APPENDIX 1 ODD+D model description

A1.1 Overview

A1.1.1 Purpose

The model was developed to investigate the short- and long-term resilience of a smallholder agricultural farming system and the effects of different household-level adaptation strategies on this resilience. It is intended to be used by researchers interested in exploring long-term dynamics of agricultural adaptation options. The model represents a mixed crop-livestock agricultural system, designed to be generally representative of a smallholder agricultural system in the Global South. Given the interest in exploring the general mechanisms through which different adaptation options affect resilience, the model is intentionally stylized and does not draw from empirical data to be representative of a specific location.

A1.1.2 Entities, state variables, and scales

The model represents smallholder households that engage in agriculture and carry their wealth in the form of livestock. Each household is defined by a static land holding and has dynamic income and livestock holdings. Livestock are grazed on a combination of on-farm crop residues and an external rangeland, which is not explicitly modeled. The household's land has an evolving level of organic nutrients, which represent SOM and soil organic N together in a stylized manner. The model is spatially implicit, no environmental feedbacks beyond the household scale are represented, and households do not interact with each other.

A1.1.3 Process overview and scheduling

The model operates at an annual time scale. Each year of the simulation involves calculation of: (1) soil nutrient flows; (2) crop yields; (3) household income; and (4) household wealth and coping measures (Figure A1.1).

