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

Emma C. Stephens[a,*], *Christopher B. Barrett*[b], *Douglas R. Brown*[c], *Johannes Lehmann*[d], *David Mbugua*[e], *Solomon Ngoze*[f], *Charles F. Nicholson*[g], *David Parsons*[h], *Alice N. Pell*[i], *Susan J. Riha*[j]

[a]*Pitzer College, 1050 N. Mills Avenue, Claremont, CA 91711, USA*
[b]*Cornell University, Applied Economics and Management, 315 Warren Hall, Ithaca, NY 14853 USA*
[c]*World Vision Canada, 1 World Drive, Mississauga, Ontario L5T 2Y4, Canada*
[d]*Cornell University, Crop and Soil Sciences, 909 Bradfield Hall , Ithaca, NY 14853 USA*
[e]*World Argoforestry Centre (ICRAF), P.O. Box 30677-00100 GPO, Nairobi, Kenya*
[f]*Cornell University, Ithaca, NY 14853 USA*
[g]*Cornell University, Applied Economics and Management, 315 Warren Hall, Ithaca, NY 14853 USA*
[h]*University of Tasmania, Agricultural Science, Private Bag 54, Hobart, Tasmania 7001*
[i]*Cornell University, Animal Science, 149 Morrison Hall, Ithaca, NY 14853*
[j]*Cornell University, Earth and Atmospheric Science, Bradfield Hall, Ithaca, NY 14853*

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Abstract

We investigate natural resource-based poverty traps using a system dynamics model of smallholder farms in highland Kenya. System dynamics modeling is well-suited to examining the complex interactions and feedback between farm-household economic decision making and long-term soil dynamics which may be at the source of 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. The flexibility to examine these different leverage points is partially provided by our use of system dynamics, rather than other modeling techniques, to develop a descriptive rather than prescriptive model of farm behaviour.

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 by recent data collected in this area from a variety of farm types. 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. Hence our use of an alternative computational economics method: system dynamics modeling.

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 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. This idea has been explored in depth for a wide range of possible candidate explanations for chronic poverty among small farm households (Barrett 2007). 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).

The Potential for Bio-economic Modeling of Rural Poverty Traps

Recognition of the importance of the interaction between economic and biophysical processes in understanding rural farming outcomes has grown in recent years. A large literature has developed around the science (and art) of bio-economic modeling as the approach has been applied to many different problems in rural development (Brown 2000). These models span a continuum of techniques, from primarily biological 'mechanistic' models with a highly simplified economics component to primarily economic models with a similarly simplified biological element designed to introduce biophysical variables into an overall household decision making process. The purposes of these models are diverse. Some of the many examples include the Burkina bio-economic village model (Barbier 1996) which explicitly includes biophysical characteristics in the analysis of trade-offs between pesticide use and household health, and the Carchi integrated simulation model (Crissman, Antle and Capalbo 1998), which uses environmental changes to describe and predict farm responses to local population pressure. A comprehensive review is included in Brown (2000).

System Dynamics Modeling

System dynamics is well suited to the analysis of the complex interactions between smallholder economic decision-making and the dynamics of the natural resource base upon which their livelihoods depend. System dynamics is a process-based modeling technique that builds upon an observed dynamic reference mode 'problem' behaviour by using the fact that there are limited numbers of possible dynamic phenomena that each have an underlying structure based on specific combinations of stocks or state variables, flow variables and feedback loops. The interactions between these structural elements move the entire system forward in time by describing how the current state of the system influences future states. The essential observation from the system dynamics modeling tradition of the existence of these fundamental structures puts a useful boundary on complex problems such as the interaction of economic and biophysical systems considered here, in that it suggests methods for combining radically different information from diverse disciplines, as well as a way to identify the most essential pieces of information from each.

