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ORIGINAL PAPER

"Modeling the impact of natural resource-based poverty traps on food security in Kenya: The Crops, Livestock and Soils in Smallholder Economic Systems (CLASSES) model"

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Abstract We investigate the interactions between natural resource-based poverty traps and food security for smallholder farms in highland Kenya using a recently developed system dynamics bio-economic model. This approach permits examination of the complex interactions and feedback between farm household economic decision-making and long-term soil fertility dynamics that characterize persistent poverty and food insecurity among smallholders in

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rural highland Kenya. We examine the effects of changing initial endowments of land and stocks of soil organic matter on smallholders' well being, as reflected in several different indicators. We show that larger and higher quality land endowments permit accumulation of cash and livestock resources and conservation of soil organic matter relative to smaller or more degraded farms. This suggests the existence of asset thresholds that divide food secure households from food insecure ones.

Keywords Poverty traps · Kenya · Food security · Bio-economic modeling · System dynamics

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 et al. 2007; Baulch and Hoddinott 2000; Chronic Poverty Research Centre 2004). Many households 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 such 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). The resulting degradation of the local ecosystem thus lowers agricultural labour and land productivity, which can discourage capital-poor farmers from investing in maintaining the natural resource base or in high productivity agricultural technologies associated with sufficient food production, like fertilizer and high yield variety seeds (Carter and May 1999; Cleaver and Schreiber 1994; Marenya and Barrett 2009a, b; Reardon and Vosti 1995; Shepherd and Soule 1998).

In Kenya, large proportions of the population still reside in rural areas and rely on agriculture as their main source of income (IFAD 2007; Thurlow et al. 2007). Low agricultural productivity plagues most of Sub-Saharan Africa (World Bank 2008) and ensuring adequate advances in productivity with a view towards improving overall food security has become a policy priority in Kenya (Kibaara et al. 2008). Increased fertilizer usage and adoption of high yield variety seeds have been associated with recently observed (but still limited) gains and most government-supported food security initiatives aim to support more widespread adoption of similar on-farm investments in more productive technology and inputs (Kibaara et al. 2008). But other recent work in Kenya has documented that such on-farm investments are conditioned on the state of the natural resource base and farmers with highly degraded soils are not expected to respond as strongly to traditional economic incentives like access to credit to finance fertilizer use (Marenya and Barrett 2009a, b).

The dynamic relationship between the state of the natural resource base and optimal investment decisions thus has the potential to be a highly non-linear one characterized by either multiple dynamic equilibria or extended periods of disequilibrium. Farmers with good soils should respond to government efforts and market incentives to increase on-farm investment, leading to higher agricultural yields and incomes as well as the financial resources to continue to invest in maintaining good soils on the farm. In contrast, farmers with highly degraded soils may not find it optimal to invest in soil maintenance, despite easing of potential economic constraints offered by government or NGO programs. Due to lower fertilizer use efficiency and returns to fertilizer use on highly degraded (low Soil Organic Matter (SOM)) soils (Marenya and Barrett 2009a, b), households may still experience falling yields and persistent poverty and food insecurity even in the presence of these programs. Fully capturing these non-linear dynamic relationships is exceedingly difficult with traditional econometric techniques because soil dynamics and welfare dynamics operate on different time scales and longitudinal data spanning the necessary variables are rarely collected. In addition, we lack clear theoretical foundations to indicate how precisely soil quality or other biophysical data affect farmer choices, which would be required by more standard dynamic optimization models.

These challenges have prompted a growing literature on bio-economic modeling, especially in the context of natural resource management in developing country agriculture (Antle and Capalbo 2001; Brown 2000; Janssen and van Ittersum 2007). These techniques allow implementation of simulation models for complex bio-economic systems, avoiding some of the more unreasonable simplifications of these relationships previously imposed for tractability in more traditional econometric or mathematical programming methods. For example, it is possible to relax highly unrealistic assumptions of perfect farmer foresight and information about biophysical stocks and flows. Such models also permit out-of-sample simulation to explore states not yet observed and the exploration of multiple research questions, rather than just a single optimal or average decision rule involving a limited number of state variables.

In this paper we describe a recently developed simulation model (the Crops, Livestock and Soils in Smallholder Economic Systems (CLASSES) model) of the feedback between the key economic and biophysical systems that affect the overall welfare trajectory for small farming households in highland Kenya. The model uses system dynamics methods; its structure and parameterization are informed by recent data collected in Kenya from a variety of farm types by a multidisciplinary team. The data include longitudinal survey information on household characteristics, behaviours and welfare, livelihoods, key livestock variables, such as animal health and nutrition indicators, productivity and herd size dynamics, as well as laboratory and experimental data on soil nutrient dynamics under a variety of farming systems, and crop growth response to a range of different interventions. Conventional econometric or mathematical programming 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 the system dynamics simulation modeling approach.

Unlike most bio-economic models, ours is a closely coupled model wherein biological processes and economic decisions are dynamically and recursively linked.[1] The CLASSES model is also distinct from other existing bio-economic household models in that it treats household consumption and production decisions as non-separable, reflecting (sometimes household-specific) market failures that heavily influence behaviour (Singh et al. 1986). The model was constructed to explore the possibility of natural resource based poverty traps, in which initial natural resource conditions on farm shape the path dynamics of longer-run household productivity and well being measures. A natural resource-based poverty trap would imply the existence of a threshold level of both biophysical and economic assets that defines divergent dynamics for households on either side of the threshold, with asset poor households unable to accumulate biophysical or economic assets sufficient to sustainably lift themselves out of poverty. Asset-based poverty traps have been explored in depth for a wide range of possible candidate explanations for chronic poverty among small farm households (Adato et al. 2006; Barrett 2007; Dercon 1998; Mookherjee and Ray 2002). Recent work on relationships between poverty and agricultural production systems in Sub-Saharan Africa indicate a very strong linkage between rural poverty and food insecurity in the region (Barrett 2010) and improved food production, lower overall poverty and improved food security (Minten and Barrett 2008). Therefore, understanding the role of the natural resource base in driving persistent poverty is likely to yield insights into overall drivers of food insecurity as well.

Except in cases where long-term panel data sets exist, 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 states, but with very few observations of households in transition (Barrett 2007). The CLASSES model, in contrast, models the key inflow, outflow and feedback processes that determine the level of biophysical and economic stock variables at each point in time and does not rely on standard equilibrium concepts. By using parameterized stock-flow and feedback relationships based on experimental and observational data from the same locations and periods, it is possible to simulate the foundations of households' agricultural productivity, income, and biophysical assets and to observe the factors that influence the household's dynamic path towards either a high or low level of overall welfare.

In this paper, we use the CLASSES model to examine the differential impact of initial farm productive assets (approximated by varying the initial farm size in hectares) on poverty and food security, as well as how farm size interacts with other factors often associated with rural food insecurity like soil degradation, and shocks to food market transactions costs that affect market participation and returns to agriculture. In addition to being associated with better food security through increased household food production, the greater initial stock of biophysical assets associated with larger farms and/or more fertile soils is hypothesized to mitigate other shocks that lead to food insecurity, by providing greater income generation and opportunities for investment in more stable and higher return economic activities that can help households maintain adequate consumption levels. This approach provides a useful method to explore the coupled dynamics of smallholder welfare and the natural resource base on which they depend, in an environment where resource degradation and persistent poverty and food insecurity are first-order concerns for both researchers and policymakers.