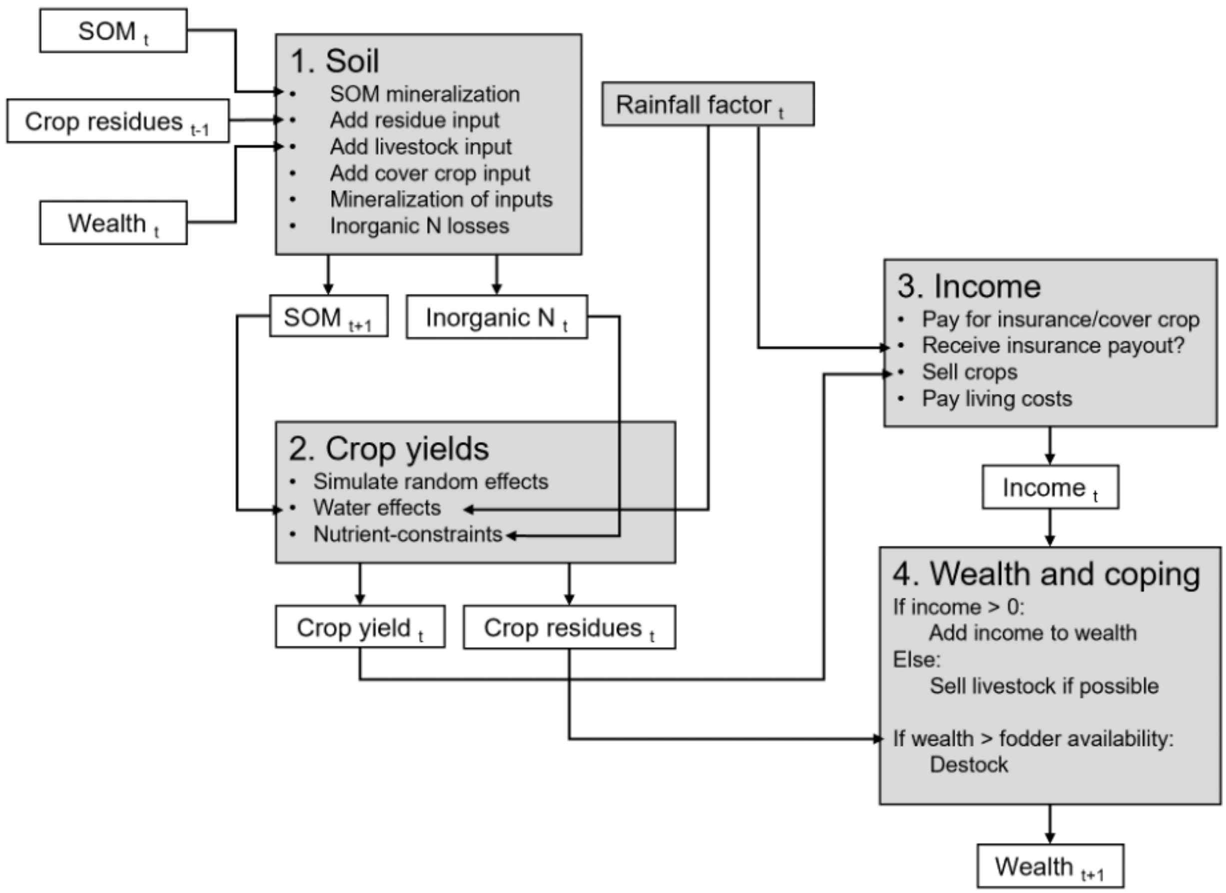

Figure A1.1: Overview of annual simulation process.

A1.2 Design concepts

A1.2.1 Theoretical and empirical background

The model represents soil nutrient dynamics in a stylized way. It models slow-evolving stocks of SOM and faster-acting pools of mineralized nutrients. Our representation is consistent with soil representations in biogeochemical models (Manzoni and Porporato 2009) and is qualitatively comparable to other more complicated process-based models of soil nutrient dynamics used for agricultural applications (e.g., CENTURY (Metherell et al. 1993), DSSAT (Jones et al. 2003), and APSIM (Keating et al. 2003)).

Our crop yield model assumes that yields are influenced jointly by climate and nutrient availability. This representation generally follows Liebig's law of the minimum, which assumes that yields are influenced solely by the most constraining of these factors and plateau when each factor is above some threshold (Tittonell and Giller 2013, Ferreira et al. 2017) (i.e., the crop can be water- or nutrient-limited). Similar representations are used in other more complicated process-based models of crop yield (e.g., CENTURY (Metherell et al. 1993), STICS (Brisson et al. 2003)) and in other simulation models (Grillot et al. 2018).

Together, our soil nutrient and crop yield representations exhibit the following qualitative characteristics:

1) Consistent cropping without replenishment of organic matter will slowly degrade soil quality and hence crop yields over time (Giller et al. 1997, Reeves 1997, Bennett et al. 2012);
2) Soil quality can be maintained and built through organic inputs (e.g., manure or leguminous cover crops) (Giller et al. 1997, Drinkwater et al. 1998, Wittwer et al. 2017); and
3) Soil organic matter has benefits for drought sensitivity and nutrient losses (Drinkwater et al. 1998, Bommarco et al. 2013).

Household decision-making represents wealth accumulation and coping measures, and is modeled using a simple heuristic. This heuristic assumes that: (1) households store their wealth in the form of livestock and do not have cash savings; (2) livestock are sold if necessary to meet immediate cash needs (Bellemare and Barrett 2006, Moyo and Swanepoel 2010); and (3) total herd size is limited by feed availability (Valbuena et al. 2012, Assefa et al. 2013).

A1.2.2 Individual decision making

The household makes two decisions related to their livestock wealth reserves, both of which are governed by simple heuristics. First, if the household's income in a given year is negative, they make up the deficit by drawing from their wealth reserves (a proxy for the selling of livestock). If wealth reserves are insufficient to make up the deficit, we assume that the household reduces their consumption. Both livestock selling and consumption reduction are considered as coping mechanisms. If, instead, their income is positive, they add this surplus to their wealth reserves (a proxy for the buying of livestock). This latter case is mediated by the second heuristic; if a household's livestock herd (i.e., wealth reserves) is larger than could be fed by their crop residues (assuming some percentage of their herd is grazed on common pastures), they are forced to destock these animals that cannot be fed. Given that wealth can only be held in the form of livestock – i.e., we do not model financial resources – the household receives no monetary benefit for this destocking.

These heuristics are not influenced by any other factors and there are no notions of beliefs, memory, learning, adaptation, or social or cultural norms.