Another key feature of system dynamics models is that they permit path dependency to emerge within the model and need not assume global optimization behaviour, which may make unrealistic assumptions about the level of information available to decision makers. More particularly, the CLASSES model spans a period of 25 years in order to examine both short-term and long-term biophysical dynamics and asset degradation/deterioration. In our case, where we wish to investigate the feedback between economic and biophysical systems, it is critical to have a modeling technique that allows for farmers to respond on a period-by-period basis to changing environmental and economic conditions. System dynamics is thus very useful for creating essentially a <u>descriptive</u> model of these complex interactions and farmer behaviour, rather than a <u>prescriptive</u> model which outlines an optimal course of action based on current state variables conditional on the model's assumptions. This also allows for the introduction of different economic and biophysical shocks to examine farm household outcomes, which would be difficult to include in a multi-period optimization model, but which are often very important drivers of chronic poverty and resource degradation poverty traps.

Poverty Traps in Highland Kenya 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 bio-physical assets of a district or household, and its economic outcomes, are thus neither direct nor simple.

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. 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.

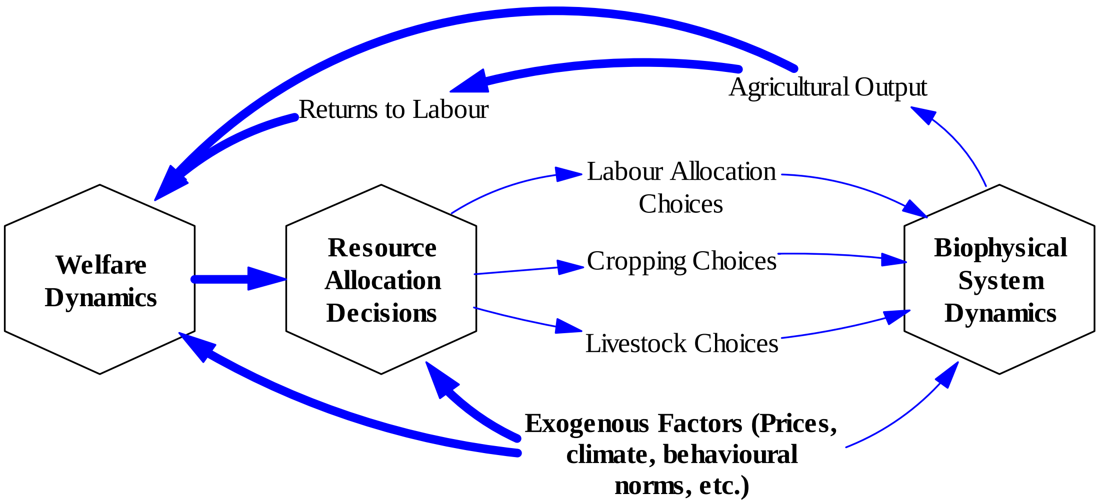

Figure 1. Stylized feedback between smallholder economic choices and biophysical dynamics represented in CLASSES

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]

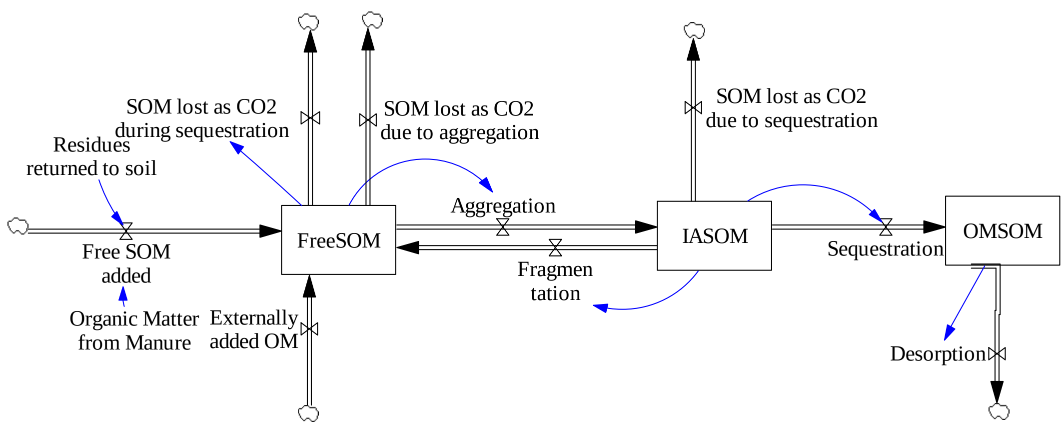

Figure 2. Model representation of the stocks and flows of organic matter between Free, Intra-aggregate and Organo-mineral Soil Organic Matter stocks (FreeSOM/IASOM/OMSOM).