System dynamics modeling methods

System dynamics (SD) 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. SD is a process-based modeling technique[2] that builds upon an observed dynamic reference mode 'problem' behaviour by using the fact that there are limited numbers of possible dynamic phenomena (behavioral modes) each generated by an underlying structure of stock (state) variables, flow variables and feedback loops (Ford 1999; Sterman 2000). The interactions between these structural elements move the entire system

[1] There are several other examples, such as Crissman et al. (1998), Brown (2008). Brown (2000) offers a more complete survey.

[2] System dynamics models are systems of (typically nonlinear) differential equations solved by numerical integration. Additional information and resources on system dynamics can be found on the System Dynamics Society webpage: www.systemdynamics.org.

forward in time by describing how the current state of the system influences future states. Moreover, SD facilitates the incorporation of information from diverse disciplines, and facilitates identification of the most essential information from each.

For farm households in Kenya, two fundamental behavioural modes are probable, conditioned on initial assets (especially the natural resource endowments) and idiosyncratic shocks (crop failure, loss of household labor). Households with initial assets above an asset threshold and who do not suffer significant or repeated shocks will experience logistic (s-shaped, goal-seeking) growth in incomes and asset accumulation. For households with sufficient initial endowments of productive assets, income growth over time will lift households out of poverty and mitigate food insecurity through both increased availability and access to food. Households with initial assets below a threshold, or who experience significant or repeated idiosyncratic shocks, will experience exponential decay in incomes and assets, including degradation of the natural resource base. These latter households thus experience natural-resource-based poverty traps resulting in persistent poverty and food insecurity. This bifurcation of behavioral modes suggests a region of increasing returns to household assets as well as the existence of asset thresholds, below which the income dynamics are not expected to result in much improvement in food security for farm households.

Another key feature of SD models is that they permit path dependency to emerge endogenously and need not assume global optimization behaviour (which may make unrealistic assumptions about the information and control available to decision makers). 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 period-by-period to changing environmental and economic conditions. System dynamics is thus very useful for creating a descriptive or predictive model of these complex interactions and farmer behaviour, rather than a prescriptive 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 a range of farm household outcomes, which would be difficult to include in a multi-period optimization model.

Data and model

The CLASSES model describes conditions for a typical smallholder farm household in highland Kenya. These households follow a mixed livelihood strategy, growing some combination of annual food crops, perennial cash crops and perennial fodder crops, maintaining small livestock herds, engaging in either unskilled or – if the household has adequate educational attainment – skilled wage labour, and receiving income transfers (often from family members residing elsewhere). Although smallholder farming systems are diverse, we represent each of these elements of the livelihood strategy with the dominant activity observed in highland Kenya (Brown et al. 2006). Thus maize represents the dominant annual food crop in the region, Napier grass represents the primary fodder crop, tea represents a common perennial cash crop, and livestock are represented by crossbred dairy cattle. Wage labour is represented by opportunities for skilled and unskilled off-farm employment, and income transfers are represented by remittance payments. The model has three primary modules that interact with each other over the course of 100 quarters (25 years). A crop and soil module describes the different cropping choices (how much land to be allocated to maize, Napier grass and tea each quarter) and subsequent yield and soil nutrient dynamics on the farm (in terms of soil organic matter, soil nitrogen and phosphorus stocks). A livestock module describes the livestock herd dynamics, tracking the number, physiological state and productivity of individual dairy cattle and their feed requirements. An economic module links farmer decision making on resource (land, labour and fertilizer) allocation to these activities each quarter and to the observed outcomes from each of the above activities, which can be complemented by off-farm skilled and unskilled employment opportunities.

A stylized representation of some of the key relationships in the CLASSES model (Fig. 1) indicates how the stock-flow-feedback structure can generate the hypothesized behavioural modes. Variables in bold italics are initial asset endowments, and bold red variables are those for which graphical results are reported subsequently. Consistent with SD diagramming conventions, boxes represent stocks and key flows are indicated with double arrows with valves. Single arrows indicate causal linkages and the direction (sign) of the linkages are indicated with "+" for positive linkages and "-"for negative linkages.

The crop and soils module describes the dynamics of biomass (crop yield as well as crop residues) and nutrients (in particular, soil organic matter, soil nitrogen and phosphorus) over time as they are cycled between the farm's naturally occurring soil stocks, agricultural biomass, and crop residues.[3] 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.

[3] For simplicity, the perennial cash crop (tea) and the perennial fodder crop (Napier) are omitted from the diagram. However, the stocks, flows and feedbacks are similar to that for the annual food crop (maize).

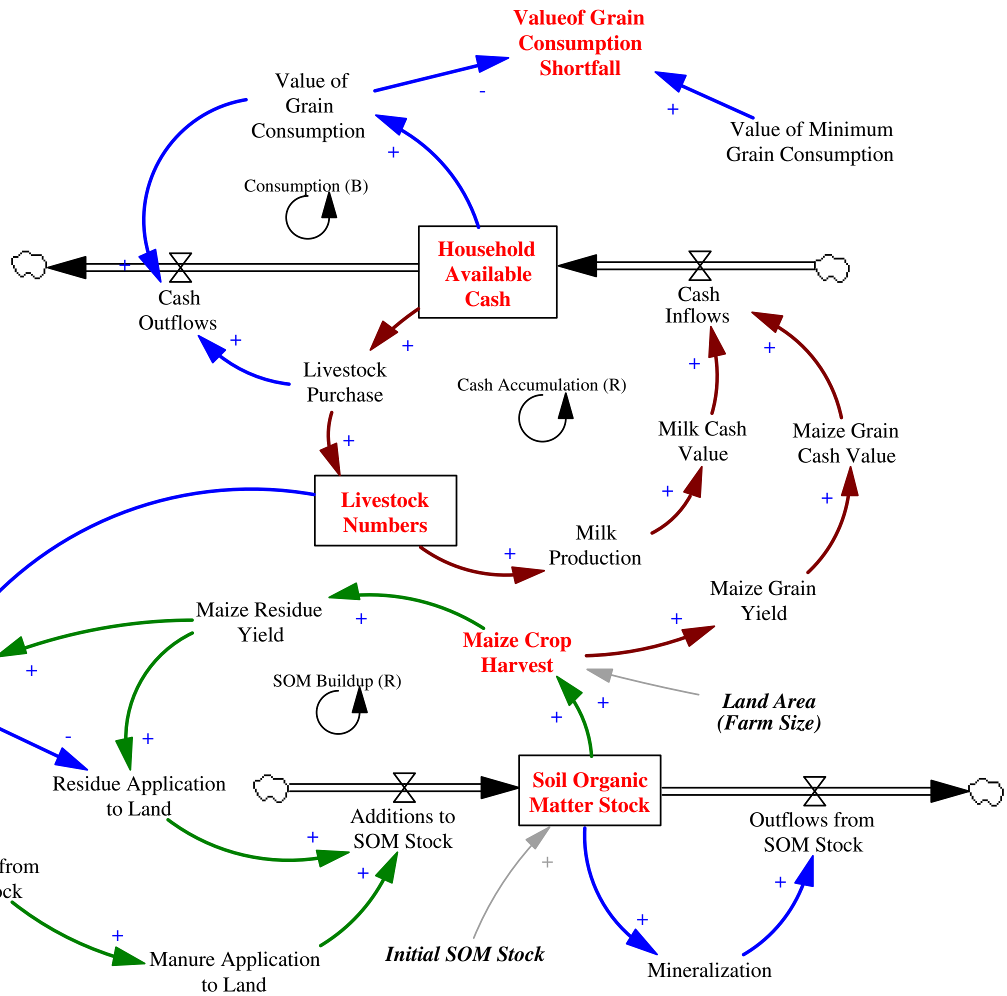

Fig. 1 A simplified representation of key stocks and flows, linkages, balancing (B) and reinforcing (R) loops, along with examples of potential feedback processes that determine dynamic behaviour in the CLASSES model. A colour version of this figure may be found in the online version