A1.2.3 Learning

There is no notion of learning in the household's decision-making.

A1.2.4 Individual sensing
Each year, the household observes its crop yields, residue production, and income, which influence the decision heuristics.

A1.2.5 Individual prediction
The household does not predict future conditions.

A1.2.6 Interaction
There are no interactions between households. Livestock are assumed to be partially grazed on common rangeland, which implies interactions with other households, but we do not explicitly model the rangeland dynamics, so this interaction is not endogenous to the model.

A1.2.7 Collectives
The household does not form collectives.

A1.2.8 Heterogeneity
The household is defined by its initial wealth reserves, initial soil quality, and land holdings. In our simulations, we consider only the implications of different levels of land holdings. Given that there are no interactions in our model, running the simulation for three households with heterogeneous land endowments is equivalent to running it three times separately with a single household.

A1.2.9 Stochasticity
There are two sources of stochasticity in the model: (1) the generation of yearly climate conditions, which is constant across all households; and (2) a household-level random effect in the calculation of crop yields. The household-level effect conceptually represents other non-modeled factors that may influence crop yields, household-level (positive or negative) shocks, and household-level variability in the experience of the regional climate condition. Together, this requires us to simulate a set of hypothetical climate time series and, for each time series, run the model for a set of households that experience different random crop yield effects. Under the baseline model settings, the variability of the household-level effect is approximately half that of the region-level effect. The model therefore allows for considerable path dependencies introduced by household-level stochasticity.

A1.2.10 Observation
Model outputs include yields, income, wealth, soil organic matter, and mineralized nutrients. These are observed at the household level at an annual basis.

A1.2.11 Emergence

There exists a positive feedback loop, in which positive income enables accumulation of livestock (wealth reserves), providing additional soil organic matter, which in turn increases future crop yields and income. The ability for the household to experience this positive feedback cycle is mediated by their land endowment, initial soil organic matter, climate, and random yield effects. As such, household "trajectories" emerge as a combination of these random and non-random factors. Given the importance of stochasticity, there exists a considerable degree of path dependence in the model; a household that is *unlucky* one year (i.e., has a large, negative random effect in their crop yields) may be pushed into a downward spiral of decreasing livestock herds, soil organic matter, crop yields, and income. We investigate the possibility for household adaptation options (cover cropping and insurance) to influence these trajectories and hence contribute to different emergent outcomes.

A1.3 Details

A1.3.1 Implementation details

The model is implemented in Python 3.6. Code is available online at CoMSES.net: https://www.comses.net/codebases/ee47544a-7eb0-4482-8967-42d6b0c05060/releases/1.0.0/

A1.3.2 Initialization

The model is stylized and does not draw from any extensive empirical datasets. To initialize a single simulation, the climate time series is first generated, followed by a population of households with heterogeneous land endowments. Household initial wealth and soil organic matter levels are homogeneous and are specified by exogenous parameters (see section A1.3.3). As stated above, a single model with multiple households is functionally no different to multiple models with a single household, but we do it in this way both for computational efficiency (through vectorization of calculations) and simpler management of random number seeds. Within an experiment, the random number seed is the only factor that is varied upon initialization.

A1.3.3 Input data and parameterization

Model parameterization is achieved through a combination of information from literature and a pattern-oriented modeling calibration process. All model parameters are displayed in Table A1.1. The calibration process is described in section A1.3.5. Although we do not intend the model to be representative of any specific region or location, we chose to draw several of the parameters from Ethiopian data sources. Ethiopia's population is primarily engaged in smallholder agriculture – many in mixed crop-livestock systems – and thus Ethiopia serves as a relevant setting from which to draw stylized information. This enabled us to represent the relative scales of different model elements (e.g., maximum crop yields and crop selling prices) without requiring these values to be determined by the calibration process, thus reducing the dimensionality of the uncertain parameter set.

