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

2016 Environ. Res. Lett. 11 115005

(http://iopscience.iop.org/1748-9326/11/11/115005)

Environmental Research Letters

OPEN ACCESS

RECEIVED
29 February 2016

REVISED
5 September 2016

ACCEPTED FOR PUBLICATION
10 October 2016

PUBLISHED
11 November 2016

LETTER

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

Drew B Gower[1], Jampel Dell'Angelo[2], Paul F McCord[3,4], Kelly K Caylor[1,5,6,7] and Tom P Evans[3,4]

[1] Department of Civil and Environmental Engineering, Princeton University, 59 Olden Street, Princeton, NJ 08544, USA
[2] National Socio-Environmental Synthesis Center (SESYNC), 1 Park Place Suite 300, Annapolis, MD 21401, USA
[3] Department of Geography, Indiana University, Student Building 120, E. Kirkwood Avenue, Bloomington, IN 47405, USA
[4] Vincent and Elinor Ostrom Workshop in Political Theory and Policy Analysis, Indiana University, 513 N. Park Avenue, Bloomington, IN 47408, USA
[5] Department of Geography, University of California, Santa Barbara, CA 93106, USA
[6] Bren School of Environmental Science and Management, University of California, Santa Barbara, CA 93106, USA
[7] Earth Research Institute, University of California, Santa Barbara, CA 93106, USA

E-mail: gower@princeton.edu

Keywords: ecohydrology, smallholders, irrigation, drylands

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* 2015).

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, ET is the evapotranspiration rate, I is the irrigation 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, λ, and the average storm depth, α. 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_λ and CV_α, respectively. For each growing season, the model randomly selects values of λ and α then uses the selected values to generate a record of rainfall events and amounts over the growing season.

$$nZ_r\frac{\mathrm{d}s}{\mathrm{d}t} = P(t) - \mathrm{SR}(s) - L(s) - \mathrm{ET}(s) + I(s, t). \tag{1}$$

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)

$$L = K_s\frac{\mathrm{e}^{\beta(s - s_{fc})} - 1}{\mathrm{e}^{\beta(1 - s_{fc})} - 1}, \tag{2}$$

where K_s is the saturated hydraulic conductivity, β 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):

$$\mathrm{ET} = \begin{cases} 0, & s \leqslant s_h \\ E_w\frac{s - s_h}{s_w - s_h}, & s_h < s \leqslant s_w \\ (E_{max} - E_w)\frac{s - s_w}{s* - s_w}, & s_w < s \leqslant s* \\ E_{max}, & s* < s \end{cases} \tag{3}$$

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 ET_{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_{rte}, and the fraction of days the household receives water, Q_{fre}. 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_{min}. If soil moisture falls below s_{min} on a day the household receives water, an amount equal to Q_{rte} 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:

$$Y_{seas} = Y_{max}(1 - \theta), \tag{4}$$

where Y_{seas} is the total yield for the growing season, Y_{max} is the maximum possible seasonal yield and θ 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):

$$\theta = \begin{cases} \left(\frac{\bar{\zeta}\overline{T_{s^*}}}{kT_{seas}}\right)^{n_{s^*}^{-r}}, & \bar{\zeta}\overline{T_{s^*}} < kT_{seas} \\ 1, & \bar{\zeta}\overline{T_{s^*}} \geqslant kT_{seas}, \end{cases} \tag{5}$$

where $\bar{\zeta}$ is the average static water stress experienced by the crop during an excursion of soil moistures below the stress point, $\overline{T_{s^*}}$ is the average duration of such an excursion, n_{s*} is the number of these excursions during the growing season, T_{seas} is the length of 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:

$$\zeta = \begin{cases} 0, & s^* \leqslant s \\ \left(\frac{s^* - s}{s^* - s_w}\right)^q, & s_w \leqslant s < s^* \\ 1, & s_h < s < s_w \end{cases} \quad (6)$$