There are different ‘reinforcing’ (R) and ‘balancing’ (B) processes that determine the overall level of on-farm soil nutrients based on the current level of soil nutrient stocks and the behaviour of these stocks over time in response to household decisions regarding crop choice and agricultural inputs. This is illustrated in simplified form for the relationship between soil organic matter, maize yields and crop residues (See Fig. 1). A reinforcing process exists between soil organic matter (SOM, a stock), maize crop harvests and the application of crop residues[4] (depicted by green arrows). Larger SOM stocks lead to larger maize crop harvest and more crop residues available for reincorporation into the soil, which adds to SOM. When livestock are present, their manure also can contribute to SOM as a reinforcing process.

[4] Note that this process only applies because biomass is accumulated through photosynthesis. For other nutrients (N in most cases and P), external applications are required because there will be nutrient losses with each harvest cycle.

A balancing feedback process exists between SOM and SOM outflows. Larger SOM stocks leads to greater outflows due to processes like mineralization.

The household’s ability to maintain adequate soil stocks and thus availabilty and access to food (e.g., grain) is therefore determined by the relative dominance of the different reinforcing and balancing processes in the model. For example, farms with already degraded soil (a smaller initial SOM stock) are less productive, meaning that there is less capacity to reincorporate sufficient nutrients (either through crop residues or purchased fertilizer obtained from crop sales) to reinforce on-farm soil stocks to counteract the outflows associated with mineralization (balancing). Such households are more likely to fall into the hypothesized natural resource based poverty trap than ones that are able to generate increasing returns to on-farm activities due to having better initial stocks of assets.

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. The livestock module represents dairy cattle in different stages of lactation, as well as their detailed nutrient requirements and the relationship between feed requirements and on-farm fodder production. As with the soils module, farmer decisions on overall livelihood activities (for example, the choice of farm area dedicated to animal fodder versus food crops) and resource allocation decisions (for example, cash allocation towards purchasing additional animals) determine the levels of stocks in the livestock module.

There are several important reinforcing feedback processes linking the crop and livestock modules, which determine dynamic behaviour (Fig. 1). One important reinforcing process (indicated by red arrows) is that larger maize crop harvests lead to greater cash accumulation (through increased maize grain values), which facilitates the acquisition of livestock assets (and more crop residues to feed them). More livestock also results in more milk production, which increases household cash available (in addition to food availability). The crop and soils module plus the livestock module comprise the model's biophysical system.

The economic module describes how the household changes its allocation of labour, land and cash resources among several important livelihood activities, including food, forage and cash crops, milk production and (skilled or unskilled) off-farm labour. Over the simulation horizon of the model, households observe deterministically[5] changing returns to agricultural activities on their farms.[6] These returns are characterized by the average value product of labour (AVP_L, measured in Kenyan Shillings (KSh) per day) and evolve over time due to the dynamics in the underlying biophysical resources that determine agricultural production. The household makes choices to allocate its land, labour and cash resources over time, based on the changing returns (AVP_L) of different activities each quarter. Activities that earn the highest average value product get priority in terms of resource allocation, as long as the household has sufficient land, labor and/or cash resources. For example, the returns to labour in livestock are often quite high, but the household is not always able to engage in this activity due to insufficient cash availabile to purchase cattle.[7] In this case, household land and labour resources would be allocated to the activity with the next highest return to labour. Consumption of grain and livestock purchases represent outflows from the household's available cash, and serve as a balancing process on cash accumulation. When insufficient cash is available to allow the minimum required value of grain consumption, the magnitude of the shortfall in value terms suggests the severity of food insecurity. A more detailed (but still simplified) representation of the combined modules is provided in Appendix 1.[8]

[5] 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 the incorporation of risk in later versions

[6] The households also compare on-farm returns to off-farm opportunities.

[7] Although it would be quite feasible to do so, the current version of CLASSES does not include credit access that could facilitate asset acquisition when insufficient cash is available.

Model simulations

The CLASSES model can be used to examine both the short- and long-run impacts of various factors associated with poverty and food insecurity on both the economic and biophysical systems on farms. It also allows more detailed study of potential leverage points to address these shocks than do models that do not include extensive interactions and feedback relationships among economic and biophysical processes. In our application of the model, we focus on the role of endogenous biophysical and economic decision processes in generating food insecurity, and therefore our scenarios do not include remittances or more highly remunerated off-farm income opportunities.

Simulation 1: The effect of farm size on long-run household welfare[9]

We first examine behaviours for several measures of productivity and farmer welfare for farms with different land areas. Land pressure and population growth are both contributing to shrinking farm sizes in Kenya (Kibaara et al. 2008). One direct result is smaller subsistence farms, less food crop production and greater reliance on non-farm sources of income to purchase daily food requirements. Smaller farms are thus expected to have lower overall agricultural output than larger farms, as well as a potentially different net marketing position, with smaller farms operating mainly as net buyers (Barrett 2008). This creates attendant risks to food security inherent in greater reliance on thin food markets. Past studies have found smaller farms experiencing soil degradation and worsening agricultural productivity alongside larger farms maintaining soil fertility and standards of living (Shepherd and Soule 1998).

Two scenarios are simulated to explore the effect of the initial land endowment on long-term household welfare, measured by cash available. One scenario assumes a farm size equal to that of the 25th percentile in the survey area

[8] The full model and accompanying documentation are available at http://pzacad.pitzer.edu/~estephen/

[9] Summaries of the parameterization of all simulations are included in the appendix.

(0.5 hectares) and another the median farm size (1 hectare). A household of three adults and two dependents is assumed to manage 10 equally-sized plots on the farm and can switch crops each quarter in response to changing returns to labour in different crop activities.[10] For each simulation run, the household starts with all 10 plots in maize and median soil quality, but each quarter can choose to switch one plot at a time to Napier or tea if the returns to labour are higher.[11] Figures 2a–d show the effects of differing farm size on the household's level of total cash resources from agricultural receipts, total maize harvests, the average level of soil N across all plots (which determines crop yields) and the size of the household's herd of livestock (in terms of Tropical Livestock Units (TLU)[12]).

The simulation results suggest that initial land allocation has a large impact on welfare outcomes and household activities, and are consistent with our initial hypotheses regarding different behavioural modes. Total cash available is larger and grows markedly over time for the 1 hectare farm (Fig. 2a). Growth in cash available for the larger farm is due to the larger maize harvests[13] (Fig. 2b), which makes maize grain available for sale and facilitates an investment in livestock (Fig. 2d).[14] As noted above, livestock represent an initial reduction in cash available but generate increased income from milk sales. The last two figures show the interaction between the farm size, soil N stocks and livestock investment. The qualitative differences in dynamics based solely on initial farm size are striking. They strongly suggest a threshold farm size, conditional on other farm attributes, above which Kenyan smallholders can maintain productivity and the soil fertility on which agricultural livelihoods depend, and accumulate livestock and cash resources, but below which, resource conservation and asset accumulation appear infeasible. In additional simulations, the threshold farm size appears to be approximately 0.7 ha (results not shown but available upon request).