Additionally, although our representation of soil nutrient dynamics is stylized and we do not claim to realistically represent actual nutrient flows, we measure the SOM pool in units of kilograms of nitrogen per hectare (kg N/ha). This again allowed us to ground several parameters in empirically observed values (e.g., nitrogen-fixation of cover crops), reducing the number of uncertain parameters. However, we note that some values, particularly the C:N ratios, remain unrealistic in this model parameterization.

The derivation of several parameters requires some explanation:

- Initial and maximum SOM: In reality, baseline amounts of organic matter in a non-degraded soil are sufficient to provide nutrients for moderate levels of crop yield. To parameterize the initial SOM, we used information from other parameters to give a rough estimate of a reasonable value. Specifically, we assumed that the soil itself would initially be able to provide 4,000 kg/ha crop yield (approximately 2/3 of the maximum yield) in the absence of other inputs. Using the C:N ratio in the crop (50), this is equivalent to 80 kg N/ha of mineralized inorganic N that is produced solely through mineralization from SOM. With a mineralization rate of 0.02, this requires an initial SOM level of 4,000 kg/ha. We then chose the maximum SOM level to be double the initial SOM level.
- Wealth to nitrogen conversion: Using values from Newcombe (1987), we calculated that a cattle might produce 6,165 kg of fresh dung or, equivalently, 5,364 kg of dry matter per year. Assuming that 1.46% of the dry weight is nitrogen (also comparable to Lupwayi et al. (2000)), this equates to 78.3 kg N/cattle/year. Assuming a price of 3,000 birr (the Ethiopian currency) for a single animal, this is equivalent to 0.026 kg N/year/birr.
- Land endowment: In reality, smallholder land holdings vary by a larger degree than we represent in the model. However, we assume that each household – regardless of their land endowment and wealth – has the same annual living costs. In reality, land-rich households might have more household members, and consumption also generally increases with wealth. For simplicity in the analysis, our households vary over a single dimension (land endowment), so we do not incorporate such secondary effects and hence parameterize the variability in land endowment from only 1 to 2 ha. These values respectively correspond to the 47th and 75th quantiles of household landholdings in the Ethiopia 2015 LSMS data.

Table A1.1: Parameter values and sources.

Parameter		Symbol	Value	Unit	Source	Uncer-tain[†]	Sensit-ivity analysis	Description / notes
Simulation settings								
	Number of households	N_A	200	-				
	Random seed	s	0	-				Varied over simulation runs.

Parameter	Symbol	Value	Unit	Source	Uncer-tain[†]	Sensit-ivity analysis	Description / notes
Households							
Land endowment	L	{1, 1.5, 2}	ha			✓	Varied over households. See text in section A1.3.3.
Initial wealth	W_0	36,165	birr		✓	✓	Proxy for livestock.
Cash requirement	CR	6,001	birr		✓	✓	Annual cash requirement for consumption.
Market							
Crop sell price	P_{crop}	2.17	birr/kg	FAO[‡]			Mean 2015 price for Maize in Addis Ababa.
Livestock price	P_{ls}	3,000	birr/head	CSA[§]			Average 2015 price.
Yields							
Crop C:N	CN_{crop}	50	gC/gN	(Metherell et al. 1993)		✓	Carbon to nitrogen ratio in harvested crop. Value loosely taken from the CENTURY model description (Metherell et al. 1993).
Residue C:N	$CN_{residue}$	196	gC/gN		✓	✓	Carbon to nitrogen ratio in crop residue. In (Elias et al. 1998) this is approximately four times the ratio of the harvested crop.
Maximum yield	Y_{max}	6,590	kg/ha	LSMS[ǀ]		✓	95th percentile maize yield over Ethiopia in 2011, 2013, and 2015
Climate upper threshold	C^{upper}	0.8	-	(Metherell et al. 1993)		✓	Climate condition above which crop yields plateau
Climate lower threshold (low SOM)	C_{low}^{lower}	0.3	-		✓	✓	Climate condition below which crop failure occurs with SOM is zero
Climate lower threshold (high SOM)	C_{high}^{lower}	0	-				Climate condition below which crop failure occurs with SOM is at its maximum
Crop yield random effect	σ_y	0.3	-			✓	Standard deviation of the crop yield random effect, simulated as $\sim N(1,0.3)$
Residue loss factor	$l_{residue}$	10	%	(Assefa et al. 2013)			Percentage of crop residues not returned to the soil or fed to livestock
Residue multiplier	$mult$	2	-	(Bogale et al. 2008, Assefa et al. 2013)			Residue production per unit of harvested crop.
Soil							
SOM mineralization rate	k_{slow}	2	%/year	(Schmidt et al. 2011)		✓	50-year turnover time of bulk SOM
Applied organic matter mineralization rate	k_{fast}	10	%/year		✓	✓	The percentage of applied organic matter (manure and/or crop residues) that mineralizes in the year of application.
Initial SOM	SOM_0	4,000	kg N/ha	-		✓	See text in section A1.3.3
Maximum SOM	SOM_{max}	8,000	kg N/ha	-		✓	See text in section A1.3.3
Maximum leaching rate	l_N^{max}	25	%	(Giller et al. 1997, Di and Cameron 2002)	✓	✓	Rate of leaching of mineralized organic matter when SOM is zero.