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_{sub} and q_{sub}, to those of the market crop, k_{mar} and q_{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_{sub} to q_{mar} refers to the relative crop sensitivity to water stress while the ratio of k_{sub} to k_{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):

$$Y_{tot} = A_{sub} Y_{sub} + \frac{1}{c_{sub}}(A_{mar} c_{mar} Y_{mar} - c_w T_{irr}), \quad (7)$$

where A_{sub} and A_{mar} are the areas planted, Y_{sub} and Y_{mar} are the yields and c_{sub} and c_{mar} are the prices of subsistence and market crops, respectively, c_w is the daily water fee charged by the CWP and T_{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:

$$R_{tot} = c_{sub} Y_{tot}. \quad (8)$$

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_{seas}, each lasting a fixed number of days, T_{seas}, plus a preseason buffer, T_{pre}, to remove the effects of initial conditions. The model additionally uses a subdaily time step, ΔT, 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:

$$V_{tot} = F_{suc} V_{suc} + R_{tot}, \quad (9)$$

where F_{suc} is the fraction of successful seasons and V_{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.

Table 1. *K* means cluster analysis results.

Cluster	Statistic	Crop count	% Crops consumed
Cluster 1 ($n = 227$)	Minimum	1	79.17
	Maximum	7	100
	Mean	3.25	98.67
	Mode	3	100
Cluster 2 ($n = 213$)	Minimum	1	0
	Maximum	5	17.58
	Mean	2.43	6.52
	Mode	2	5.33
Cluster 3 ($n = 145$)	Minimum	1	18
	Maximum	7	43.75
	Mean	2.79	29.25
	Mode	3	27.76
Cluster 4 ($n = 102$)	Minimum	1	44.12
	Maximum	7	78.57
	Mean	3.2	58.85
	Mode	3	57.31

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.

As shown in figures 1 and 2, subsistence crop-based strategies, on average, allow for higher success rates while market-crop based strategies result in higher average net returns. Wetter growing seasons and access to irrigation both decrease the difference in

Table 2. Base parameters used in model runs.

Type	Parameter	Value
Climate parameters	$\hat{\alpha}$ (m)	0.015
	$\hat{\lambda}$ (d^{-1})	0.3
	CV_{α} (dim)	0.25
	CV_{λ} (dim)	0.25
	E_w (m d^{-1})	0.0001
	E_{max} (m d^{-1})	0.005
	T_{seas} (d)	110
Household parameters	A_{tot} (m^2)	5000
	Y_{min} (kg)	1000
Crop parameters	Z_r (m)	0.5
	Y_{max} (kg m^{-2})	0.3
	q_{sub} (dim)	2
	q_{mar} (dim)	1
	k_{sub} (dim)	1
	k_{mar} (dim)	0.5
	r (dim)	0.5
Soil parameters (sandy loam)	K_s (m d^{-1})	0.8
	n (dim)	0.43
	β (dim)	13.8
	s_h (dim)	0.14
	s_w (dim)	0.18
	s^* (dim)	0.46
	s_{fc} (dim)	0.56
Economic parameters	c_{sub} (\$ kg^{-1})	0.20
	c_{mar} (\$ kg^{-1})	0.28
	c_w (\$ d^{-1})	0.02
Irrigation parameters	Q_{rate} (m^3 d^{-1})	10
	Q_{freq} (d^{-1})	none, 1/3, 1
	s_{min} (dim)	0.46
	s_{max} (dim)	0.56
Simulation parameters	N_{seas} (seas)	10 000
	T_{pre} (d)	10
	ΔT (d^{-1})	24

the success rates while amplifying the difference in average net returns.

For simulations with no irrigation (figure 3), the average total value decreases monotonically with the percent area planted with subsistence crop at low levels of V_{suc} but then reverses direction as V_{suc} increases. With irrigation every third day and every day (figures 4 and 5, respectively), strategies favoring subsistence crops never outperform those favoring market crops, even at high levels of V_{suc}.