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.

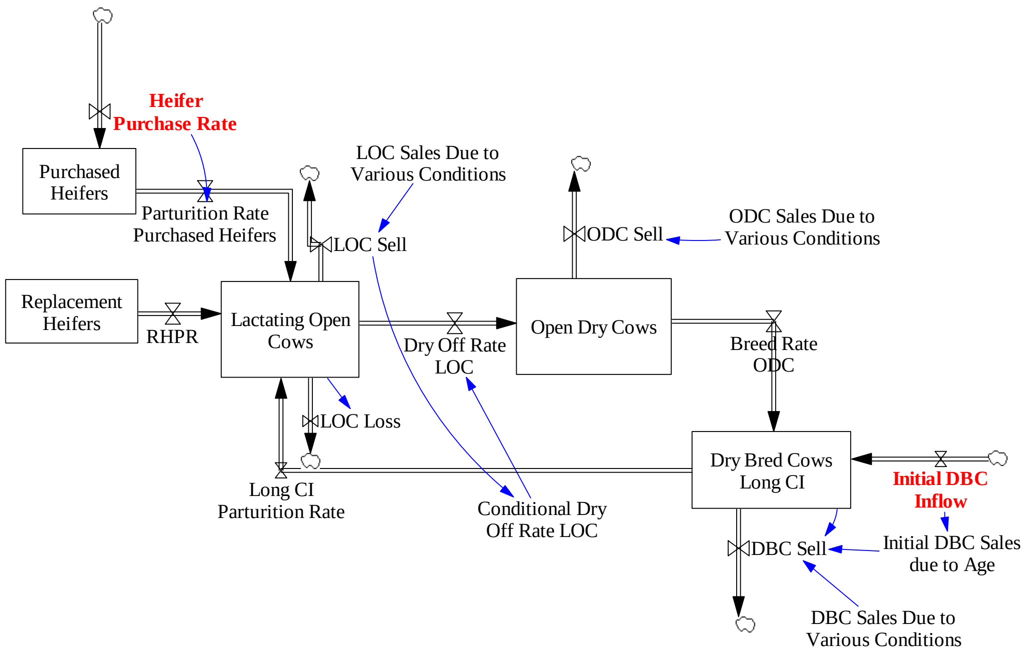

Figure 3. Aging-chain structure for household dairy cattle, showing different growth and physiological states.

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.

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). 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. This decision criterion assumes that labour is the most limited resource for the household. 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. This adjustment process, while stylized, again allows us to use the CLASSES model to examine the trajectory of the household's assets over a longer time scale in a descriptive fashion, rather than what would be the outcome of a prescriptive optimization model.

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 (25^{th} 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 4-7 show the resultant effects of changing farm size on the household's level of cash availability, maize harvests, the average agricultural receipts 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.

The maize harvests are smaller in total quantity for the half-hectare farms, and show an initial decline for both farm sizes during the simulation (Figure 5).[9] This decline reflects the net export of nutrients off-farm, and results in a corresponding decline in average agricultural receipts (Figure 6). The value of agricultural receipts increases with increasing farm size.

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 7). 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.[10] Investing in

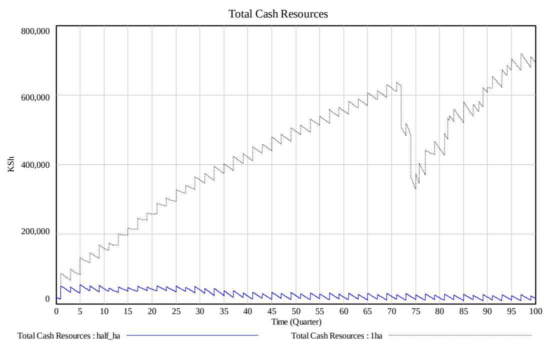

Figure 4. Household cash resources (Kenyan Shillings Ksh)