Parameter	Symbol	Value	Unit	Source	Uncer-tain†	Sensit-ivity analysis	Description / notes
Minimum leaching rate	l_N^{min}	5	%	(Di and Cameron 2002)		✓	Rate of leaching of mineralized organic matter when SOM is at its maximum.
Livestock							
Wealth:nitrogen conversion	WN_{conv}	0.018	kg N/year/birr	-	✓	✓	0.026 kgN/year/birr is the derived value for comparison (see text in section A1.3.3)
Percent crop grazing	$c_{residues}$	52	%	(Keftasa 1988, Bediye et al. 2001)	✓	✓	Percentage of livestock food requirements that come from crop residues. The remainder comes from a non-modeled external rangeland.
Consumption requirement	cf	2,280	kg DM/ TLU/ year ¶	(Amsalu and Addisu 2014)		✓	We assume all residues are dry matter
Climate							
Mean	μ_c	0.5	-			✓	
Standard deviation	σ_c	0.2	-			✓	
Adaptation option: insurance							
Climate percentile	Ins_{perc}	10	%				Climate threshold (percentile of cumulative distribution function) below which an insurance payout is received.
Payout magnitude	Ins_{payout}	1	-				Insurance payout relative to the expected yield. For example, if this is 1, the insurance payout will equal the income from an average year's yields (assuming no nutrient limitations on crop growth).
Cost factor	Ins_{cost}	1	-				Fairness of insurance. A value of 1 indicates an actuarially fair policy, where the annual cost is equivalent to the expected annual benefit.
Adaptation option: cover crop							
Nitrogen fixation	$CC_{N\,fix}$	95	Kg N/ha	(Büchi et al. 2015, Wittwer et al. 2017, Couëdel et al. 2018)			Maximum value with no water limitation.
Cost factor	CC_{cost}	1	-				Annual cost of cover cropping relative to the cost of insurance.

† The values displayed for the uncertain parameters were calibrated using the pattern-oriented modeling process (section A1.3.5)
‡ http://www.fao.org/giews/food-prices/tool/public/
§ CSA = Ethiopian Central Statistical Agency. Source = annual retail price sheets.
| LSMS = Living Standards Measurement Study
¶ DM = dry matter, TLU = tropical livestock unit

A1.3.4 Sub-models

A1.3.4.1 Soil nutrients

The model contains two main pools of soil nutrients: organic and mineralized. The states of these pools are measured in kg N/ha. Each year, a portion of the organic pool of nutrients (SOM) mineralizes according to a linear decay process. Organic nutrients applied to the soil (manure and crop residues; N_{added}) also are partially mineralized in the year of application (with a linear rate constant larger than that of the SOM), with the non-mineralized component added to the bulk SOM. We do not differentiate between the addition of "organic matter" and "nitrogen" and use a single variable to retain simplicity.