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 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 famers who are relatively risk-neutral, represented by low levels of V_{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_{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_{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

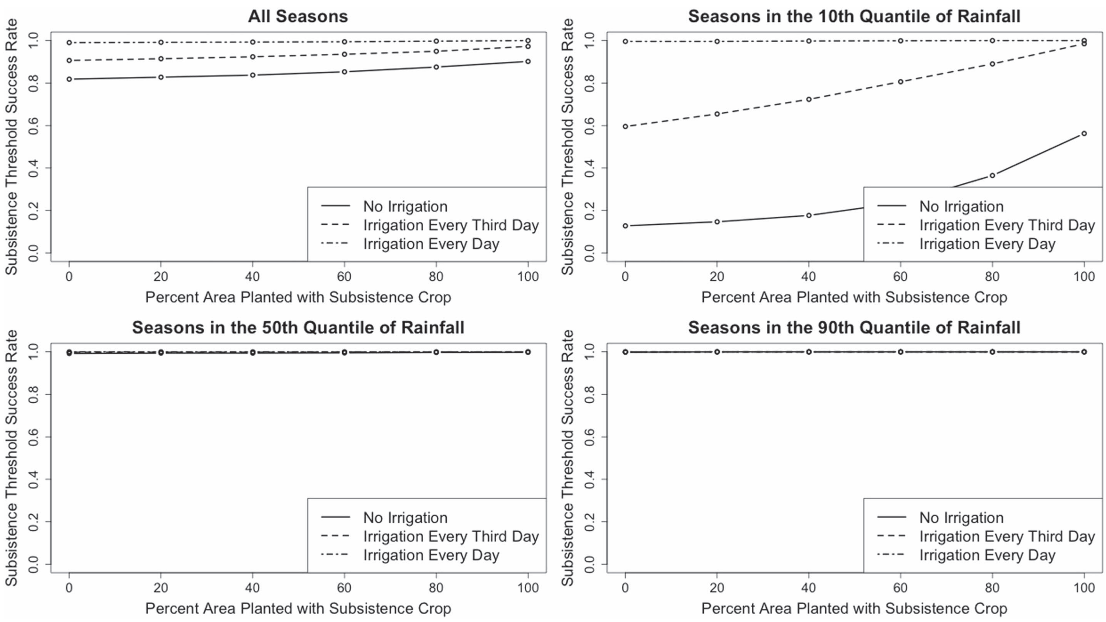

Figure 1. Fraction of growing seasons exceeding the minimum subsistence threshold plotted against the percent area planted with subsistence crop for the simulation average and selected quantiles.

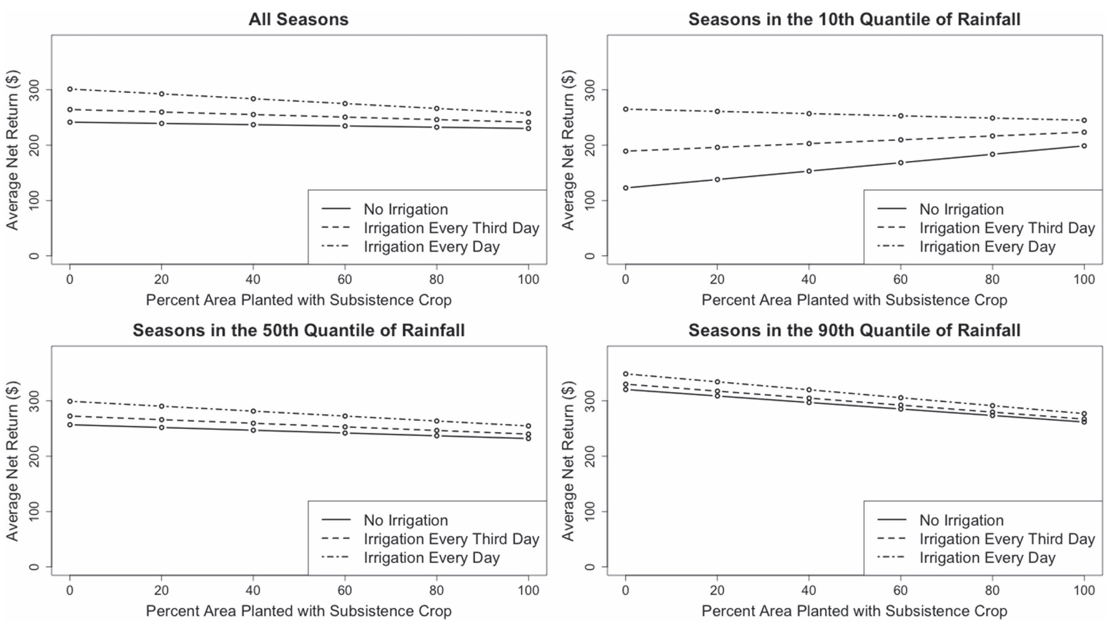

Figure 2. Average net return plotted against the percent area planted with subsistence crop for the simulation average and selected quantiles.