Farm size also has an impact on the household's ability to secure a minimum level of food consumption. As farm sizes shrink, the cash value of crops falls, due to the fact that overall agricultural harvests are smaller for these farms. This limits the household's ability to accumulate cash to invest in higher return activities, like livestock and/or cash crops. Figure 3 shows the impact of lower initial farm size on the household's level of consumption of the main staple crop (maize) by comparing two farm sizes (1 hectare and 0.25 hectares). Negative values indicate the amount by which the value of household consumption has fallen below a minimum consumption level defined as the monetary cost (in KSh) of 100 kg of maize per person per quarter. The 1 hectare farm is able to maintain subsistence consumption.[15] However, the 0.25 ha farm experiences repeated consumption shortfalls driven partly by smaller and declining maize harvests as the natural resource base on the farm gradually deteriorates.

The overall implication of these results is that initial conditions matter for long-term welfare and food security outcomes. Those households with larger initial farms are able to generate sufficient accumulated savings over time to have the capacity to invest in higher return activities, like livestock. Holding initial soil quality constant, small farms are never able to take advantage of these opportunities, as their smaller harvests do not bring in sufficient income to enable investment in future periods. The ability to invest in livestock specifically as a livelihood activity is also an important driver of these results, as this activity both generates sufficient levels of income through sales of milk, heifers and calves, but also imports significant levels of nutrients (soil N and phosphorus) to the farm system,[16] allowing continued high agricultural yields for longer periods than is the case without livestock. The larger cash availability generated by higher crop yields and livestock is sufficient to avoid consumption shortfalls and food insecurity, as households can always purchase food even if on-farm production falls short of subsistence levels.

[10] The dependents add to household consumption levels but do not contribute to the level of available labor on the farm.

[11] The levels of soil nutrients and other farm parameters for each simulation are included in tables in Appendix 2. 'Median soil quality in our simulations is soil that begins the simulation with half of the initial level of soil nutrient stocks available after the land has been converted from primary forest into agricultural farmland. The stocks, flows and returns related to each plot are modelled individually so as to be able to understand how, for example, soil fertility on each part of the farm evolves over time.

[12] Tropical Livestock Units index livestock quantities across species based on feed intake. The baseline compares all animals to the intake requirements for camels (1 TLU). In our model, cows are also 1 TLU, heifers are 0.7 TLU and calves are 0.3 TLU reflecting differences in intake requirements for male and female cattle as well as adults versus younger animals.

[13] Although the model is deterministic, we have included regular seasonal variation in agricultural yields, with short rains harvests systematically smaller than long rains harvests.

[14] The previous discussion about behavioural modes hypothesized logistic growth or exponential decay based on the simplified feedback structure depicted in Fig. 1. The simulation model results incorporate a number of additional processes (e.g., expenditures for livestock or seasonal crop production) and therefore have additional variation. However, the results are broadly consistent with a bifurcation of behavioural modes—growth for the larger farm and exponential decay and stagnation for the smaller farm.

[15] The 0.5 ha farm is also able to maintain subsistence consumption even though it becomes a net buyer of maize around t=30 in the simulation (not shown).

[16] Nutrient imports to the farm system resulting from livestock ownership are due primarily to purchased feeds (e.g., maize bran), which are commonly used in the Kenyan highlands, and collection of other feed resources not produced on the farm (such as gathering roadside grasses or weeds). Note that manure *per se* typically does not represent a source of imported nutrients in this system. Rather, it is one component of nutrient cycling in the farm system.

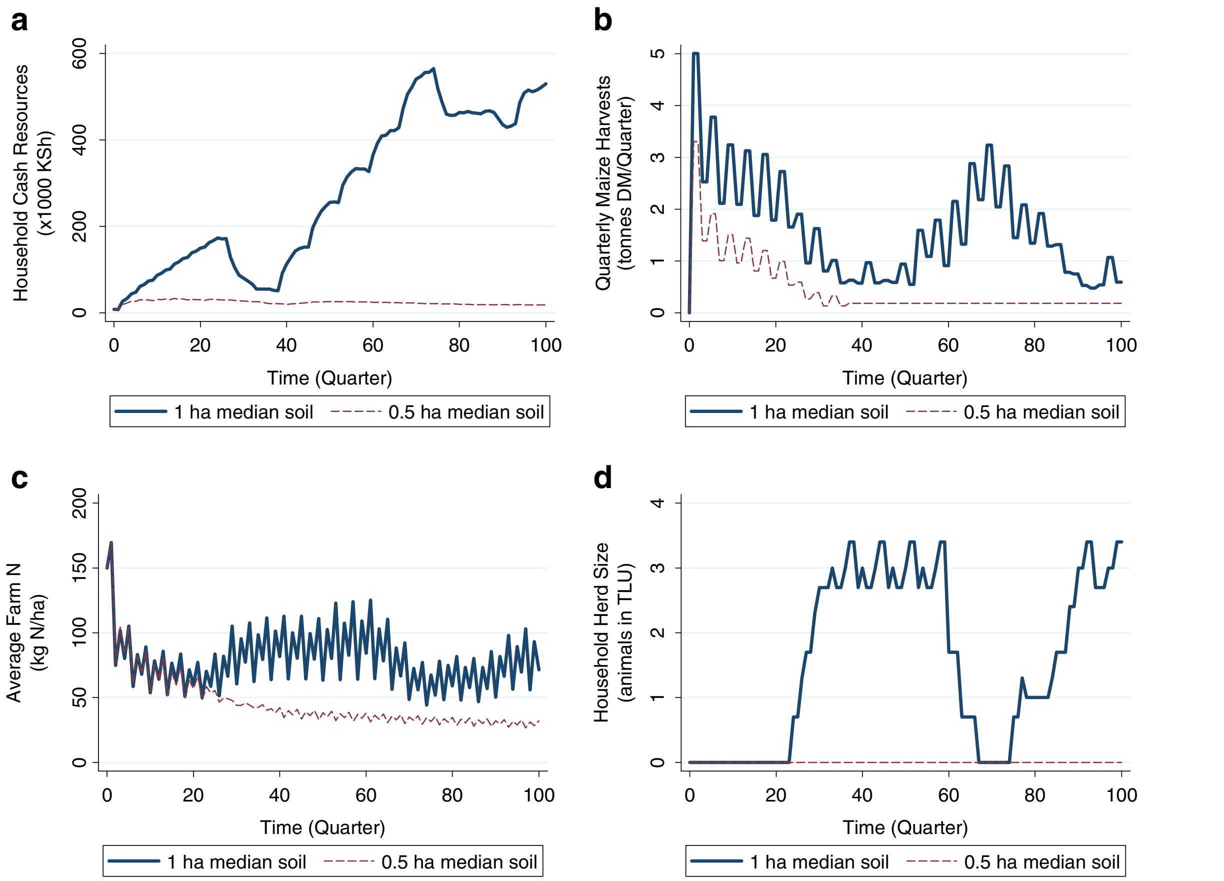

Fig. 2 **a** Household Available Cash resources, 1 ha vs. 0.5 ha farms (in Kenyan Shillings KSh). **b** Quarterly Maize Grain Harvests, 1 ha vs. 0.5 ha farms (tonnes dry matter (DM)/Quarter). **c** Average Farm Available Soil N Stocks, 1 ha vs. 0.5 ha farms (kg N/ha). **d** Size of the Household Livestock Herd, 1 ha vs. 0.5 ha farms (animals)

Simulation 2: The effects of degraded soil organic matter stocks

Recent research on agricultural livelihood strategies in east Africa indicates that households that are able to engage in a portfolio of different agricultural activities, particularly those that involve livestock, typically enjoy higher overall welfare and also earn higher returns for non-livestock activities (Brown et al. 2006; Dercon 1998). The main dynamic 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, whereas poorly endowed households remain trapped in low-return activities. The CLASSES model allows us to examine asset thresholds that 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.