$$N_{mineralized}^{SOM} = k_{slow}\, SOM_t \tag{A1.1}$$

$$N_{mineralized}^{added} = k_{fast}\, N_{added} \tag{A1.2}$$

$$N_{mineralized}^{total} = N_{mineralized}^{SOM} + N_{mineralized}^{added} \tag{A1.3}$$

$$SOM_{t+1} = (SOM_t - N_{mineralized}^{SOM}) + (N_{added} - N_{mineralized}^{added}) \tag{A1.4}$$

After mineralization, a percentage of the mineralized nutrients is leached from the system. Higher levels of SOM contribute to lower leaching rates (Drinkwater et al. 1998). Specifically, we assume a maximum leaching rate with no SOM (l_N^{max}) and a minimum leaching rate when SOM is at its maximum (l_N^{min}), with a linear interpolation between these two points (see Table A1.1 for parameter values).

Mineral N that remains after leaching is assumed to be fully available to the crop. If this is higher than the crop's N requirements, any excess mineral N is assumed to be lost from the system via leaching (i.e., the mineral nutrient pool is reset each year).

This nutrient balance is partial and we do not model soil erosion (Cobo et al. 2010), yet the loss pathways that we include represent the largest magnitude pathways in mixed cropping-livestock systems (Tittonell et al. 2006). However, in its stylization, our representation of soil nutrient dynamics contains a number of simplifying assumptions, namely: (1) no endogenous or dynamic representation of C:N ratios, (2) a single soil layer, (3) a single pool of organic nutrients with a single mineralization rate, (4) no explicit modeling of soil microbial biomass or other labile SOM pools, (5) no climate dependence in nutrient mineralization or leaching, (6) no nutrient dependence (e.g., N-limitations) in mineralization, (7) no differentiation between ammonium and nitrate as forms of inorganic N, and (8) no atmospheric losses of N through denitrification. Despite these assumptions, we believe that our representation provides a reasonable first-level approximation of more complicated soil dynamics and requires far less parameterization.

A1.3.4.2 Climate

Climate is represented through a single value, which is drawn each year from a normal distribution (parameters in Table A1.1) that is bounded between 0 and 1. This value does not represent a specific physical climate characteristic (e.g., rainfall), but a stylized notion of the "climate condition". Under baseline conditions, the simulated climate values interact with the model solely through crop yields. Under the insurance scenario, payouts are received in years in which the climate condition is below the insurance index value, which is defined as some percentile of the cumulative distribution of the climate condition (i.e., a 10% index represents the 10th percentile of the cumulative distribution). With cover cropping, the climate condition also affects cover crop nitrogen fixation. The climate value is qualitatively similar to the outputs of process-based methods that calculate ratios of actual evapotranspiration to potential evapotranspiration (e.g., applications of the FAO crop water requirements methodology (FAO 1984, Allen et al. 1998, Block et al. 2008) and the CENTURY model (Metherell et al. 1993)), but requires far less parameterization.

A1.3.4.3 Crop yields

Crop yields can be reduced from a maximum potential value (Y_{max}) through water and/or nutrient limitations (Tittonell and Giller 2013). First, we calculate a water factor, C_{water}, with $0 \leq C_{water} \leq 1$. It is assumed that (see Figure A1.2): (1) if the climate value is greater than C^{upper} (0.8 in the parameterized model), then $C_{water} = 1$; (2) there is a critical climate value (≥ 0) at which $C_{water} = 0$; (3) higher levels of SOM lead to higher drought tolerance and hence a lower critical climate value; and (4) C_{water} scales linearly between the critical value and C^{upper}. The maximum water-constrained yield (Y_w) is then assumed to be:

