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Modeling ecohydrological dynamics of smallholder strategies for food production in dryland agricultural systems

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Abstract

In dryland environments, characterized by low and frequently variable rainfall, smallholder farmers must take crop water sensitivity into account along with other characteristics like seed availability and market price when deciding what to plant. In this paper we use the results of surveys conducted among smallholders located near Mount Kenya to identify clusters of farmers devoting different fractions of their land to subsistence and market crops. Additionally, we explore the tradeoffs between water-insensitive but low-value subsistence crops and a water-sensitive but high-value market crop using a numerical model that simulates soil moisture dynamics and crop production over multiple growing seasons. The cluster analysis shows that most farmers prefer to plant either only subsistence crops or only market crops, with a minority choosing to plant substantial fractions of both. The model output suggests that the value a farmer places on a successful growing season, a measure of risk aversion, plays a large role in whether the farmer chooses a subsistence or market crop strategy. Furthermore, access to irrigation, makes market crops more appealing, even to very risk-averse farmers. We then conclude that the observed clustering may result from different levels of risk aversion and access to irrigation.

1. Introduction

Small-scale farming is one of the main systems of food production in the world, producing over 80% of the food consumed in Asia and Sub-Saharan Africa (IAASTD 2009, IFAD 2013). The demand for food is surging steadily; estimates indicate that a 70%–100% increase in global food supply will be needed by 2050 to keep up with anticipated impacts of population growth and climate change on food security (Schmidhuber and Tubiello 2007, Godfray et al 2010). In the context of this global challenge, a central debate exists as to adequate production systems and approaches for food production (Cotula et al 2009, De Schutter 2011, Chakrabarti and da Silva 2012, GRAIN 2014, World Bank 2015). Two archetypes most often juxtaposed in the debate are the alternatives of smallholder agriculture and large-scale intensive agriculture.

We focus on smallholder agriculture in this paper because it remains the primary livelihood activity among rural populations and because it comprises a multitude of farmer decision-making strategies that will become ever more important as climate change increases uncertainty and variability. Smallholder farming is often described as a relatively homogenous system of production. A common trend is to describe smallholding either as an undefined mixture of subsistence farming and cash crop production or by characterizing the features of the transition from subsistence to commercial production (Salami et al 2010, Lambin and Meyfroidt 2011). However, smallholders often engage in both systems of production and dynamically move back and forth on the spectrum from complete subsistence to cash crop farming influenced by multiple social and ecological drivers (Anderman et al 2014, McCord et al 2015).
Understanding the complexity of smallholding requires attention to the biophysical and environmental characteristics as well as social dynamics. Additionally, there is a wide range of institutional (Ostrom 1990, Cody et al 2015), socio-psychological (Niles et al 2013), and political-economic factors (Patel 2009) affecting the production strategies and decisions that smallholders engage with. To resolve this level of detail, in-depth fieldwork and anthropological approaches are necessary. However, modeling approaches are useful to explore dynamics and patterns in a more generalizable way (Magliocca et al 2015, Troy et al 2013).

We apply an interdisciplinary approach that uses data gathered from extensive fieldwork to inform the development of a numerical model of biophysical processes. We use this model to investigate the tradeoffs that smallholders potentially face when choosing between subsistence-based versus market-oriented production strategies, with an emphasis on outcomes related to economic and household well-being. The fieldwork was conducted in rural Kenya, looking at smallholders who are part of small-scale community irrigation projects. The numerical model then uses parameters based on this fieldwork to simulate soil moisture dynamics and crop growth under different scenarios of irrigation availability, climatic variability and crop characteristics.

1.1. The Mount Kenya context
Throughout Kenya, community water projects (CWPs) allow smallholder farmers to receive water for domestic use and to engage in small-scale irrigation efforts. A CWP typically receives water from a river or spring and can vary in membership size from a small group of households to several hundred households. On Mount Kenya’s north-facing leeward side, many of the region’s CWPs rely on surface water runoff from the mountain. In the more humid upper slopes of the mountain annual rainfall is over 1200 mm, while in the northern semi-arid to arid lands of the Laikipia plateau rainfall is less than 400 mm annually (Ericksen et al 2011). The timing of rainfall events themselves are also variable with smallholders relying on two rainy seasons: a long rains period from March to June and a short rains period from mid-October through December. Given the spatial and temporal irregularities of water availability, proper management is necessary to ensure the success of smallholder livelihood practices.

