Tipping points in sustainable agriculture adoption

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Abstract

The emergence and impact of tipping points are of immense interest in both social and ecological systems. Despite widespread recognition of the importance of coupled human and natural systems, it is often assumed that the underlying forces that lead to nonlinear behaviors like tipping points rest squarely within either human or natural processes. Our work shows how tipping points can arise in a stylized model representing adoption of sustainable agricultural practices, in which neither system alone has these dynamics. Temporal feedbacks between a farmer's investment choice, based on their perceived utility over a given time horizon, and probabilistic changes in the ecological services derived from the environment, can result in alternate stable states. Because benefits of ecosystem services take time to accrue, farmers in environments with degraded land are unlikely to invest in agroecology, while farmers who benefit from ecosystem services are more likely to bolster those services further. This path dependency leads to a bifurcation into either a more-simplified or more-diversified farming approach, which echoes empirical findings. We show that these alternate stable states need not be an inherent feature of either ecological or decision dynamics but can emerge as a very general pattern by dynamically coupling a simple ecosystem model with a rational decision process over time. We suggest that better understanding such tipping points has important implications for policy design across a range of domains, including land tenure and agricultural subsidies.

Keywords: agriculture, ecosystem services, tipping points, diversification practices, decision-making

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Introduction

Both ecosystems and social systems have been observed to abruptly change states as the result of crossing some critical threshold. Theories of ecological multistability have long described this phenomenon [20] and explored how ecological management impacts stability landscapes [9], with underlying tipping dynamics assumed to stem from ecological processes. Similarly, examples from social science suggest that tipping points may result from complex features of human systems; from the collapse of societies [4], to social networks dynamics such as the spread of innovations [13]. Despite widespread interest in the causes and location of tipping points in integrated socio-ecological systems, it has generally been assumed that the underlying dynamical complexity must be ascribed either to social process or natural phenomena alone.

Empirically exploring tightly coupled dynamic systems to better understand the causees and consequences of regime shifts presents numerous challenges [11]. Human decisions impact ecological processes and the resultant changes create feedbacks that alter the scope and efficacy of future decisions [18, 26, 15]. Management decisions can enhance or degrade ecological services that affect the long-term productive capacity of the land base and impact future financial returns [29]. However, the temporal dynamics of ecological processes do not always align with the temporal scale of human decision-making. For example, many ecosystem services result from sequential investments over time and take years to accrue, meaning adoption of these practices requires decisionmakers to be forward looking, adaptive, and cognizant of environmental and economic uncertainty.

Agriculture is among the most fundamental drivers of anthropogenic ecological change [24], providing a valuable context for examining core properties of the human-environment nexus. While agriculture influences both human and ecosystem well-being, practices vary in their environmental impacts, long-term sustainability, financial viability, and climate resilience. It is increasingly recognized that effective policies to address environmental issues, including the long-term sustainability of agricultural practices, requires interdisciplinary approaches which consider both human decision-making and ecology as a coupled human and natural system (CHANS) [15, 1] .

Here we focus on Diversified Farming Systems (DFS), which are characterized by practices which promote beneficial biodiversity and bolster ecosystem services, enhancing farm- and landscape-scale productivity [12]. While existing DFS research has increased our understanding of how diversification practices affect ecological and financial outcomes, an integrated approach requires a consideration of the feedback loop between adoption of a given practice, resultant ecological outcomes, and future investment decision factors. An integrated CHANS approach to questions about sustainability provides an framework to increase scientific understanding of the potential synergies and tradeoffs of how diversified farming practices affect and are affected by ecosystem processes.

While understanding structural attributes and qualitative dynamics of human-environment systems can provide valuable information on effective levers of change and important assumptions to explore empirically, much of the existing literature in this area focuses either on human decision-making (with ecological processes being exogenous to the model), or explores the complexity of ecological processes without sufficiently considering adaptive human agents [25]. Further, those techniques that do explore dynamic processes and responsive decision-making don't generally allow for forward looking agents [14], ultimately misrepresenting the complex coupling of these systems. This paper presents a stylized coupled human and natural systems model of DFS adoption to explore the complex dynamical properties that result specifically from interactions between adaptive decision making and an ever-changing environment. We find a novel mechanism for bistability that is the result not of complex structural assumptions in either system, but simply the rates at which two systems interact. While we do not suggest that our model captures the full complexity of individual decision making or environmental processes, it does provide a novel framework for integrating empirical findings and exploring emergent dynamics of CHANS. Additionally, we show how such tipping point dynamics can have important implications for agroecological policy design.