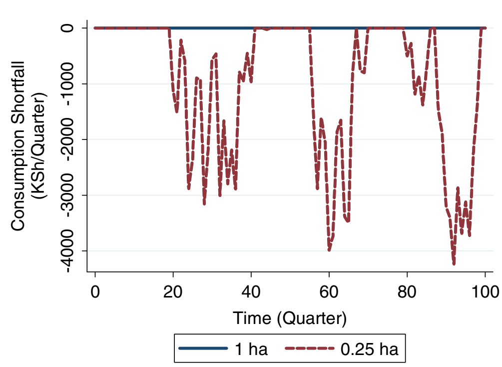

Fig. 3 Consumption shortfalls below subsistence consumption as a function of farm size (KSh/Quarter)

Figures 4a-f 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 ('median soils'), to an identical household that is farming on soils whose nutrient and organic matter stocks are initially one half of this level ('degraded soils'). The figures on the left show results for the small (0.5 ha) farm, while those on the rightshow equivalent results for the median (1.0 ha) farm such that for median soil quality, the displayed results replicate those in Figs. 2a to d to facilitate comparison. In order to calibrate the model with data on soil stock levels over the time frame of the model (25 years), the multidisciplinary team collected soil nutrient stocks data from farms in the survey area that had been converted from forest for varying lengths of time, starting with the oldest conversions from 1900 and then sampling progressively newer conversions in approximately 20 year intervals up to the newest conversions from 2000. This sampling procedure along a 'chronosequence' of farm ages allowed us to approximate the dynamic path of soil nutrient stocks versus the amount of time the land has been in agricultural use over time frames relevant for the CLASSES model (see Marenya and Barrett (2009b) for further descriptive details).

The cash availability comparison in Figs. 4a and b indicate that the total cash earned from agricultural activities is lower for both farm sizes when each begins with more degraded soil stocks. Further, they are also less able to accumulate enough cash to purchase livestock, so the maize harvest patterns are quite different for farms with initially degraded soils (Figs. 4c and d). For example, the 1 ha farms with degraded initial soils have smaller and less variable harvests because they do not get additional fertility from incorporation of livestock manure, but they also do not switch out of maize as often and do not experience the same kinds of harvest shortfalls as farms with good soils that pursue a mixed strategy with both maize and Napier crops and livestock. For the 0.5 ha farm, maize harvests are larger on degraded soils, but this is because the household is also unable to afford to switch into Napier grass, which has a higher return to farm labour. Neither farm with degraded soils is able to purchase livestock (not shown).

Finally, there are dramatic differences in the farm stock of soil N. For the small farm with median quality soils, the average on farm availability of soil N per hectare is initially higher, but eventually falls to the same low level of farms with degraded initial soil quality (Fig. 4e). By contrast, the larger farm with the median quality soils has generally higher levels of soil N stocks. These stocks also do not appear to deteriorate as rapidly as is the case with the same size farm with badly degraded initial soil stocks (Fig. 4f).

In terms of subsistence food consumption, a combination of deteriorating soil quality and shrinking farm size results in greater food insecurity. A very small farm will experience greater food insecurity as initial soil stocks decline. Figure 5 shows the impact on a 0.25 ha farm of diminishing soil stocks by comparing the results for median initial quality soils (at 50% of the level immediately after a conversion of forested land to farm land) and poor soils (25% of the value immediately after forest conversion). As can be seen, the consumption shortfalls begin earlier and are more prevalent for the very small farm with poor initial soils. The 1 ha and 0.5 ha farms have sufficient on-farm resources to maintain subsistence consumption even as soil quality deteriorates, primarily because they are both able to afford to plant more Napier grass on their farms and sell it to purchase food (not shown). Napier grass is not as extractive as maize, and helps the farm to maintain productivity even when soil stocks are low.

These scenarios demonstrate that farm size is not sufficient to escape a natural resource based poverty trap, although it does seem to mitigate food insecurity problems. Larger 1 ha farms with degraded soils have much lower accumulated cash surpluses, which limits their ability to invest in higher return activities. The value of the yields on these farms is still sufficient to guarantee food security, but they are limited in their ability to maintain on-farm natural capital for long periods of time. It is likely that eventually even the larger farms will start to experience consumption shortfalls as the natural capital base deteriorates further without additional resources generated by livestock investment.

Simulation 3: Biophysical assets and resilience to shocks

Given the interactions between livelihood choices and the underlying dynamics of the biophysical resource, farming households in Kenya can respond in a variety of ways to different biophysical and economic shocks, with longer-term consequences for both welfare and the condition of the farm's natural capital. As can be seen above, apparent thresholds exist in the household's stock of natural capital that separate households that are able to achieve subsistence consumption from those which are food insecure. Shocks to either the biophysical system or economic returns from farming may alter the location of these thresholds and the ultimate welfare trajectory for households that have not experienced such shocks.

Simulation 3a: Agricultural yield shocks

In order to explore this hypothesis, we subjected the model household to a 50% decline in food crop yields starting at $t=10$ and lasting for 1 year and examined the impact compared to the baseline with no shock on the household's ability to manage the natural resource base, invest in higher return activities and maintain subsistence consumption (Figs. 6 through 8). We imposed this shock on a 0.7 ha farm with median initial soil quality (Yield Shock), as in previous simulations; this represents a threshold farm size below which households are not able to maintain soil stocks, invest in livestock (a high return activity that also helps to maintain on-farm soil nutrients) and accumulate cash resources. We also imposed the same shock on a slightly larger farm (0.8 ha) to examine whether larger initial assets can mitigate the shock (Larger Farm), as well as on a 0.7 ha farm with better initial soil quality (at 100% of the value after forest conversion; Better Soils).