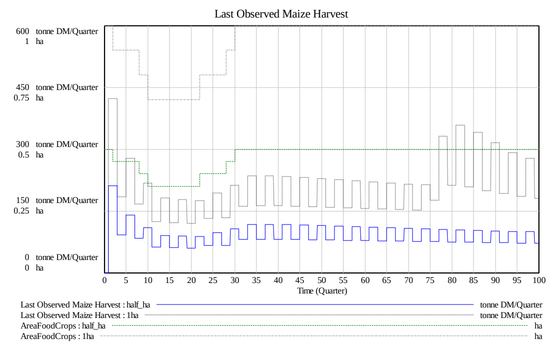

Figure 5. Maize Crop Harvests (tonnes DM/Quarter)

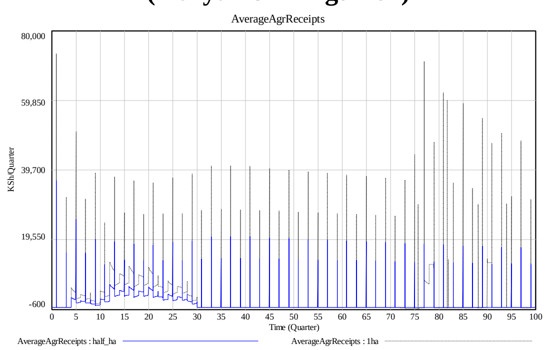

Figure 6. Average agricultural receipts (Ksh/Quarter)

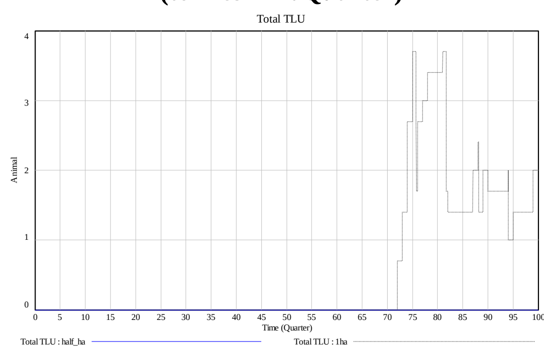

Figure 7. Total 'Tropical Livestock Units' (Animal equivalents)

livestock has the effect of helping to maintain cash stocks, as well as improve crop harvests through the incorporation of manure (Figures 4 and 5). 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 8-13).

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 (Figures 8 and 9). In addition, on the smaller farm with the labour force shock, the household switches from its position as a net seller of maize to a net buyer to the point that household consumption starts to be affected with higher effective maize prices due to positive transactions costs (Figure 10). Note that the minimum consumption for the median sized farm with more dependents is maintained at approximately 6,000 Ksh/Quarter for most of the simulation (Figure 11).

Household maize harvests are not greatly affected for the small farm (Figure 12). On-farm needs are small enough that the household can complete food crop labour requirements as well as search off-farm for additional cash resources to pay for subsistence consumption, although when interacted with the larger number of dependents, this does affect the household's marketing position and the effective market price for maize. Harvests are eventually reduced for the median farm, as the constraint of diminished cash resources for hiring-in extra labour for the larger farming area begins to bind (Figure 13).

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.

Small Farm (0.5 ha)	Median Farm (1 ha)

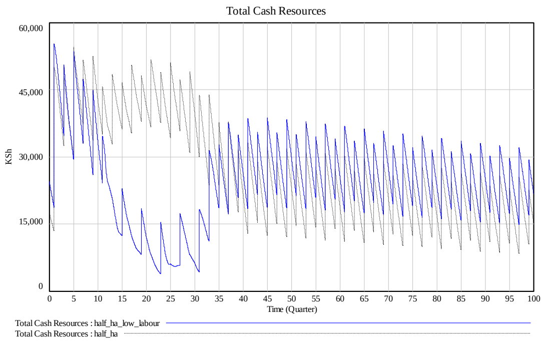

Figure 8. Labour impact on household cash resources, small farms (Ksh)