Conceptual model description

We explore the transition to and from diversified farming systems using a Markov Decision Process (MDP), in which an agent makes a series of choices about their interactions with the environment (1). In this case, the agent represents a single farm unit. We formulate a 'system state' to represent the degree of beneficial ecological services derived from the farm's investments into diversification practices. Each farming season the agent chooses an action, described by a spectrum from 0% to 100% investment in adopting or maintaining diversification practices. More investment corresponds to a greater probability of transitioning to a higher (more beneficial) ecological state the next year. While transitioning to a higher ecological state provides the agent an increased benefit, higher investment actions also come with a greater associated cost. Using these parameters (values given in Methods, Tab 1), we can calculate the optimal action for each state, known as the 'policy', based on the agent's future cumulative discounted rewards over a defined time horizon.

Results

Using the model described above, we observe the behavior of agents' sequential choices and resultant environmental outcomes over time. Agents' initial ecosystem states are distributed normally with a mean at $\bar{s} = 0.5$. Fig 2 shows that, after having followed policy π for nine timesteps, at $t = 10$ agents have largely bifurcated into two groups, with some farms transitioning to more "simplified" farming systems, and others to more "diversified" systems. Further, we find strong path dependency, with only 11% of runs which started in a simplified ($s < 0.5$) state concluding in a diversified ($s > 0.5$) state, and only 7% of runs initially in the diversified state transitioning to simplified.

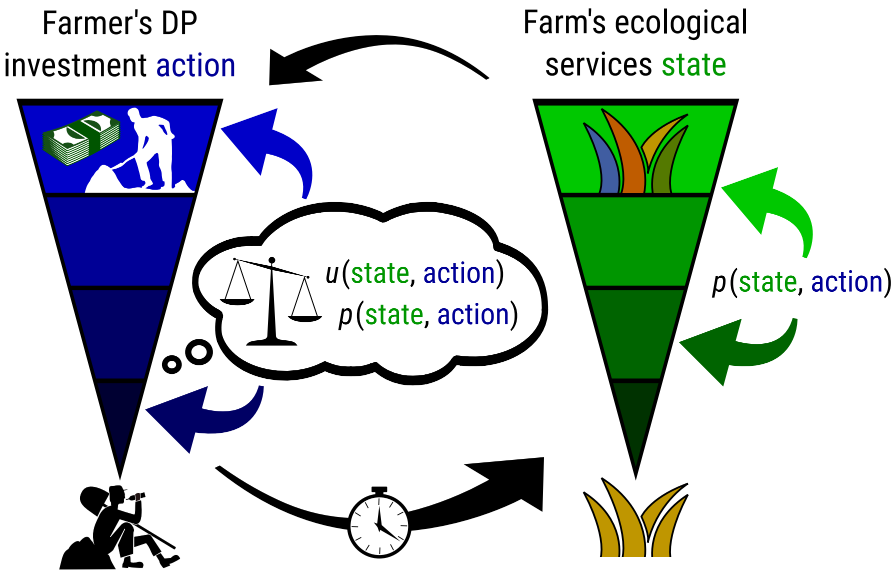

Figure 1: Conceptual diagram: A higher system state (green) corresponds to increased diversification practices. The diversification investment decision (blue) and the interaction between the farmer's perceived utility function $u()$ and the state transition probability function $p()$.