$$Y_w = C_{water} * Y_{max} \qquad \text{(A1.5)}$$

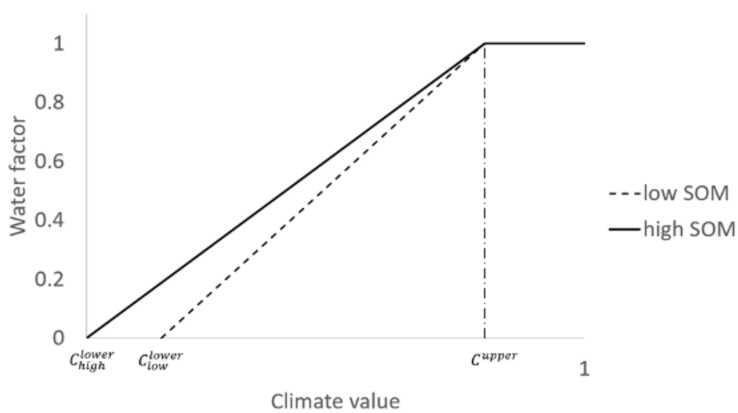

Figure A1.2: Effect of climate on crop yields.

Second, we determine the maximum attainable nutrient-constrained crop yield (Y_N) given the available mineral N in the soil ($N_{mineralized}^{total}$):

$$Y_N = \frac{N_{mineralized}^{total}}{\frac{1}{CN_{crop}} + \frac{mult}{CN_{residue}}} \tag{A1.6}$$

This represents a partitioning of the $N_{mineralized}^{total}$ between the N in the harvested crop (adjusted by CN_{crop}) and the crop residues (adjusted by $CN_{residue}$ and multiplied by $mult$).
The actual yield (Y^{obs}) is then calculated as

$$Y^{obs} = \min(\mathrm{Y_w}, Y_N) * \varepsilon \tag{A1.7}$$

where $\varepsilon \sim N(1, {\sigma_y}^2)$ is a household-level stochastic effect with σ_y given in Table A1.1.

In this stylized crop yield model, we omit or simplify several processes that are included in more detailed process-based crop yield models, for example: (1) our one-dimensional representation of the effects of climate proxies any non-linearities in relationships between climate and yield as well as potential interactions between rainfall and temperature; (2) we do not model solar irradiation and growth of leaf area; and (3) we do not model the partitioning of growth between above- and below-ground biomass. Given the modular nature of our yield model, additional reduction factors could be added (e.g., see (Schreinemachers et al. 2007)) or more sophisticated process-based calculations could replace the existing calculations of water and nutrient limitations. However, this increased complication would require a greater amount of data and calibration, as well as reduce transparency in how specific inputs and structures mechanistically influence yields and the broader model dynamics.

A1.3.4.4 Cover crop N_2 fixation

As with vegetable crops, cover crops' biomass generation, and thereby their soil organic matter contributions, is also constrained by rainfall (Ewansiha and Singh 2006). We assume that the N fixed by the cover crop follows the same water response function as vegetable crop yields (i.e., Figure A1.2). Thus, in a year with no rainfall, no N is fixed. We set the default upper bound on N_2 fixation as 95 kg N/ha (Figure A1.3).

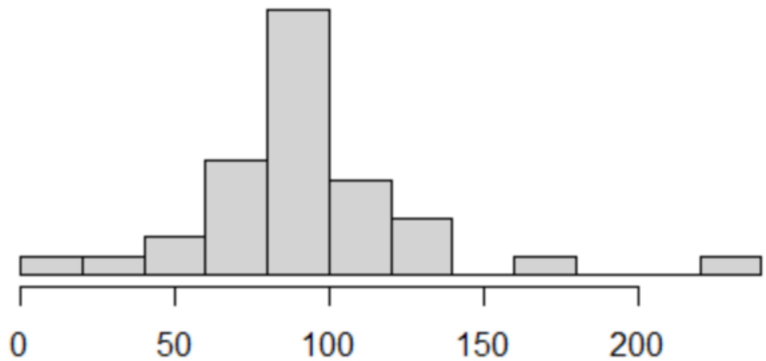

Figure A1.3: Distribution of cover crop N fixation (kg N/ha) in temperate climates reported in Badgley et al. (2007). The median value is 95 kg N/ha.