Water governance in Kenya relies on a series of multilevel arrangements that are the result of the 2002 national water resources management reform (Baldwin et al 2016). At the community level, the CWPs exist to distribute water from a withdrawal point to members of a particular CWP. A management committee, consisting of members of the community, is formed within each CWP to ensure that water is distributed to members in an effective manner. These committees devise rules that, among other things, assign labor and maintenance duties, distinguish who is and is not allowed to join the CWP, and penalize members for water misuse. The management committee is also critical in determining how best to rotate water amongst the CWP members during times of scarcity. Under some rotation schedules, a smallholder may receive water only once or twice a week (Dell’Angelo et al 2016).

At the sub-catchment level, water is managed by the water resource users association (WRUA), which oversees water use activities of the CWPs within its geographical borders. In other words, all CWPs within a particular sub-catchment are nested within the same WRUA. During periods of low rainfall, a WRUA institutes a rationing schedule wherein CWPs must limit their water abstractions. These rationing schedules often dictate that a CWP is only allowed to withdraw water once or twice a week from the water source; on all other days the river intake of the CWP must be closed (Dell’Angelo et al 2014).

To understand smallholder production outcomes in the Mount Kenya region, it is critical to account for the availability of irrigation water, an element of semi-arid agriculture that the CWPs and WRUAs within the region attempt to guarantee to all smallholders. Our model accounts for the presence of water governance by modeling different levels of water availability (characterized through the amount and frequency of water delivery), as well as the financial costs of water use.

2. Methods
Decomposition of the smallholder farming strategies within the CWP’s was achieved through a series of $k$-means cluster analyses using data from household surveys conducted in the study region. These cluster analyses provide a contextual element to the numerical model, explained below, and allow us to identify groupings of smallholders who may be more risk averse than others. Household survey responses ($N=750$) were obtained during fieldwork in 2013 that included households from 25 CWPs grouped into 5 different WRUAs. Observations were dropped if a household did not answer one or more of the questions used to derive variables for the cluster analyses, resulting in a final count of 687 observations for the exercise. The variables initially included in the analyses were field size, crop count and percent of crops consumed, while observations of these variables were grouped into between 3 and 5 clusters. The optimal number of variables and clusters were then selected by maximizing observation variability within clusters. These groupings provide distinctions between smallholders growing crops predominantly for subsistence purposes and those primarily engaged in cultivation for markets.
The effects of different smallholder cropping strategies are explored with a numerical model that simulates decisions made by a theoretical smallholder farmer. In the model scenario, the farmer can devote variable fractions of land to two types of crops: subsistence crops that are less sensitive to water availability but have a lower average monetary value or market crops that are more water sensitive but also more valuable. This assumption rests on the likelihood that subsistence crops would be better adapted to local, water-limited conditions but would also be less valuable due to their availability. Even though the main subsistence crop in the region, maize, has a high yield response factor (Doorenbos and Kassam 1979), indicating a high water sensitivity, this assumption may hold true on average for representative samples of all subsistence and market crops in the region. The model farmer is then successful if a minimum subsistence crop threshold is reached for the growing season by growing subsistence crops directly and/or by selling market crops for money to buy additional subsistence crops. Once the subsistence crop threshold has been reached, the farmer accumulates profits from selling remaining crops after paying water fees, assessed based on the volume of water used, to the CWP.