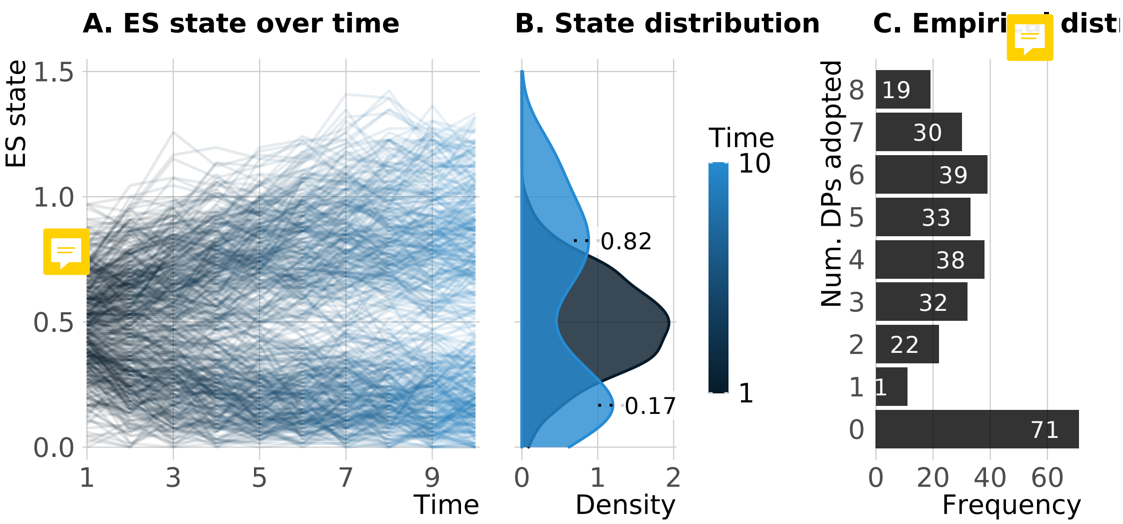

Figure 2: Simulations of 500 agents over ten farming seasons. Initial ES states follow a truncated normal distribution (mean = 0.5; S.D. = 0.2; truncated at [0,1]). Agents utilize decision policy π as shown in Fig 3 for nine timesteps. (A) shows the state of each agent throughout each run. (B) shows the initial ES distribution (dark blue) and bimodal density distribution at $t = 10$ (light blue), with peaks annotated. (C) shows the observed bimodal DP adoption distribution in our survey data.

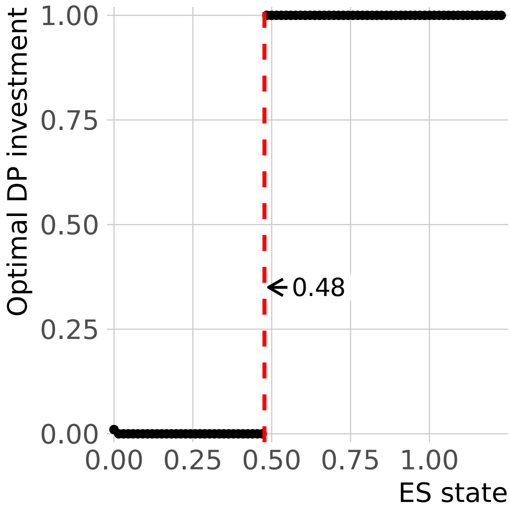

Figure 3: Optimal decision policy π as a function of ecosystem state. The upper x axis limit is the 99th percentile of observed states in our simulation results (≈ 1.23).

Optimal decision policy

The decision policy π describes the optimal course of action for a given state, with each agent in the simulation above using this policy to guide their decision-making. Fig 3 reveals that there is a critical bifurcation, or tipping point, at an specific ecosystem state, below which the highest expected value is derived by investing little to nothing into diversified farming systems. Above the threshold, the optimum action becomes near-full investment into diversified farming systems. Over time, this results in a bimodal distribution of ecosystem states, as seen in Fig 2.

Land tenure

With 39% of U.S. farmland under lease [21], and with widely-varying rental agreements, the impact of land tenure on best-managment-practice adoption has been increasingly examined in agricultural lands. For example, a study of U.S. corn producers found that cash renters were less likely than land owners to implement grassed waterways, strip cropping, contour farming, or conservation tillage [23]. A study conducted in British Columbia found that tenant farmers planted fewer perennial crops than land owners [6]. Our own ongoing research with lettuce farmers in California's Salinas Valley suggests that land tenure is an important factor in decisions about cover cropping and crop rotation. In addition, investments in diversified farming practices may require access to credit, which often also hinges on secure land tenure as a form of collateral [19].

Using the same parameters outlined above, we solve the decision model on a finite, two-year time horizon, representing the shorter window within which many tenant farmers may make decisions (Fig 4). Comparing the final state distribution of the baseline model to the short tenure model shows that, as length of land tenure or stability of lease agreements decline, optimal decisions are calculated more myopically and farmers are incentivized to severely limit investment into diversified practives. This results in a degredation of ecosystem state even among those plots with an initially high value, with 92% of farmers ending up in the simplified state. Our model data echoes empirical findings from a recent large-scale survey of U.S. west coast produce growers, which shows that farmers who primarily own their land are roughly 20% more likely to invest in at least one diversification practic

Subsidy structures

While land tenure is intertwined with land use decisions, agricultural subsidies have also become an integral part of farming over the past half-century, and policymakers are continually called upon to weigh farm