A1.3.5 Pattern-oriented modeling (POM)

A1.3.5.1 Description

We use latin hypercube sampling to generate 100,000 potential parameter sets, where each parameter is drawn uniformly from the ranges in Table A1.2. For each potential parameterization we run the model 10 times (to encompass climate variability) for a population of 100 households (to encompass variability induced by the random yield effect) for a period of 100 years. We choose only 10 model replications here due to computational reasons.

We assess whether each simulation generates a set of qualitative "patterns" (Table A1.3). These patterns collectively represent desired model behavior under baseline simulation conditions. To evaluate a potential parameter set we: (1) measure which patterns are generated in each simulation, (2) calculate the probability that each pattern is generated over the 10 replications, and (3) sum these averages over all patterns.

Table A1.2: Parameters included in the POM calibration

	Parameter	**Symbol**	**Minimum**	**Maximum**	**Notes**
1	Households: initial wealth	W_o	5,000	50,000	
2	Households: annual cash requirement	CR	5,000	30,000	Median annual expenditure in 2015 LSMS is 17,261 birr
3	Yields: climate lower threshold (low SOM)	C_{low}^{lower}	0	0.5	
4	Yields: residue C:N	$CN_{residue}$	25	200	Bounding the crop C:N ratio
5	Livestock: percent crop grazing	$c_{residues}$	0.5	1	Livestock are often grazed primarily on crop residue (e.g., (Keftasa 1988, Bediye et al. 2001))
6	Livestock: wealth:nitrogen conversion	WN_{conv}	0.01	0.05	Bounding the empirically-derived value
7	Soil: applied organic matter mineralization rate	k_{fast}	0.05	0.95	Must be faster than the SOM mineralization
8	Soil: maximum leaching rate	l_N^{max}	0.05	0.95	

Table A1.3: Patterns used for the POM calibration

	Pattern	Requirements
1	Divergent household wealth trajectories	(a) All land-rich households finish the simulation with positive wealth AND (b) All land-poor households finish the simulation with no wealth AND (c) 20%-80% of the middle households finish the simulation with positive wealth.
2	Households can recover from shocks	There is at least one middle household that: (a) Has no wealth at some point during the simulation AND (b) Has positive wealth at the end of the simulation.
3	No saturation of SOM	There are no households consistently at the maximum level of SOM throughout the last 10 years of the simulation.
4	Some households can build SOM	At least 10% of households finish the simulation with a higher SOM than the initial value

A1.3.5.2 Results

Of the 100,000 parameter sets, three generated on average 3.2 of the four patterns (Figure A1.4). We retained one of these parameterizations for the analysis presented in this paper. Experimentation with the other two parameterizations yielded qualitatively similar results that do not affect the conclusions drawn in this paper.

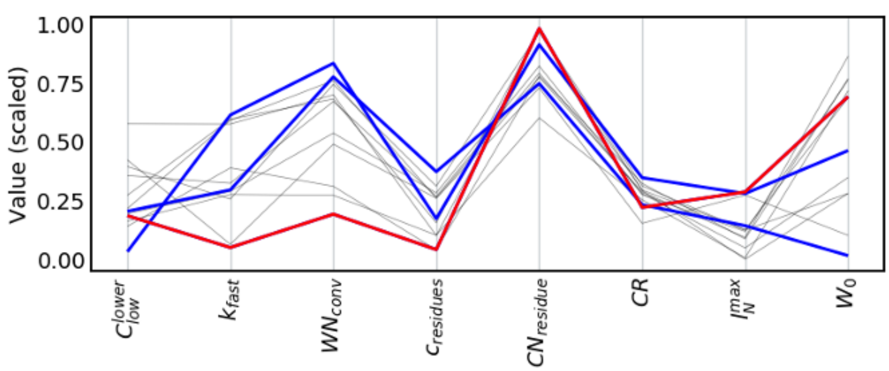

Figure A1.4: Scaled parameter values of the resultant POM parameterizations. The red line represents the selected parameterization. Blue lines represent the other parameterizations that reproduced the same number of patterns. Grey lines show parameterizations that were within 20% of the best.

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