The numerical model tracks soil moisture fluctuations in the hypothetical farmer’s fields using a simple bucket-filling framework similar to the one described in Guswa et al. (2002). This framework is presented in equation (1), where $P$ is the rainfall rate, $SR$ is the rate of surface runoff, $L$ is the leakage rate, $I$ is the evapotranspiration rate, $Z_r$ is the rooting depth, $n$ is porosity and $s$ is soil moisture. Rainfall is represented as a marked Poisson process defined by the average arrival rate of storms, $\lambda$, and the average storm depth, $\alpha$. Following D’Odorico et al. (2000), these two variables are assumed to vary seasonally within independent gamma distributions with means, $\hat{\lambda}$ and $\hat{\alpha}$, and coefficients of variation, $CV_\lambda$ and $CV_\alpha$, respectively. For each growing season, the model randomly selects values of $\lambda$ and $\alpha$ then uses the selected values to generate a record of rainfall events and amounts over the growing season.

\[ nZ_r \frac{dt}{dr} = P(t) - SR(s) - L(s) - ET(s) + I(s, t). \]  

(1)

During the simulation, water from rainfall events infiltrates the soil column and is either added to storage or lost to surface runoff, leakage and evapotranspiration. Surface runoff occurs once soil moisture reaches saturation, at which point all excess water is instantaneously removed. Leakage to the subsurface is governed by the following exponential equation proposed in Laio et al. (2001)

\[ L = K_s e^{\beta(s-s_{fc})} - 1, \frac{e^{\beta(s-s_{fc})} - 1}{s_{fc}} \]  

(2)

where $K_s$ is the saturated hydraulic conductivity, $\beta$ is a soil parameter, and $s_{fc}$ is the soil moisture at field capacity. The evapotranspiration rate equation was also proposed in Laio et al. (2001):

\[ ET = \begin{cases} 0, & s \leq s_h \\ E_w \frac{s-s_h}{s_w-s_h}, & s_h < s \leq s_w \\ (E_{max} - E_w) \frac{s-s_w}{s_{max}-s_w}, & s_w < s \leq s^* \\ E_{max}, & s^* < s \end{cases} \]  

(3)

where $E_w$ is the bare-soil evaporation rate, $E_{max}$ is the maximum possible evapotranspiration rate, $s_h$ is the soil moisture at the hygroscopic point, $s_w$ is the soil moisture at the wilting point, and $s^*$ is the soil moisture at the stress point. The evapotranspiration rates above the stress point and below the wilting point are $E_{max}$ and 0, respectively.

Water can also be added to the soil column through irrigation, which is applied at the same rate to areas planted with subsistence and market crops. Irrigation water availability is modeled as a function of two variables, the flow rate of water arriving at the household, $Q_{ins}$, and the fraction of days the household receives water, $Q_{ins}$. Irrigation applications follow the framework outlined by Vico and Porporato (2011a) where water is applied only when soil moisture falls below an intervention point, $s_{max}$. If soil moisture falls below $s_{min}$ on a day the household receives water, an amount equal to $Q_{ins}$ multiplied by the time step is added to the soil column. If this added water is enough to bring the soil moisture to a target level, $s_{max}$, irrigation is discontinued until the soil moisture again falls below $s_{min}$.

Crop yields are calculated using the following formulation:

\[ Y_{seas} = Y_{max}(1 - \theta), \]  

(4)

where $Y_{seas}$ is the total yield for the growing season, $Y_{max}$ is the maximum possible seasonal yield and $\theta$ is the dynamic water stress, a measure of the total water stress experienced by the crop over the growing season. The dynamic water stress is calculated using the formula proposed by Porporato et al. (2001):

\[ \theta = \begin{cases} \frac{\bar{T}_s}{\hat{T}_{seas}}, \bar{T}_s < kT_{seas} \\ 1, \bar{T}_s \geq kT_{seas} \end{cases} \]  

(5)

where $\bar{T}_s$ is the average static water stress experienced by the crop during an excursion of soil moisture below the stress point, $T_{seas}$ is the average duration of such an excursion, $n_{exc}$ is the number of these excursions during the growing season, $k$ is a parameter governing the amount of stress that leads to complete crop failure and $r$ is parameter governing the effect of the number of excursions below the stress point. The static stress, a measure of the stress experienced by the plant at any given point, is calculated for each time step using the formula:
where \( q \) is a parameter governing the sensitivity of the crop to water stress. The ratio of the stress parameters of the subsistence crops, \( k_{\text{sub}} \) and \( q_{\text{sub}} \), to those of the market crop, \( k_{\text{mar}} \) and \( q_{\text{mar}} \), represents the relative stress sensitivity of one crop to the other, one of the tradeoffs investigated in the model. In general, the ratio of \( q_{\text{sub}} \) to \( q_{\text{mar}} \) refers to the relative crop sensitivity to water stress while the ratio of \( k_{\text{sub}} \) to \( k_{\text{mar}} \) refers to the relative crop sensitivity to total seasonal stress.

