy and earn lower and gradually declining incomes from crop farming that match the overall nutrient degradation cycle. Thus, the interactions captured in the CLASSES model suggest the existence of potential natural resource-based poverty traps.

In addition to allowing for more complete feedback between the economic and biophysical components of the model, the simulation approach to household modeling used in developing the CLASSES model greatly expands the number of research questions in comparison to those possible with other modeling techniques. For example, many more combinations of interventions on either the biophysical or economic side of the model might be entertained and tested.

The ability of small farmers to escape from deteriorating agricultural incomes appears to be highly dependent upon the existence of reinforcing feedback between sufficient natural capital stocks and their mapping to agricultural incomes and the availability of attainable investments in activities, like livestock, that do not export so many nutrients off the farm. The window of opportunity for households to make this transition is narrow, with households with highly degraded, very small farms, destined to remain in low-return activities. The CLASSES model provides a framework for examining many of these complex interactions and can help to identify a potentially larger pool of possible interventions that might help prevent small farmers from falling into such poverty traps.

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[1] At this stage in model development, we do not model stochastic outcomes from agricultural production. However, the model is structured in such as way as to facilitate their incorporation on later versions.

[2] Clouds represent sources and sinks for flows that are outside the model boundary.

[3] Shown as Lactating Open Cows (LOC), Open Dry Cows (ODC) and Dry Bred Cows (DBC), Long Calving Interval (CI).

[4] For computational reasons, AVP_L is far more tractable than the marginal value product of labour (MVP_L). The two are equivalent here under the reasonable assumption of constant returns to scale in production technologies.

[5] Due to local labour market imperfections, the effective wage for off-farm unskilled labour is modified by a labour market transactions cost for both sellers and buyers of this type of off-farm labour.

[6] The labour norms are determined by observed average labour inputs per hectare in the sample area. Labour inputs include days required for ground preparation, planting, weeding and harvesting for the represented crops.

[7] Livestock are an exception to this; labour requirements per animal decrease with larger herd sizes, based on a log-linear formulation.

[8] Summaries of all experiments in this paper are included in the appendix.

[9] The average price for an in-calf heifer in the sample area is Kshs 120,000. The 2007-2008 average exchange rate with U.S. dollars is approximately USD 1= Kshs 70.00.

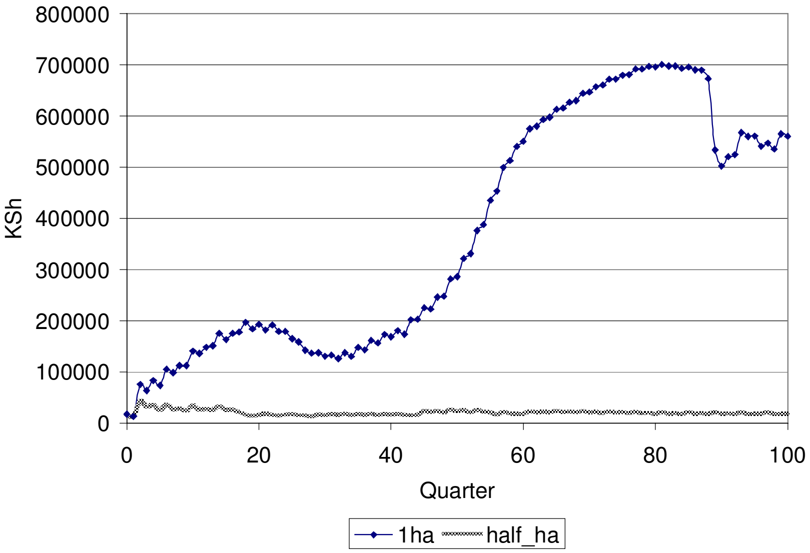

Figure 4. Experiment 1: Total cash resources for a small and average sized farm (KSh)