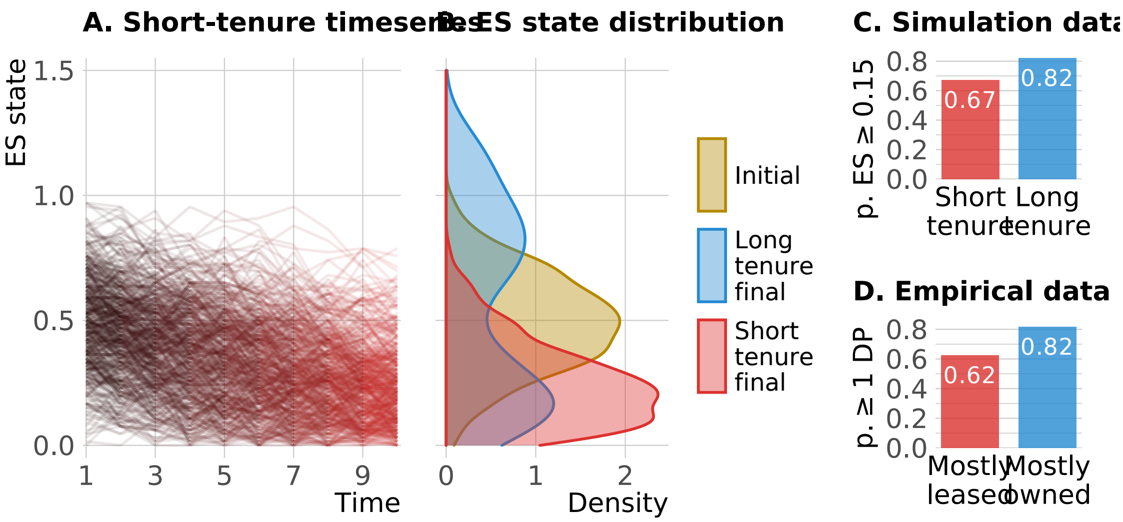

Figure 4: (A) Result of short land tenure on DEP adoption. The simulation is identical to that in Fig 2, but the MDP is solved under a finite, two-year time horizon. (B) Comparison between final state distribution of short- vs. long-tenure model runs. (C) Probability of ecosystem services state being ≥ 0.15 at $t = 10$ for the short-tenure simulation vs. the base-case simulation. (D) Impact of land tenure on the probability of a farmer in our survey dataset adopting at least one DP.

viability against food affordability and environmental sustainability and design effective subsidy packages [7]. We implement two competing subsidy structures: a short-term (two-year) subsidy which completely covers the cost of transitioning to a more diversified state, versus a longer-term (ten-year) subsidy which only marginally offests the transition cost. Formally, the cost of each subsidy package to the issuing organization is equal, and in fact the short-term subsidy is technically more valuable if economic discounting is applied. Within the model, agents adapt their decision policy π during the subsidy period, and at its conclusion they revert to subsidy free decision rules.

Fig 5 shows that longer, more sustained subsidies may be more beneficial to nudge behavior over the critical threshold toward more sustainable systems in the long-term. Comparing these experimental results to those in Fig 2, we find that both subsidy packages were effective in shifting farmers to a sustained higher ecosystem-services state. However, the sustained subsidy was much more effective at moving the needle. Due to the previously-discussed tipping point dynamic that emerges in the model, once an agent has crossed the threshold to the diversified state, it becomes much less likely that they will fall back toward the “simplified” state, at least in the short term. With state-transition stochasticity a major factor in a given model run, and the real world, longer-term subsidy packages have a higher chance of nudging behavior beyond the critical threshold.

Discussion

Recent research in complexity theory highlights the importance of understanding nonlinear behaviors within dynamical systems. For example, when pushed beyond some threshold, even given potent countervailing actions on the part of a decision-maker, a system may enter a virtually-irreversible state, driving its behavior into divergent basins of attraction [2]. These types of complex dynamics have been observed empirically across a wide variety of coupled human and natural systems, and the identification of effective policy measures to effect change in these areas has been described as a “wicked problem” that often confounds traditional methods of analysis for precisely this reason [8].