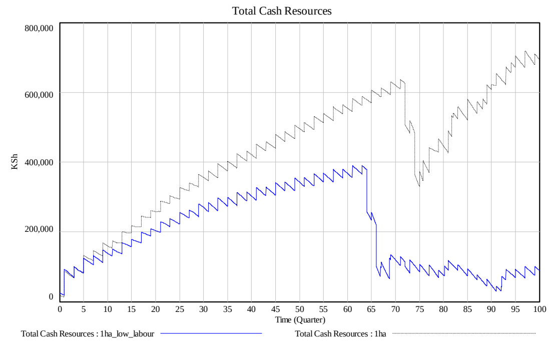

Figure 9. Labour impact on household cash resources, median farms (Ksh)

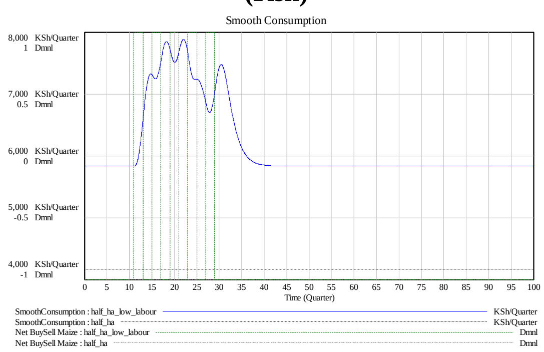

Figure 10. Labour impact on consumption, small farms (Ksh/Quarter)

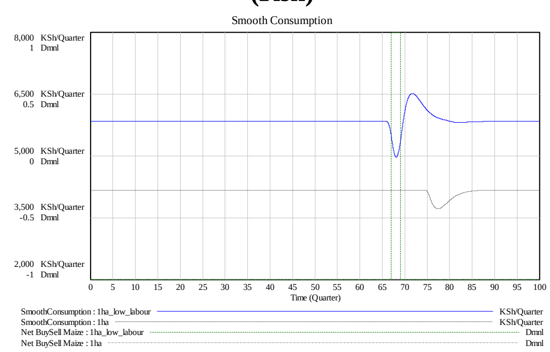

Figure 11. Labour impact on consumption, median farms (Ksh/Quarter)

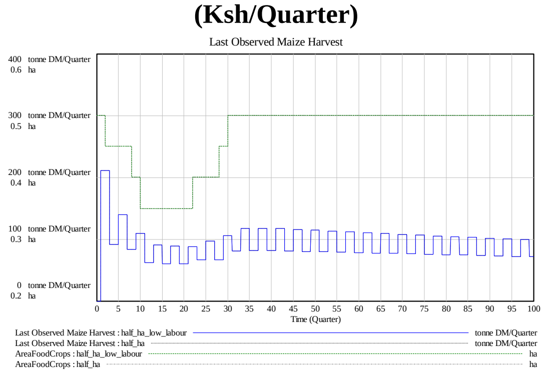

Figure 12. Labour impact on maize harvests, small farms (tonnes DM/Quarter)

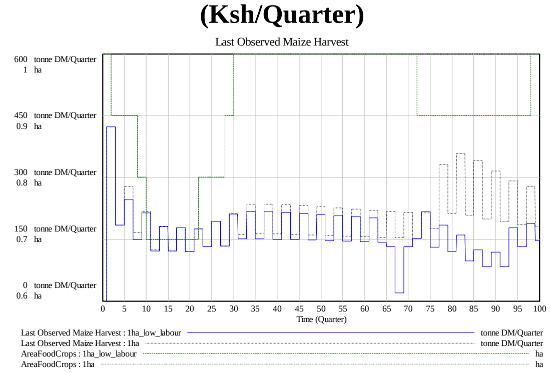

Figure 13. Labour impact on maize yields, median farms (tonnes DM/Quarter)

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 14-21 compare the outcomes for a 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 Figures 14 and 15 indicates the total cash earned from agricultural activities with which households can invest in livestock or other higher return activities. For both farm sizes, the degraded soil stocks lead to lower overall cash availability.