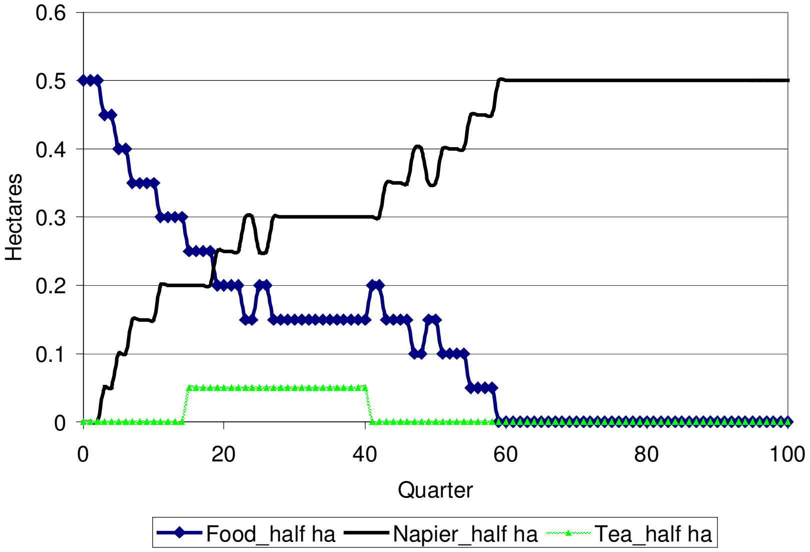

Figure 5. Experiment 1: Land allocation between the three crops, small farms (0.5 ha)

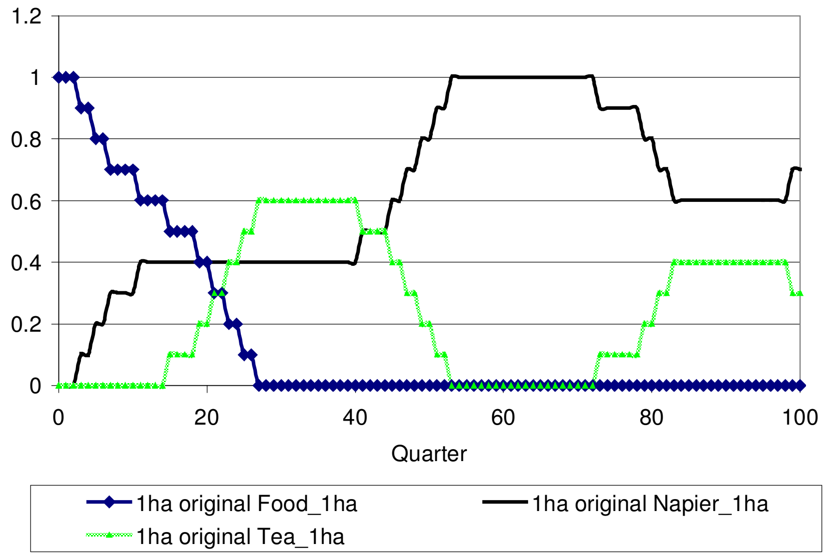

Figure 6. Experiment 1: Land allocation between the three crops, median farms (1 ha)

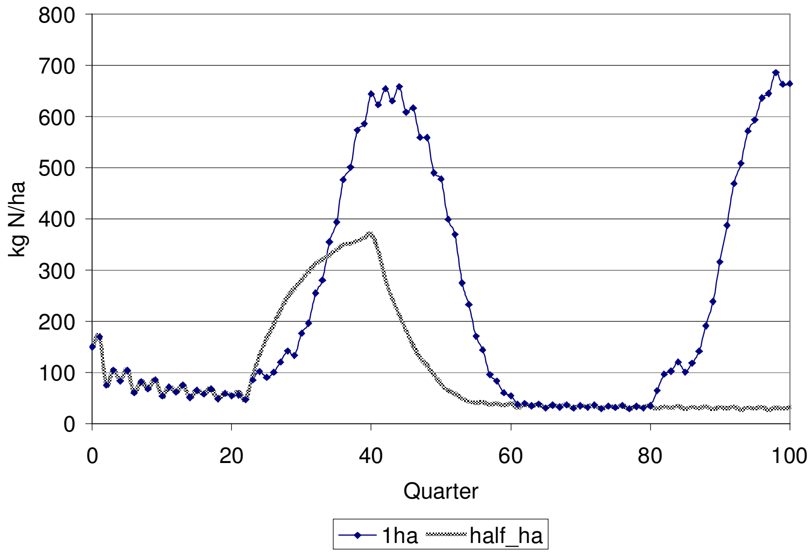

Figure 7. Experiment 1: Average available soil nitrogen on the farm (kg N/ha)