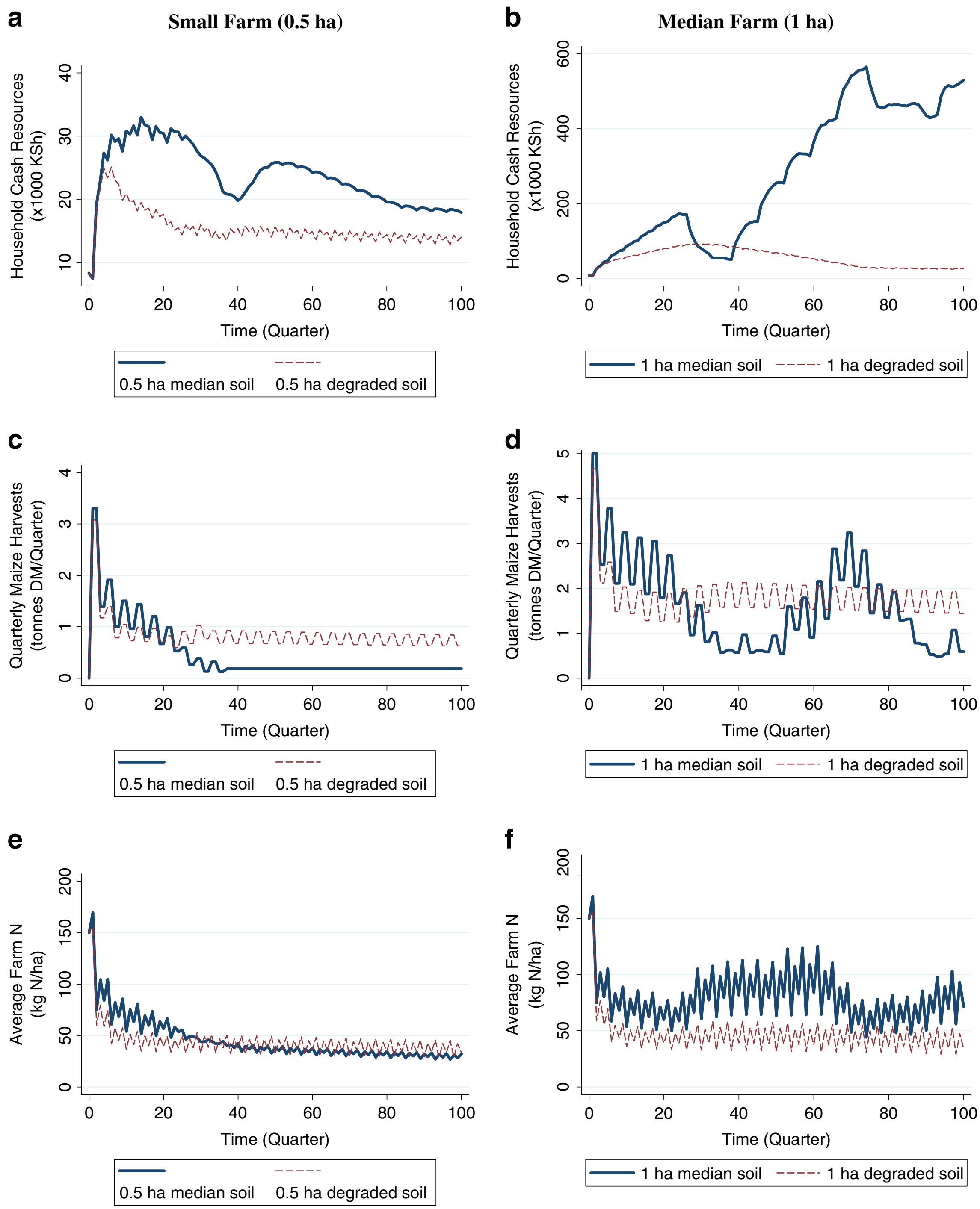

Fig. 4 **a** Effect of poor soils on cash resources, 0.5 ha farms (KSh). **b** Effect of poor soils on cash resources, 1 ha farms (KSh).**c** Effect of poor soils on on maize harvest, 0.5 ha farms (tonnes DM/Quarter). **d** Effect of poor soils on maize harvest, 1 ha farms (tonnes DM/Quarter). **e** Effect of poor soils on average farm available soil N stocks, 0.5 ha farms (kg N/ha). **f** Effect of poor soils on average farm available soil N, 1 ha farms (kg N/ha)

Figure 6 shows dramatic differences in the total cash resources for each of these simulations. The yield shock by itself modestly reduces the available cash resources for the 0.7 ha farm. But the larger farm size or better initial soil stocks more than compensate for the impact of the yield shock on cash resources.

The level of available cash affects the farm's ability to invest in livestock (Fig. 7). For the 0.7 ha farm with median soil quality, the shock is severe enough to ensure that this farm will never invest in livestock (final cash availability is 25% smaller at the end of the simulation after the yield shock in comparison to the baseline). In contrast, the shock

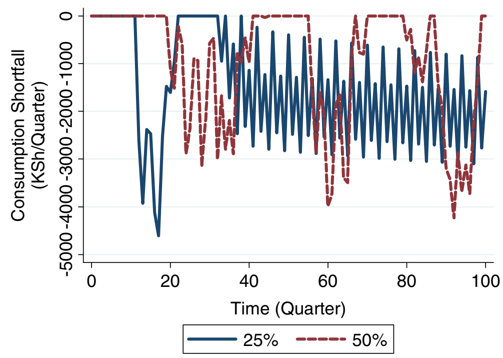

Fig. 5 Consumption shortfalls for varying levels of initial soil nutrient stocks (25% vs. 50%) for very small farms (0.25 ha)

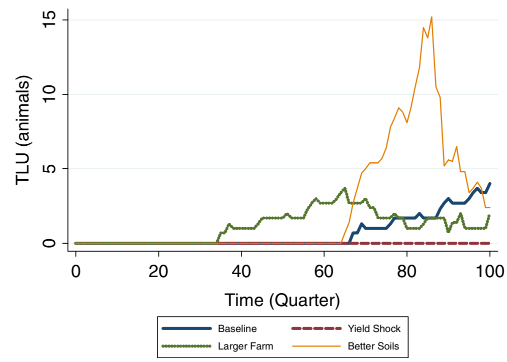

Fig. 7 Impact of 50% yield shock on investment in livestock for several farm types

does little to alter the investment decisions of the larger farm and the 0.7 ha farm with better soils, although without the shock, both of these farms would have invested in even more livestock (not shown).

The long-term impact of a temporary yield shock becomes clearer when we examine the consequences for on-farm available soil N stocks (Fig. 8). Initially, the 0.7 ha farm without the yield shock is able to invest in livestock at $t=67$ because it has accumulated sufficient cash resources to be able to purchase a first animal at that time (which costs 120,000 KSh in the region of study); the larger farm and the farm with the higher soil quality are able to make this investment earlier. However the 0.7 ha farm with the yield shock falls short of the level of cash necessary to make this purchase at $t=67$.

As was shown in Simulation 1, the presence of livestock on the farm leads to larger on-farm nutrient stocks, like soil N. So, without the ability to invest in livestock due to the yield shock, on-farm soil nutrients deteriorate, leading to lower yields and less cash accumulation to such an extent that it is never possible for the household to purchase livestock. For the larger farm and the farm with higher soil quality, the yield shock does not have a similar impact on investments, with the longer-term consequence that soil stocks, crop yields and cash resources are maintained and growing after the initial investment in livestock, despite the temporary shortfall in agricultural receipts.

In terms of subsistence consumption, despite the shock, the different households in this simulation are able to maintain subsistence consumption (not shown). Shortfalls in subsistence consumption for the 0.7 ha farm are only seen after a much larger (100%) and more sustained (5 years) yield shock. For smaller yield shocks and/or of shorter duration, the household uses the high levels of accumulated surplus earned from earlier agricultural activities to purchase food in the market. The size of the farm helps the household to build up this buffer stock of savings to successfully protect it against yield shocks in all but the most extreme cases.