As can be seen, the households with ‘poor soils’ have consistently smaller crop harvests (Figures 16 and 17). For the 0.5 ha farm, the implication is that this household

Small Farm (0.5 ha)	Median Farm (1 ha)

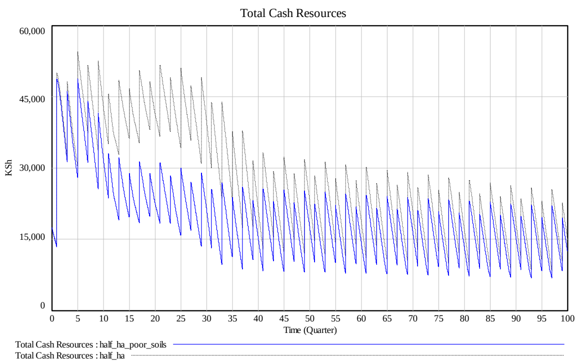

Figure 14. Effect of poor soils on cash available, small farms (Ksh)

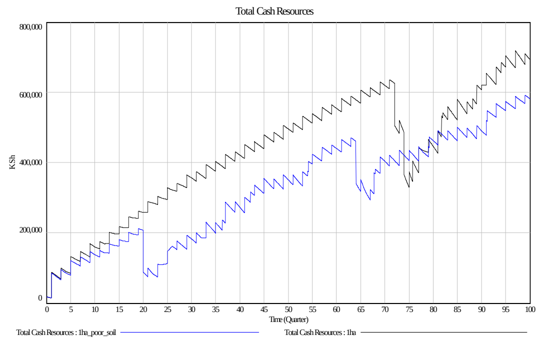

Figure 15. Effect of poor soils on cash available, small farms (Ksh)

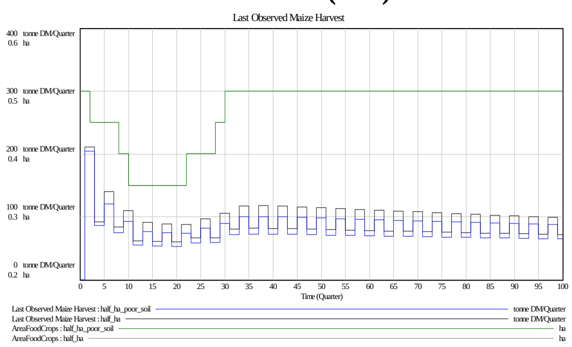

Figure 16. Soil stock impact on maize harvests, small farms (tonnes DM/Quarter)

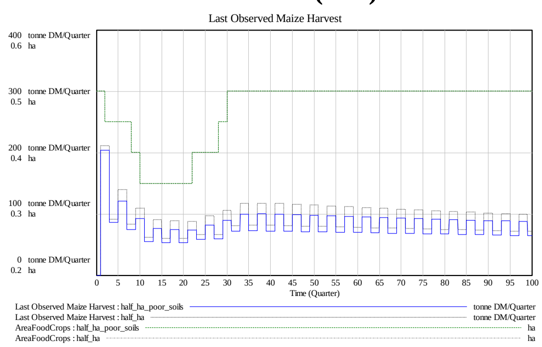

Figure 17. Soil stock impact on maize harvests, median farms (tonnes DM/Quarter)

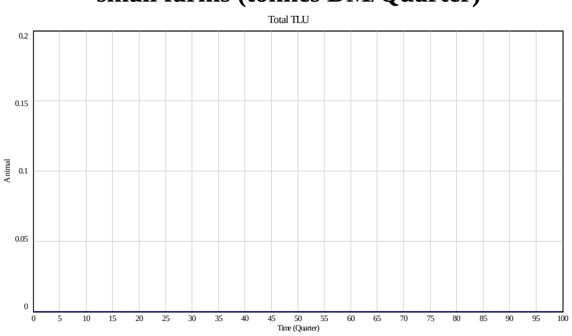

Figure 18. Tropical Livestock Units, small farms (TLU)

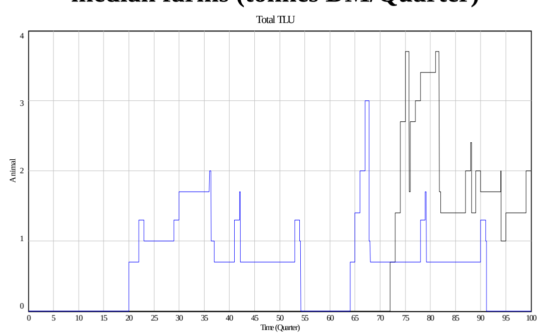

Figure 19. Tropical Livestock Units, median farms (TLU)