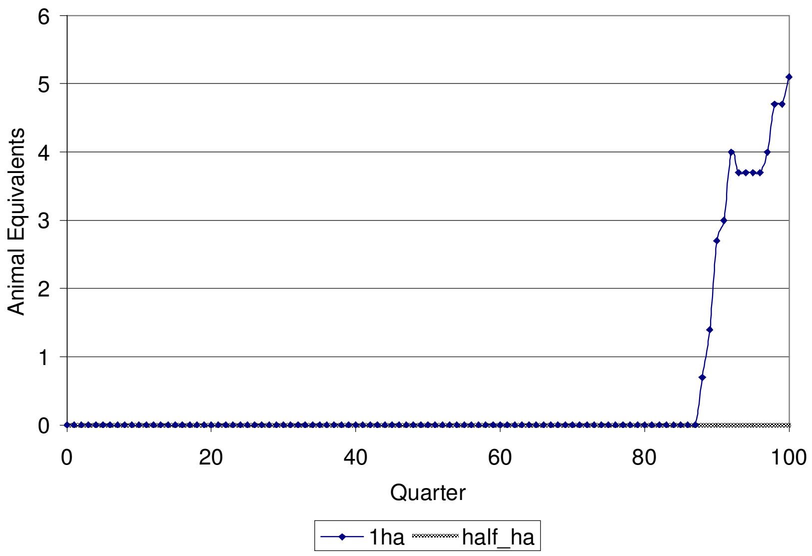

Figure 8. Experiment 1: Total livestock investment on small and median sized farms (in terms of animal equivalents)

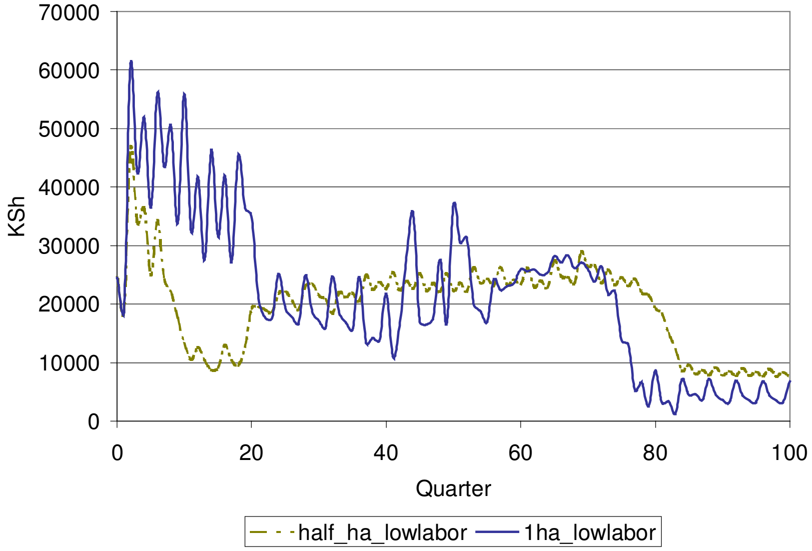

Figure 9. Experiment 2: Total cash resources after a shock to household labour (KSh)