After calculating crop yields for each growing season, the model calculates the total amount of subsistence crops available to the farmer using the following equation, similar to that described in Vico and Porporato (2011b):

\[
Y_{\text{tot}} = A_{\text{sub}} Y_{\text{sub}} + \frac{1}{c_{\text{sub}}} (A_{\text{mar}} c_{\text{mar}} Y_{\text{mar}} - c_{\text{w}} T_{\text{irr}}),
\]

where \( A_{\text{sub}} \) and \( A_{\text{mar}} \) are the areas planted, \( Y_{\text{sub}} \) and \( Y_{\text{mar}} \) are the yields and \( c_{\text{sub}} \) and \( c_{\text{mar}} \) are the prices of subsistence and market crops, respectively, \( c_{\text{w}} \) is the daily water fee charged by the CWP and \( T_{\text{irr}} \) is the number of days of irrigation received during the growing. Because the model assumes that water availability is the primary determinant of yield, the costs of other inputs, such as labor and fertilizer, are not considered. The total is then compared to the minimum amount of subsistence crops needed by the farmer. If the total surpasses this amount, the farmer is successful. The model also calculates the net return from the harvest using the formula:

\[
R_{\text{tot}} = c_{\text{sub}} Y_{\text{tot}}.
\]

This amount refers to the financial value of the crops harvested, minus any water fees paid to the CWP.

To produce a distribution of the outcomes of such choices, the model simulates a set number of growing seasons, \( N_{\text{seas}} \), each lasting a fixed number of days, \( T_{\text{seas}} \), plus a preseason buffer, \( T_{\text{pre}} \), to remove the effects of initial conditions. The model additionally uses a subdaily time step, \( \Delta T \), to ensure numerical accuracy. From the resulting distributions, the model then calculates the fraction of growing seasons that the farmer is successful and the average net return for each season. These two results are then combined into one metric, referred to here as the total value and calculated using the formula:

\[
V_{\text{tot}} = F_{\text{Suc}} V_{\text{Suc}} + R_{\text{tot}},
\]

where \( F_{\text{Suc}} \) is the fraction of successful seasons and \( V_{\text{Suc}} \) is the value the farmer assigns to a successful season. In terms of risk aversion, it is the amount the farmer would pay to ensure a successful season.

3. Results

The best performing cluster analysis was one with four groups (\( k = 4 \)) and two variables: crop count and percent of crops consumed. The field size variable was dropped from the analysis as it offered little to distinguish between groups. The results of the cluster analysis are shown in table 1 and indicate that clusters 1 and 4 consume most of their crops while clusters 2 and 3 sell most of their crops. On average, clusters 1 and 4 grow nearly one more crop compared to cluster 2 and half-of-a-crop more than cluster 3.

The model results below were produced using the parameters listed in table 2. Climate, crop, household, irrigation and economic parameters were loosely based on those found in the Mount Kenya region. The minimum subsistence yield was not known and so was set at a value considered to be reasonable for a single household. Both of the stress parameter ratios were set at 2, which fixes parameters for both the subsistence and market crops within the range of typical values.

The ratio of the market crop price to the subsistence crop price was set at 1.4, resulting in prices for both crop types that were within the range observed in surveys. Soil parameters were taken from those in Rodriguez-Iturbe and Porporato (2007) representing a sandy loam soil. The number of simulated seasons, the time step length and the pre-season buffer length were all chosen to ensure adequate representation of soil processes and a satisfactory distribution of outcomes.
of diversity intermediate between clusters 1 and 2. These results show that smallholder farmers in the Mount Kenya region range from strictly subsistence-oriented to strictly market-oriented with some farmers planting both crops in different proportions. Thus the numerical model provides insight into how these groups fare under different conditions.