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

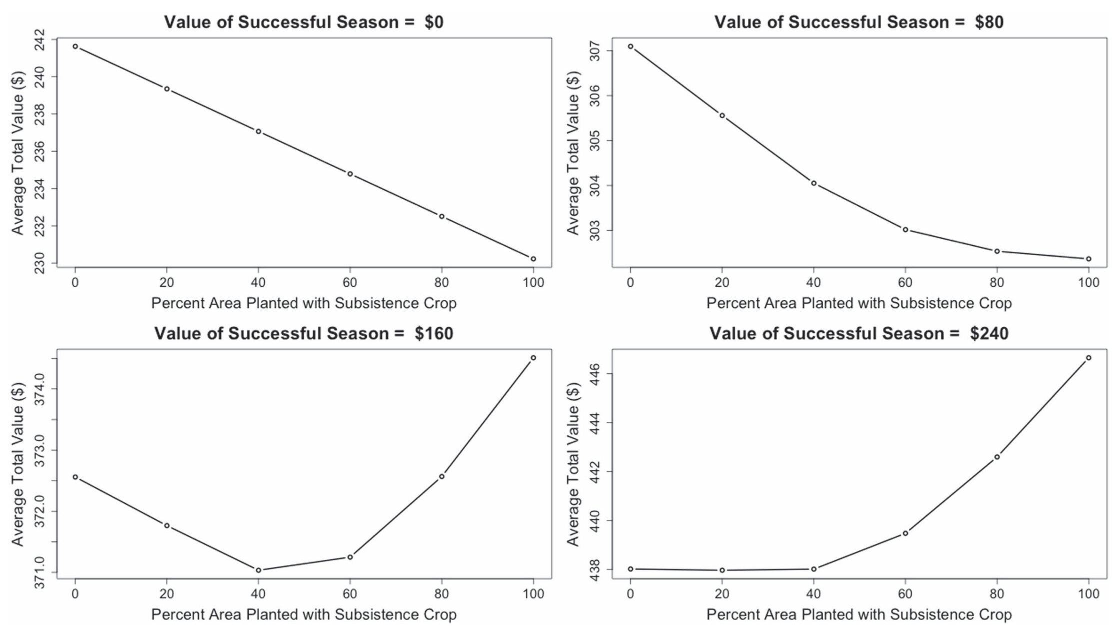

Figure 3. Average total value for simulations with no irrigation plotted against the percent area planted with subsistence crop for four levels of values of a successful season.