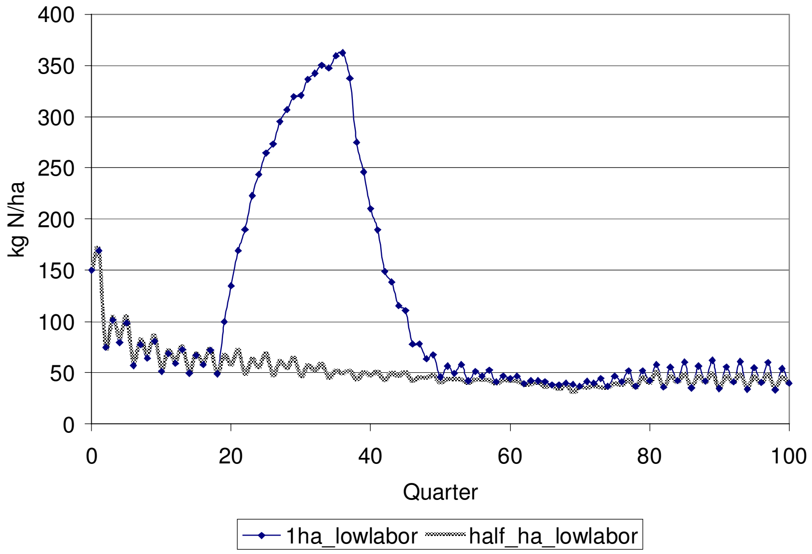

Figure 10. Experiment 2: Average available soil nitrogen on the farm after a shock to household labour (kg N/ha)

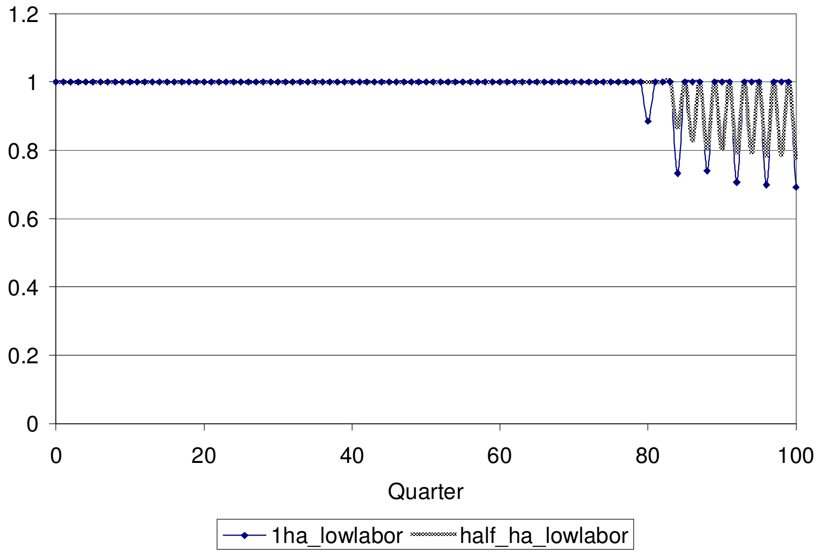

Figure 11. Experiment 2: Subsistence consumption shortfall for small and median sized farms after a labour shock (dmnl).

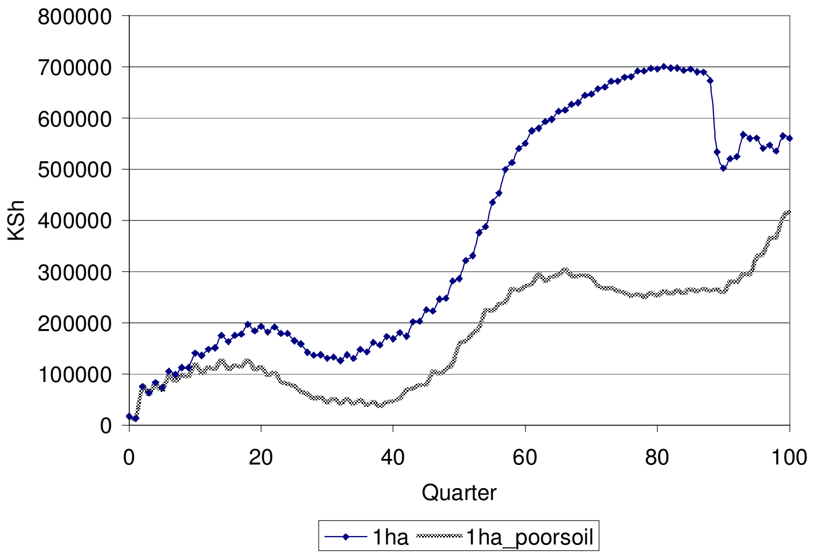

Figure 12. Experiment 3: Total cash resources for 1 hectare farms with good vs. highly degraded soils (KSh)