The results of the model simulations suggest that, in the absence of irrigation, smallholders specializing in subsistence crops may have a greater fraction of successful seasons but a lower average return than those specializing in market crops. When the fraction of successful seasons and average return are combined into the total value metric, the most successful strategy depends on the value the farmer places on a successful season. Those farmers who are relatively risk-neutral, represented by low levels of $V_{\text{suc}}$, receive the greatest total value using market-based strategies, as those provide the greatest average returns, particularly during very wet years. For slightly risk-averse farmers with intermediate levels of $V_{\text{suc}}$, either the entirely market crop-based or entirely subsistence crop-based strategies outperform linear combinations of the two. Finally, very risk averse-farmers with high levels of $V_{\text{suc}}$ have the best results with subsistence-based strategies, as these minimize the likelihood of failure, particularly in dry years.

The results of the simulations with irrigation indicate that irrigation applications, even in small daily amounts, have a positive impact on the success rate and average net return along the market to subsistence crop spectrum. Since the upper limit to the fraction of successful seasons is more accessible than the upper limit to the average net return, however, irrigation tends to more greatly favor those farmers growing market crops. As illustrated in figures 1 and 2, daily irrigation flattens the distinction between subsistence and market-based strategies with regards to the fraction of successful seasons but exacerbates it with regards to the average net return. This change is reflected in figures 4 and 5, where total value under irrigation every third day and every day, respectively, is greater for market-dominated strategies, even for very risk-averse farmers. Yokwe (2009) reported a similar result by observing that returns to irrigation were greater for higher value vegetables like cabbage and tomatoes than for maize.

The model structure, particularly the assumption of a somewhat arbitrary economic assessment of what constitutes a successful season, is a greatly simplified representation of the actual situation in the Mount Kenya region. Nevertheless, the model output can provide an interesting lens through which to view the cluster analysis results. For instance, the observation that clusters 1 and 2 are made up of exclusively subsistence crop farmers and exclusively market crop farmers, respectively, coincides with model results suggesting that total value can be maximized through either entirely subsistence or market crop-based strategies.

### 4. Discussion

The cluster analysis, based on 687 household surveys, identified four groupings of farmer types. Cluster 1 is a subsistence-oriented group that grows the most diverse array of crops. Cluster 2 is the most market-oriented group and the group with the least diverse set of crops. Clusters 3 and 4 are more balanced between market and subsistence crops and grow crops in levels of diversity intermediate between clusters 1 and 2. These results show that smallholder farmers in the

| Table 2: Base parameters used in model runs. |
|----------------------------------------------|
| **Type** | **Parameter** | **Value** |
|---------|---------------|-----------|
| Climate parameters | $\tilde{\alpha}$ (m) | 0.015 |
| | $\tilde{\lambda}$ (d$^{-1}$) | 0.3 |
| | $C_{V_1}$ (dim) | 0.25 |
| | $C_{V_2}$ (dim) | 0.25 |
| | $E_{\text{w}}$ (m d$^{-1}$) | 0.0001 |
| | $E_{\text{max}}$ (m d$^{-1}$) | 0.005 |
| | $T_{\text{su}}$ (d) | 110 |
| Household parameters | $A_{\text{su}}$ (m$^2$) | 5000 |
| | $y_{\text{su}}$ (kg) | 1000 |
| Crop parameters | $z_{\text{suc}}$ (m) | 0.5 |
| | $\eta_{\text{su}}$ (dim) | 2 |
| | $\eta_{\text{su}}$ (dim) | 1 |
| | $k_{\text{suc}}$ (dim) | 1 |
| | $k_{\text{suc}}$ (dim) | 0.5 |
| | $r$ (dim) | 0.5 |
| Soil parameters (sandy loam) | $K_{\text{suc}}$ (m d$^{-1}$) | 0.8 |
| | $n$ (dim) | 0.43 |
| | $\beta$ (dim) | 13.8 |
| | $n_{\text{suc}}$ (dim) | 0.14 |
| | $w$ (dim) | 0.18 |
| | $s$ (dim) | 0.46 |
| | $n_{\text{suc}}$ (dim) | 0.56 |
| Economic parameters | $c_{\text{suc}}$ ($\$ kg^{-1}$) | 0.20 |
| | $c_{\text{su}}$ ($\$ kg^{-1}$) | 0.28 |
| | $c_{\text{su}}$ ($\$ d^{-1}$) | 0.02 |
| Irrigation parameters | $Q_{\text{suc}}$ (m$^3$ d$^{-1}$) | 10 |
| | $Q_{\text{su}}$ (d$^{-1}$) | none, 1/3, 1 |
| | $\gamma_{\text{su}}$ (dim) | 0.46 |
| | $\gamma_{\text{su}}$ (dim) | 0.56 |
| Simulation parameters | $N_{\text{suc}}$ (seas) | 10 000 |
| | $T_{\text{pre}}$ (d) | 10 |
| | $\Delta T$ (d$^{-1}$) | 24 |
strategies but not through mixed strategies. The model thus suggests that these clusters represent opposite ends of the risk aversion scale. Another interpretation may be that farmers in cluster 2 may benefit from access to more reliable or a higher volume of irrigation than farmers in cluster 1.