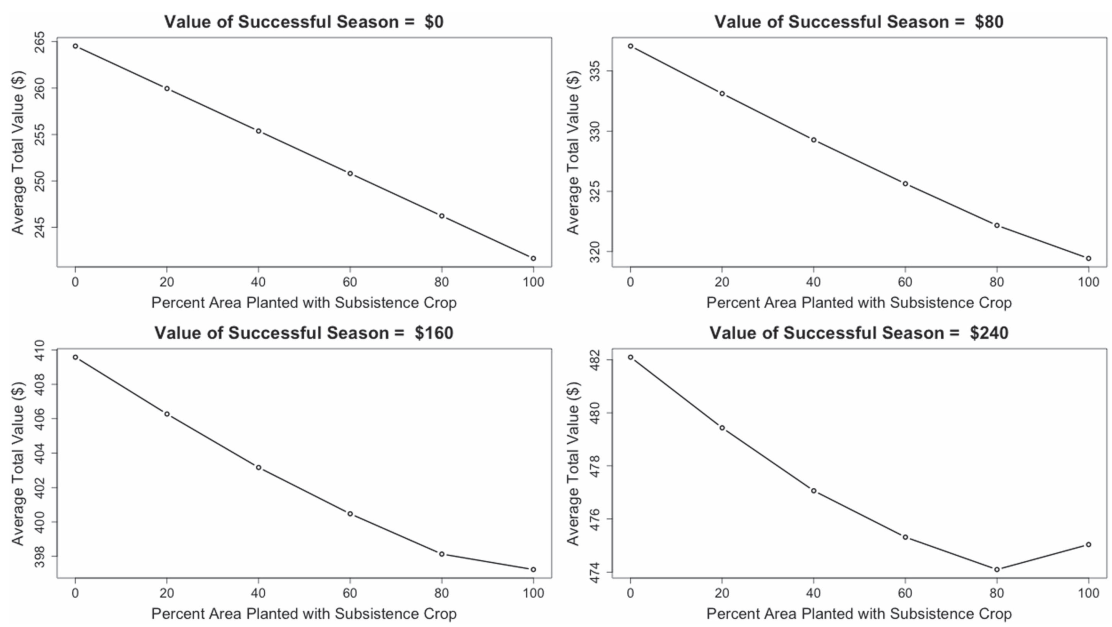

Figure 4. Average total value for simulations with irrigation every third day plotted against the percent area planted with subsistence crop for four levels of values of a successful season.

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

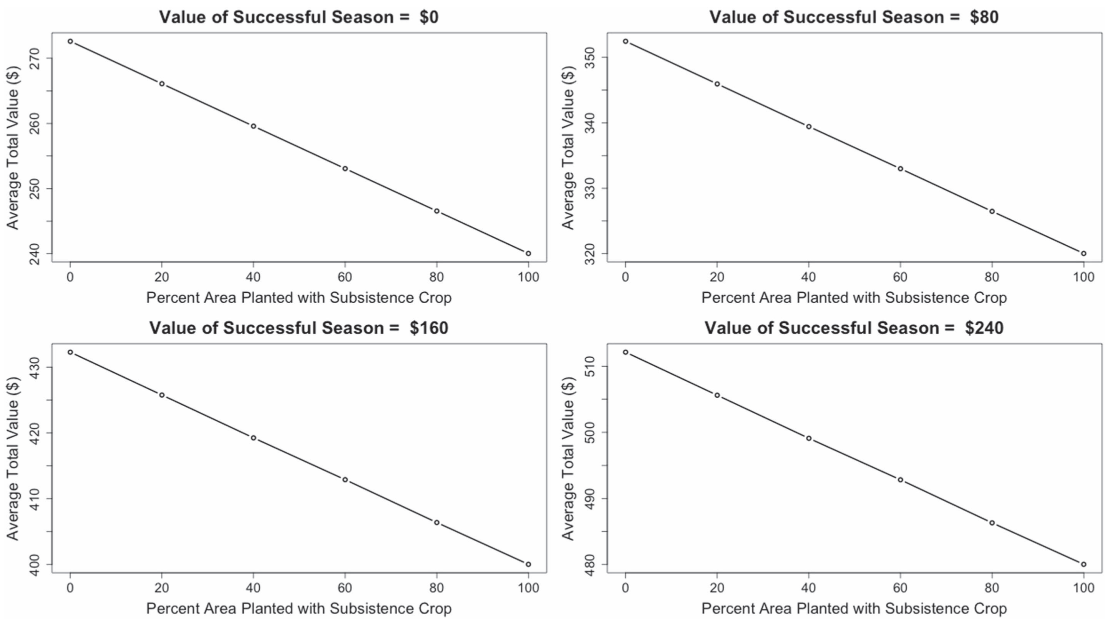

Figure 5. Average total value for simulations with irrigation every day plotted against the percent area planted with subsistence crop for four levels of values of a successful season.

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 smallholder 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.

Acknowledgments

We gratefully acknowledge support from the US National Science Foundation (grants BCS-1115009, SES-1360463 and SES-1360421) and the US Environmental Protection Agency (STAR Fellowship Assistance Agreement no. FP-91763001-0). Additionally, Jampel Dell'Angelo was supported through a postdoctoral fellowship from the National Socio-Environmental Synthesis Center (SESYNC).