Simulation 3b: Market access shocks

Market frictions are pervasive in Kenya and elsewhere in Sub-Saharan Africa. The high costs associated with market transactions can greatly impact the dynamic processes of asset accumulation to maintain both economic wellbeing and the natural resource base. To further examine the role of market access costs on farm household dynamics, we subject the same threshold household (0.7 ha with median soil fertility) to a positive and negative shock to transactions

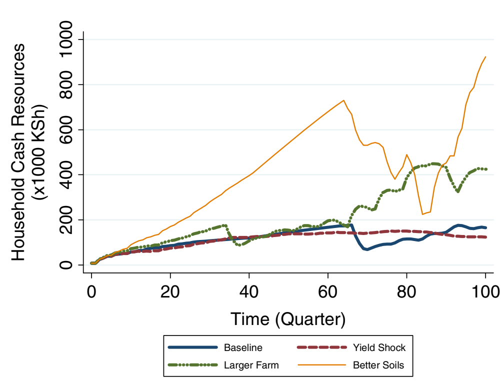

Fig. 6 Impact of a 1-year, 50% decrease in maize yields at $t=10$ on cash available for different farm types

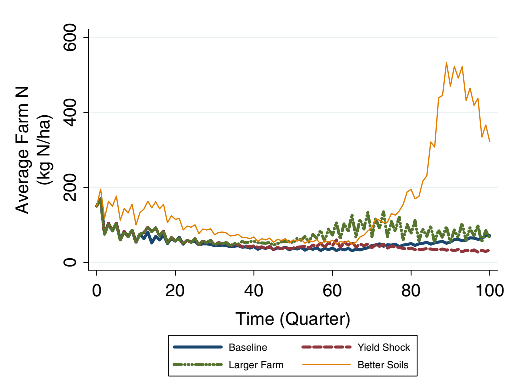

Fig. 8 Impact of 50% yield shock on nitrogen available for several farm types

costs associated with selling maize in the market and compare these to the baseline outcomes. The positive shock examines the impact of eliminating all transactions costs in a 'best-case' type scenario (No Transactions Costs), while the negative shock doubles transactions costs (Double Transactions Costs).[17] We also compare the relative impact of shocks to transactions costs with the same yield shock as described in simulation 3a (Yield Shock No Transactions Costs).

These shocks to the market environment have long-term consequences for farmer welfare, the level of on-farm natural capital and the ability to meet subsistence consumption. Figure 9 shows the impact of these transactions costs shocks on the total cash resources available to the household. Predictably, eliminating transactions costs allows the household to accumulate cash resources more rapidly, while increasing them diminishes cash resources. Interestingly, the impact of eliminating transactions costs is sufficiently large to essentially eliminate the impact of the yield shock on this household's cash resources. Low-cost market access enables the household to overcome the temporary adverse effects of a yield shock.

The difference in accumulated cash resources also leads to differences in ability to invest in livestock and subsequent maintenance of on-farm soil nutrients (not shown), in a manner similar to the impact of the yield shock described earlier. In the 'best-case' no transactions cost scenario (with or without the yield shock), the household invests in livestock earlier (at t=30 instead of t=67), while in the case of doubled transactions costs, the household never invests in livestock. Consequently, soil N stocks are the lowest and deteriorate the most in the high transactions cost scenario, and are highest in the no transaction cost scenario. Market access can thus directly affect the biophysical dynamics of farming systems.

In the absence of transactions costs, the threshold (0.7 ha) household is always able to meet its subsistence consumption requirements. For smaller farms that are more food insecure, removing the transactions costs seems to minimize consumption shortfalls. Figure 10 shows the impact of removing transactions costs on the 0.25 ha farm. The results suggest that the farm with better market access can accumulate more cash resources to resolve occasional consumption shortfalls, although the small size of the farm makes ensuring a consistent consumption level difficult no matter the ease of access to output markets.

Raising transactions costs forces the farm into self-sufficiency in maize production. Given the soil quality data used to parameterize the model, self-sufficient farms can sustain minimum food consumption for periods longer than

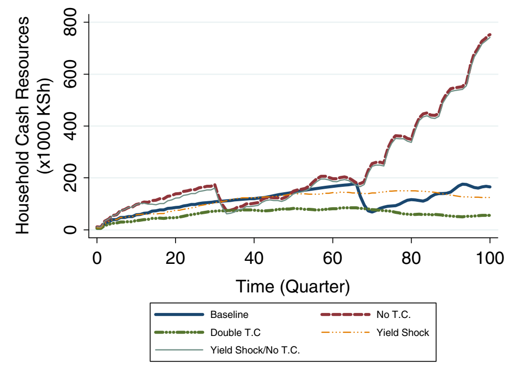

Fig. 9 Impact of either zero or doubled transactions costs on cash availability under different scenarios

the one generation time frame of interest in this paper, but at the cost of eliminating all household cash resources and ability to invest in any other activity besides food production (not shown).

Conclusions

Using a system dynamics bio-economic model of farming households in Kenya, we examine the interactions among the farm's biophysical (crop, livestock and soil nutrient) assets and their economic well being as well as identify important asset thresholds that characterize households that are unable to escape from poverty and associated food insecurity. We show that the natural resource base has strong influence on poverty, livelihood choices and consumption and that economic phenomena, such as the transactions costs of market access, likewise affect biophysical phenomena. Natural resource base degradation or insufficient levels of initial natural capital are associated with low levels of accumulated surplus and growing insecurity in consumption of staple grains.

The feedback and interactions between economic decision-making and the dynamics of the natural resource base also suggest that policies to address poverty and food insecurity in

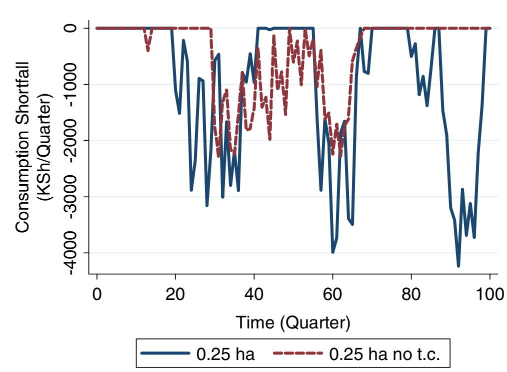

Fig. 10 The impact of eliminating transactions costs on consumption levels for a 0.25 ha farm

[17] The baseline transaction cost in the model is 250 KSh/1,000 kg sack of maize, and the baseline price is 1,000 KSh/sack.

either an economic or biophysical capacity may reinforce one another. For example, initiatives to remove market frictions may counteract the impacts of biophysical yield shocks; similarly, improving on-farm yields may have long-term consequences for maintenance of the natural resource base and for households' accumulation of cash reserves. However, without any kind of intervention, negative biophysical and economic shocks can have long-term negative consequences for both economic well-being and the natural resource base, both directly and by reducing incentives for important investments in high return activities, like livestock, that can have reinforcing feedback on the accumulation of both cash resources and soil nutrient stocks.

In terms of food insecurity, our findings underscore how critical shortfalls in both the quantity and quality of natural capital assets generate conditions where households cannot maintain subsistence consumption. Given the observed low levels of investment in soil quality in Kenya (Duflo et al. 2008; Marenya and Barrett 2009a, b), and predicted continued reduction in farm size due to high fertility and Kenya's inheritance institutions (Shreffler and Nii-Amoo Dodoo 2009), it seems likely that food insecurity will continue to be a pressing issue in rural Kenya without intervention on either the land quantity or quality side.