While much of the research on agricultural management has continued to focus on traditional unidisciplinary approaches [5], novel computational methods like agent-based modeling, network analytics, and machine learning have been increasingly employed, providing important insights into its complexities

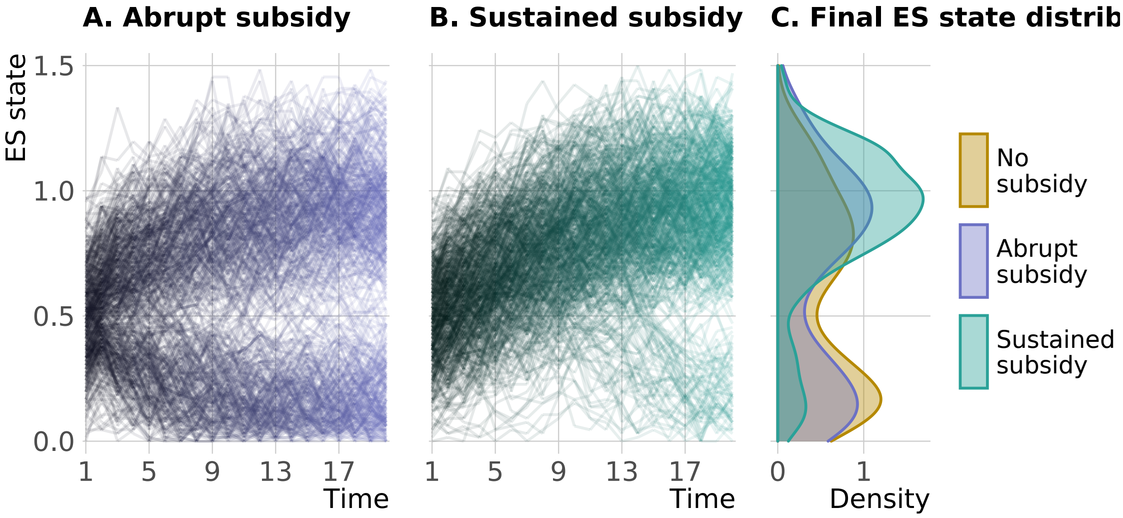

Figure 5: Replicate simulations from 500 normally-distributed starting states (mean = 0.5; S.D. = 0.2; truncated at [0,1]) over 20 timesteps. (A) shows the effects of a large, abrupt subsidy (100% of adoption expenses are covered during the initial two years). (B) simulates a smaller, yet more sustained subsidy (adoption cost is 80% of baseline during the first 10 years). Ingoring discounting, subsidies have the same total cost to the funder (the equivalent of 2 years' worth of full adoption cost offsets). After subsidy is removed, agents adjust their decision rule to that of the base case (i.e. no subsidy) for the remainder of the run. (C) shows that the sustained subsidy drove more adoption at $t = 20$.

[14, 28, 27]. However, these tools often rely on predefined decision rules, removing the dynamic and responsive nature of agent decision-making and planning, and thus limiting the capacity to explore levers of change that stem from interactions between adaptive agents and a changing environment.

Representing agriculture management in silico as a dynamic CHANS, we find that the empirically-observed bistability in diversification practice adoption may be the result of tipping points in optimal sequential control, rather than inherent tipping points in the ecological dynamics themselves, or in the predispositions of human agents. The model we present here represents a simplified and stylized version of the feedbacks between human decision-making and ecological processes, but even still we show that complex dynamics can arise as a direct result of human-environment interaction. While the concept of alternate stable states and tipping points within agricultural SESs has been previously explored [25], our experimental results cast light on several core mechanisms that help to explain this phenomenon, suggesting novel considerations as policymakers work to enhance the sustanability and resilience of agricultural production systems.

In light of historical agricultural catastrophes like the dust bowl, the importance of swift action around stressors like climate change, soil degradation, water quality, and biodiversity loss has been increasingly recognized. Policymakers have responded by offering incentives and support for agroecological practice adoption, yet designing effective policies has proved challenging. Recent case studies emphasize that policy mechanisms designed to promote agricultural sustainability have complex ramifications across various contexts [10]. Critical to designing incentives is an understanding of the thresholds which render a given management practice viable to one farmer while nonviable to another.

Because agroecological practice adoption is often characterized by uncertainty and a time delay before beneficial effects are realized [3, 16], we find a threshold such that farmers on each side of a tipping point are drawn to alternate stable states, one being more simplfied and the other more diversified. This leads to path dependency, whereby a farmer who begins with degraded land is incentivized to transition even more toward the simplified state, while a farmer who begins with well-cared-for, fertile land is incentivized to adopt management practices that maintain and improve functional diversification.