References

Anderman T L, Remans R, Wood S A, DeRosa K and DeFries R S 2014 Synergies and tradeoffs between cash crop production and food security: a case study in rural Ghana *Food Secur.* **6** 541–54

Baldwin E, Washington-Ottombre W, Dell' Angelo J, Cole D and Evans T P 2016 Polycentric water governance in response to failures of centralized irrigation policy in Kenya *Governance* **29** 207–25

Barrett C B 2008 Smallholder market participation: concepts and evidence from eastern and southern Africa *Food Policy* **33** 299–317

Barrett C B, Little P D and Carter M (ed) 2008 *Understanding and Reducing Persistent Poverty in Africa* (New York: Routledge)

Borras S M 2009 Agrarian change and peasant studies: changes, continuities and challenges–an introduction *J. Peasant Stud.* **36** 5–31

Carter M R and Barrett C B 2006 The economics of poverty traps and persistent poverty: an asset-based approach *J. Dev. Stud.* **42** 178–99

Chakrabarti S and da Silva J G 2012 Hungry for Investment *Wall Street Journal* (http://wsj.com/articles/SB10000872396390443686004577633080190871456)

Cody K C, Smith S M, Cox M and Andersson K 2015 Emergence of collective action in a groundwater commons: irrigators in the San Luis Valley of Colorado *Soc. Nat. Resour.* **28** 405–22

Cotula L, Vermeulen S, Leonard R and Keeley J 2009 *Land Grab or Development Opportunity? Agricultural Investment and International Land Deals in Africa* (London/Rome: IIED, FAO and IFAD)

D'Odorico P, Ridolfi L, Porporato A and Rodriguez-Iturbe I 2000 Preferential states of seasonal soil moisture: the impact of climate fluctuations *Water Resour. Res.* **36** 2209–19

De Schutter O 2011 How not to think of land-grabbing: three critiques of large-scale investments in farmland *J. Peasant Stud.* **38** 249–79

Dell'Angelo J, McCord P F, Baldwin E, Cox M E, Gower D, Caylor K and Evans T P 2014 Multilevel governance of irrigation systems and adaptation to climate change in Kenya BT—the global water system in the anthropocene *The Global Water System in the Anthropocene* (Berlin: Springer) pp 323–41

Dell'Angelo J, McCord P F, Gower D, Carpenter S, Caylor K and Evans T P 2016 Community-based water governance on Mount Kenya: an assessment based on Ostrom's design principles of natural resource management *Mt. Res. Dev.* **36** 102–15

Doorenbos J and Kassam A H 1979 *Yield Response to Water. FAO Irrigation and Drainage paper No. 33* (Rome: Food and Agriculture Organization)

Ericksen P, Said M, de Leeuw J, Silvestri S, Zaibet L, Kifugo S and Stickler M 2011 *Mapping and Valuing Ecosystem Services in the Ewaso Ng'iro Watershed* (Nairobi: International Livestock Research Institute)

Godfray H C J, Beddington J R, Crute I R, Haddad L, Lawrence D, Muir J F and Toulmin C 2010 Food security: the challenge of feeding 9 billion people *Science* **327** 812–8

Govereh J and Jayne T S 2003 Cash cropping and food crop productivity: synergies or trade-offs? *Agric. Econ.* **28** 39–50

GRAIN 2014 *Hungry for Land*. Small farmers feed the world with less than a quarter of all farmland (https://grain.org/article/entries/4929-hungry-for-land-small-farmers-feed-the-world-with-less-than-a-quarter-of-all-farmland)

Guswa A J, Celia M A and Rodriguez-Iturbe I 2002 Models of soil moisture dynamics in ecohydrology: a comparative study *Water Resour. Res.* **38** 5-1–5-15

IAASTD 2009 *Agriculture at a Crossroads. Global Report* (Washington, DC: Island)

IFAD 2013 *Smallholders, Food Security and the Environment* (Rome: International Fund for Agricultural Development)