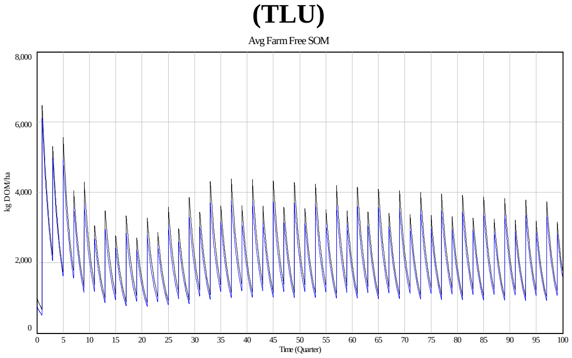

Figure 20. Average Free Soil Organic Matter, small farms (kg DOM/ha)

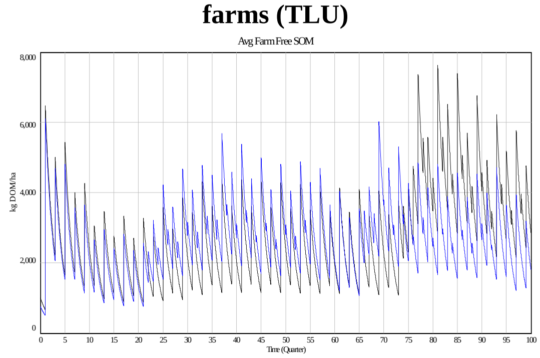

Figure 21. Average Free Soil Organic Matter, median farms (kg DOM/ha)

cannot generate enough revenue each cropping season to be able to save for the purchase of an in-calf heifer, and is thus unable to accumulate a dairy herd, unlike for the median sized household (Figures 18 and 19). Furthermore, the median-sized household with poor soils still has sufficient cash available that it is able to switch into the livestock activity even *earlier* than the equivalent household with better soils in response to more rapid soil nutrient deterioration. The consequent difference in all farm indicators of this capability is striking in comparison with that of the smaller farm. The long-run outcomes for the median-sized farms that start with degraded soils show higher levels of free soil organic matter necessary for continued cultivation (Figure 21) along with almost as much cash availability as the farm with better soils. So, median-sized households are able to move into a more mixed portfolio of agricultural activities with both crops and livestock contributing to household income, while smaller farms are unable to diversify into livestock when crop yields fall. The slight decline in the free soil organic matter stock is similar between the two scenarios (Figures 20 and 21), but the fact that the household begins with a smaller endowment of organic matter is sufficient to change the long run dynamics for the household.

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 (as in Experiment 3) and generating additional revenue from both crops and the livestock activity.

Further, only sufficiently large farms 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 system dynamics 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, as system dynamics focuses on modeling the specific mechanisms at work in farmer decision making or adjustments to biophysical dynamic processes. This allows for much greater flexibility within the model to respond to changing information than a computable general equilibrium model, for example, where the actual transition process between different states is not explicitly modeled. Further, even complex mathematical programming models that have been used to great effect by the agricultural economics field would still require a global optimization framework, which is less appropriate for the sequential decision-making we wish to represent with the CLASSES model. Econometric techniques are limited by the ‘curse of dimensionality’ and by the non-comparability of data sets – especially units and frequency of observation – across biophysical and socioeconomic variables. It would typically be intractable to consider the numbers of state variables involved in the CLASSES model in dynamic estimation, and similarly infeasible to blend data from different empirical research domains. These factors sharply limit the purview of econometric modeling to very specific relationships. Further, given the time frame of the CLASSES model, underlying assumptions about farmer foresight that would be inherent in any econometric model are not likely to be realistic.

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.

[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] Note that total maize yields also decline initially for both farms due to a temporary reduction in total area cultivated with maize, as shown.

[10] 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.

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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)[xi]	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)	750	750
Intra-aggregate SOM (kg DOM/ha)	237.4	237.4
Organo-Mineral SOM (kg DOM/ha)	23749.9	23749.9

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