The simulation modeling approach used for the CLASSES model allows for the exploration of several possible leverage points to address food security issues. Furthermore, it also illustrates the inextricable linkages between biophysical and economic phenomena in such settings, which can help identify potential unintended consequences (positive or negative) to policy interventions. For example, a policy to reduce staple grain market transactions costs, according to our simulation results, appears to not only help resolve more immediate food insecurity problems for smaller farms, but also encourages investment in livestock which in turn helps maintain on-farm biophysical resources into future periods. Such conclusions would be harder to reach with a more conventional econometric approach to market participation and household food security, for example. Given the limited resources available to address food security issues, a model like CLASSES can be used to search for similar complementarities and spillovers to maximize the impact of government policy.

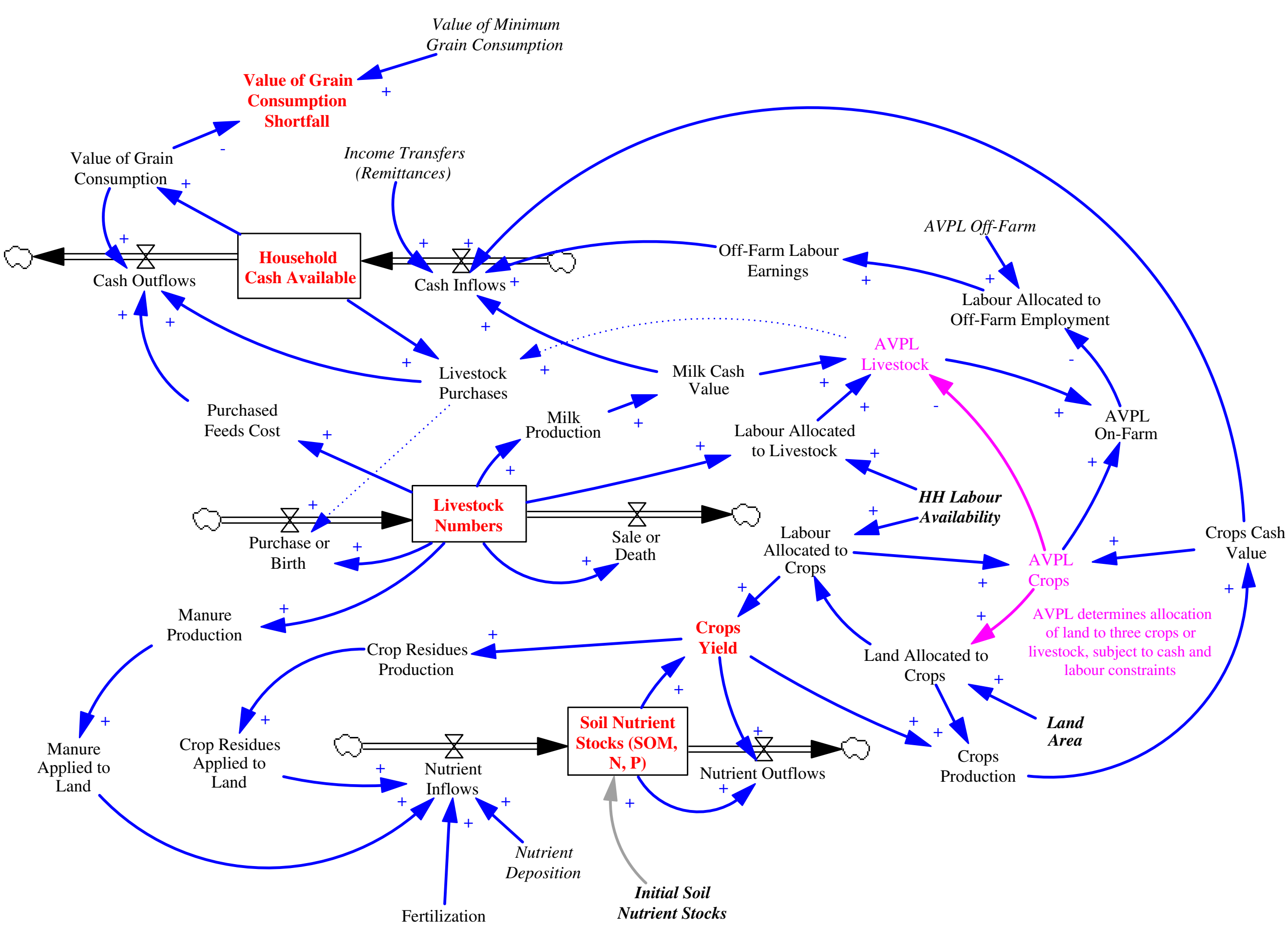

Fig. 11 Diagrammatic representation of key relationships in CLASSES, emphasizing the linkages among the crops, soils, livestock and economic decision making components. A colour version of this figure may be found in the online version

Appendix 1: CLASSES Basic Model Assumptions and Diagrammatic Representation

1. Basic Model Assumptions

- Initialization: household has 10 patches with either food, cash or Napier grass, has some or no livestock (model will be initialized with different starting conditions to explore poverty traps).
- On-farm averages are used to calculate expected average value product of labor in: food crops, cash crops (tea), Napier, livestock
- At time 0: Crop starts to grow, animals are fed, household cash is spent on soil amendments, labor
- At time=decision point (each quarter): any fully grown food crops are harvested (Napier and tea have continuous harvesting once established), nutrients extracted from soil, farmer sells output.
- After each decision point: farmer updates the expected average value product of labor in each livelihood activity, reallocates land into highest return activity, invests or disinvests in livestock (based also on expected feed availability, cash constraints and animal health)
- After each decision point: new soil quality determines crop growth at time 1 and cycle begins again

2. Causal Loop Diagram Representation

Appendix Fig. 11 indicates in more detail the main feedback relationships in CLASSES. As in the figure in the text, this follows SD diagramming conventions: boxes are stocks, flows are indicated by double arrows and valves, and causal linkages are shown by arrows that also indicate the sign of the relationship. Bold italicized variables indicate initial asset endowments (land, labour and soil nutrients). Italicized variables (not bold) indicate important exogenous values. Red bold variables indicate key outcomes of interest discussed in the text. Pink arrows and variables describe key resource allocation decisions made by the household each planting season (land allocated to three crops: maize, Napier grass, or tea).

This structure is capable of generating the hypothesized fundamental behaviours. However, because the model contains numerous interacting feedback processes, a diagrammatic representation alone is inadequate to determine likely system behaviours (Sterman 2000). Thus, parameterization and simulation are essential to determine likely behaviours for different plausible sets of initial asset endowments. In order to observe a natural resource based poverty trap consistent with food insecurity, there must be a region of increasing economic returns to the farm's chosen livelihood activities. Households that fall below an identifiable asset threshold, either because of biophysical resource degradation, or economic and/or biophysical shocks, will experience gradually deteriorating welfare outcomes on the farm.

Appendix 2: Selected Model Simulation Parameters

Table 1 Simulation #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)[a]	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)[b]	1000	1000
Intra-aggregate SOM (kg DOM/ha)	316.5	316.5
Organo-Mineral SOM (kg DOM/ha)	31666.5	31666.5

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

[b] *SOM* soil organic matter; *DOM* dry organic matter

Table 2 Simulation #2 on varying soil organic matter stocks

Initial assets	Small farm	Median farm
Farm Size (ha)	0.5	1
Initial Crop Labour (people)	3	3
Initial Household Dependents (people)	2	2
Initial Accumulated Surplus (Ksh)	0	0
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)	15833.5	15833.5

SOM soil organic matter; *DOM* dry organic matter

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