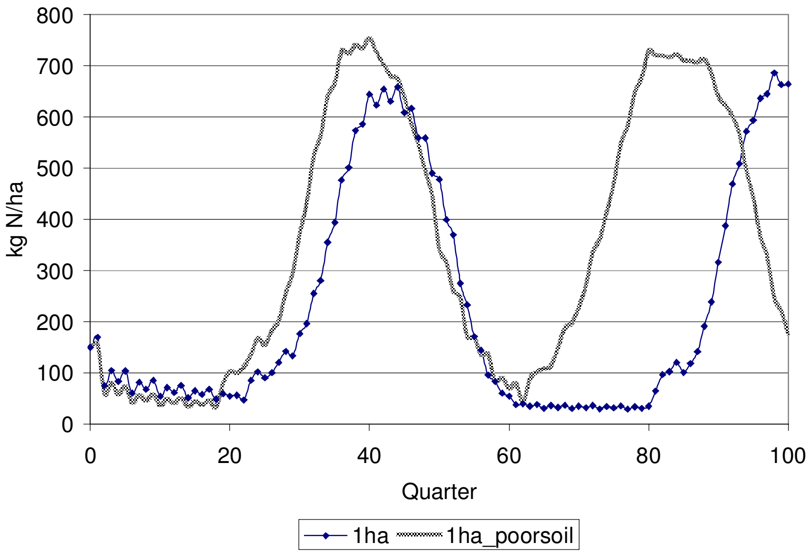

Figure 13. Experiment 3: Average available nitrogen on the farm for the 1 hectare farm with good vs. highly degraded soils (kg N/ha)

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Appendix

Model Experiment Conditions

Table 1: Experiment #1 on varying Farm Sizes

Initial Assets	**Small Farm**	**Median Farm**
Farm Size (ha)	0.5	1
Initial Crop Labour (people)	3	3
Initial Household Dependents (people)[10]	2	2
Initial Accumulated Surplus (Ksh)	0	0
Initial Crop Allocation	100% Maize	100% Maize
Initial Soil Stocks	Average	Average
Free SOM (kg DOM/ha)	1000	1000
Intra-aggregate SOM (kg DOM/ha)	316.5	316.5
Organo-Mineral SOM (kg DOM/ha)	31666.5	31666.5

Table 2: Experiment #2 on varying Household Labour and Dependents

Initial Assets	**Small Farm**	**Median Farm**
Farm Size (ha)	0.5	1
Initial Crop Labour (people)	1	1
Initial Household Dependents (people)	6	6
Initial Accumulated Surplus (Ksh)	0	0
Initial Crop Allocation	100% Maize	100% Maize
Initial Soil Stocks	Average	Average
Free SOM (kg DOM/ha)	1000	1000
Intra-aggregate SOM (kg DOM/ha)	316.5	316.5
Organo-Mineral SOM (kg DOM/ha)	31666.5	31666.5

Table 3: Experiment #3 on varying soil organic stocks

Initial Assets	**Small Farm**	**Median Farm**
Farm Size (ha)	0.5	1
Initial Crop Labour (people)	3	3
Initial Accumulated Surplus (Ksh)	0	0
Initial Household Dependents (people)	2	2
Initial Crop Allocation	100% Maize	100% Maize
Initial Soil Stocks	Low	Low
Free SOM (kg DOM/ha)	500	500
Intra-aggregate SOM (kg DOM/ha)	158.3	158.3
Organo-Mineral SOM (kg DOM/ha)	15833.3	15833.3

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[10] These household members do not contribute to on-farm labour, but do consume household food resources.