Laio F, Porporato A, Ridolfi L and Rodriguez-Iturbe I 2001 Plants in water-controlled ecosystems: active role in hydrologic processes and response to water stress: II. Probabilistic soil moisture dynamics *Adv. Water Resour.* **24** 707–23

Lambin E F and Meyfroidt P 2011 Global land use change, economic globalization, and the looming land scarcity *Proc. Natl Acad. Sci.* **108** 3465–72

Magliocca N R, van Vliet J, Brown C, Evans T P, Houet T, Messerli P and Yu Q 2015 From meta-studies to modeling: using synthesis knowledge to build broadly applicable process-based land change models *Environ. Modelling Softw.* **72** 10–20

Markelova H, Meinzen-Dick R, Hellin J and Dohrn S 2009 Collective action for smallholder market access *Food Policy* **34** 1–7

McCord P F, Cox M, Schmitt-Harsh M and Evans T P 2015 Crop diversification as a smallholder livelihood strategy within semi-arid agricultural systems near Mount Kenya *Land Use Policy* **42** 738–50

Niles M T, Lubell M and Haden V R 2013 Perceptions and responses to climate policy risks among California farmers *Glob. Environ. Change* **23** 1752–60

Orr A and Mwale B 2001 Adapting to adjustment: smallholder livelihood strategies in Southern Malawi *World Dev.* **29** 1325–43

Ostrom E 1990 *Governing the Commons: The Evolution of Institutions for Collective Action* (Cambridge: Cambridge University Press)

Patel R 2009 What does food sovereignty look like? *J. Peasant Stud.* **36** 663–73

Porporato A, Laio F, Ridolfi L and Rodriguez-Iturbe I 2001 Plants in water-controlled ecosystems: active role in hydrologic processes and response to water stress *Adv. Water Resour.* **24** 725–44

Ravera F, Scheidel A, dell'Angelo J, Gamboa G, Serrano T, Mingorr'ia S and Ariza P 2014 Pathways of rural change: an integrated assessment of metabolic patterns in emerging ruralities *Environ., Dev. Sustainability* **16** 811–20

Rodriguez-Iturbe I and Porporato A 2007 *Ecohydrology of Water-Controlled Ecosystems: Soil Moisture and Plant Dynamics* (Cambridge: Cambridge University Press)

Rulli M C and D'Odorico P 2014 Food appropriation through large scale land acquisitions *Environ. Res. Lett.* **9** 64030

Salami A, Kamara A B and Brixiova Z 2010 *Smallholder Agriculture in East Africa: Trends, Constraints and Opportunities Working Paper No. 103* (African Development Bank) p 52 April

Schmidhuber J and Tubiello F N 2007 Global food security under climate change *Proc. Natl Acad. Sci.* **104** 19703–8

Suweis S, Carr J A, Maritan A, Rinaldo A and D'Odorico P 2015 Resilience and reactivity of global food security *Proc. Natl Acad. Sci.* **112** 6902–7

Troy T J, Pavao Zuckerman M and Evans T P 2015 Debates—Perspectives on socio-hydrology: socio-hydrologic modeling: tradeoffs, hypothesis testing, and validation *Water Resour. Res.* **51** 4806–14

Turner B L and Ali A M 1996 Induced intensification: agricultural change in Bangladesh with implications for Malthus and Boserup *Proc. Natl Acad. Sci. USA* **93** 14984–91

Vico G and Porporato A 2011a From rainfed agriculture to stress-avoidance irrigation: I. A generalized irrigation scheme with stochastic soil moisture *Adv. Water Resour.* **34** 263–71

Vico G and Porporato A 2011b From rainfed agriculture to stress-avoidance irrigation: II. Sustainability, crop yield, and profitability *Adv. Water Resour.* **34** 272–81

World Bank 2015 Closing Plenary *Land and Poverty Conference* World Bank (http://worldbank.org/en/news/video/2015/04/11/land-and-poverty-conference-2015-closing-plenary)

Yokwe S 2009 Water productivity in smallholder irrigation schemes in South Africa *Agric. Water Manage.* **96** 1223–8