However, clusters 3 and 4, although smaller than clusters 1 and 2, do include farmers growing both subsistence and market crops, a strategy that is never dominant according to the model. Cluster 3 farmers, who mostly produce market crops, may allocate some land to subsistence crops as a hedge against price fluctuations, which were not included in this model. Cluster 4, the smallest of the groupings, includes farmers who produce roughly half subsistence and half market crops. Such a strategy is difficult to explain using the current model but may represent farmers transitioning from one strategy to another, either by observing the neighbors or experiencing a recent failure. To address these discrepancies, future versions of the

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**Figure 1.** Fraction of growing seasons exceeding the minimum subsistence threshold plotted against the percent area planted with subsistence crop for the simulation average and selected quantiles.

**Figure 2.** Average net return plotted against the percent area planted with subsistence crop for the simulation average and selected quantiles.
model will be updated to explore variations in water price, crop price fluctuations and the effects of consecutive seasons.

Our results raise a particularly important element in light of the debate on smallholding productive strategies and food security. While it is important to focus on the economic drivers and processes such as barriers to market integration, it is fundamental to investigate the ecological determinants of farming strategies success. Climate change raises new challenges that produce unprecedented variations to smallholder practices and that are not fully considered in the conventional rural development wisdom nor addressed by disciplinary approaches. Continuing to integrate natural and social science approaches will be fundamental to improve the understanding of these complex socio-ecological dynamics that impact the food security of a large share of the global population.

5. Conclusions

While food security at a global level is studied looking at the interactions among globalization, global trade

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Figure 3. Average total value for simulations with no irrigation plotted against the percent area planted with subsistence crop for four levels of values of a successful season.

Figure 4. Average total value for simulations with irrigation every third day plotted against the percent area planted with subsistence crop for four levels of values of a successful season.
and large-scale agricultural production systems (Rulli and D’Odorico 2014, Suweis et al. 2015), focusing on local systems of production highlights smallholder adaptation strategies, decision making and integration in regional markets (Orr and Mwale 2001, Markelova et al. 2009). There are multiple factors that directly influence the economic, social, cultural, productive, behavioral and metabolic aspects of smallholders lives (Turner and Ali 1996, Borras 2009, Ravera et al. 2014). As a result, one of the most critical structural agrarian transformations in developing countries concerns the transition from subsistence to market-oriented small-holder agricultural systems (Lambin and Meyfroidt 2011).

Understanding these transitions and dynamics is central in the debate of whether increased cash crop production and market integration is a viable solution for poverty reduction and food security (Govereh and Jayne 2003, Anderman et al. 2014). However, while many agricultural economics studies have tackled this question (Carter and Barrett 2006, Barrett et al. 2008, Barrett 2008) the ecohydrological drivers of these transformations are less investigated. We contribute to this debate by shedding light on the potential tradeoffs smallholders in semi-arid environments face when choosing between subsistence-based versus market-oriented production strategies under different modeled ecohydrological scenarios.

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Figure 5. Average total value for simulations with irrigation every day plotted against the percent area planted with subsistence crop for four levels of values of a successful season.
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