Given this finding, we suggest that a key lever of change for policymakers interested in promoting adoption of agroecological practices may be to increasingly focus on supporting farmers' transitions within the critical window from the simplified to the diversified state by opening space for viable intermediate states. Given this, binary certifications like the organic standard, which offer immediate market benefits, may be critiqued for some of their unintended consequences. Organic certification stipulates allowable inputs rather than strategic management of soil health; and producers are either certified or not, even if the ways in which they implement organic agriculture is quite heterogeneous [22]. Our work suggests that an increasing focus on rewarding adoption of individual sustainable practices, rather than a cut and dried overall standard, may allow for a process of incremental transition, with farmers embedded in monocultural agricultural systems able to move stepwise toward the adoption of diversified farming.

Land tenure is an often-cited decision factor that has been found to impinge upon sustainable agricultural practice adoption [23, 6, 19, 16]. Land owners or holders of long-term lease agreements have a personal stake in the productive quality of their soil ecology, and a rational actor will take the long view and invest in practices that will benefit them years down the line. On the other hand, growers who are uncertain whether they will personally continue to farm a given parcel are less incentivized to adopt such practices. By coupling the rate of ecological change with the time horizon of decision-makers in different contexts, our simulations illustrate why secure land tenure is so integral to the adoption of diversification practices. Given the CHANS dynamics at play, if farmers maximize their expected utility on a short time horizon, there is a strong incentive to disinvest in diversification practices. Further, as we have seen, farmers who start with more degraded land will be less likely to invest in agroecology, due to the path dependency that arises from the tipping point dynamic. Policies that increase land tenure duration, such as regulating lease agreement terms, providing low- or zero-interest loans, or promoting stable farm succession plans, may therefore represent a key lever to nudge farmers toward diversified systems.

Subsidies are a fundamental part of modern agricultural policy, be they through direct payments, or, under more recent farm bills, heavy subsidization of crop insurance premiums [7]. We show that a given quantity of taxpayer funding will more-effectively move the needle toward DFS if it is guaranteed over a longer period rather than being offered as a lump sum. In our simulations, a ten-year subsidy was successful in moving 43% of farmers who started in the simplified state to the diversified state, compared to only 24% for the two-year subsidy, despite their costs being equal. A ramification of this finding is that the perceived stability of subsidy programs over time may be an important driver of their efficacy. Since, as we have seen, the transitional "hump" between the two stable states represents a precarious economic position, if a subsidy is not guaranteed for a long enough period to get over the hump toward DFS, the rational farmer will be incentivized to simply continue in their simplified state. With U.S. farm bills being completely overhauled every five years or so, a farmer may have limited confidence that a critical subsidy program will be sufficiently long-lived, suggesting that a policy lever may be to extend the sunsetting of agroecological policy bills.

Several limitations of this study should be acknowledged. We do not draw distinctions between diversification practices that require large up-front costs versus those that require continual maintenance, instead lumping practices together into a generalized framework. Our model does not capture market dynamics resulting from feedbacks between production and consumption, but rather conceives of the system as a commodity market within which an individual grower's production does not influence the overarching market price. We also do not consider ecosystem services and/or deleterious environmental effects that spill over from neighboring farmland, nor do we examine the impact of education or social effects on the adoption rate. Each of these areas remains a potential avenue for future research.

Even based on a relatively-simple stylized model, our analysis suggests a novel approach to studying sustainable farming as a coupled human and natural system. Specifically, we show that complex dynamical behaviors like tipping points can emerge purely from the interaction between human agents and their ecological surroundings. Even with no inherent complexity in the ecological model, and decision-making agents that do nothing but optimize their expected utility based on current conditions, our model generates the bimodal distribution of agroecological practice adoption that we see in the real world. By conceiving of sustainable agricultural management through this lens, we offer new insights into some classic agricultural policy conundrums.

Methods

The state space S is a vector with a lower bound of 0, and a soft upper bound of 1, with the system state s_t representing the degree to which the agent derives ecosystem services benefits b_s such as soil productivity, water infiltration, and climate resilience from the diversification practices they have implemented on their farm. Actions to increase investments in diversification practices probabalistically increase or decrease the future system state, with r defining the rate at which the ecosystem responds to change. While agents may stochastically transition to $s > 1$, investments into diversification practices do not positively correlate with the probability of upward state transitions beyond $s = 1$.

The action space A is a continuous vector from 0 to 1, with $a = 0$ representing no investment of resources into DP adoption and maintenance and $a = 1$ representing the highest conceivable level of investment. Investment in diversification practices incurs costs c_a, either as a direct result of implementation (e.g. equipment, materials, and labor), opportunity costs (e.g. forgone yields due to reduced cultivated acreage or lost production efficiency), or both.

The time step t corresponds to a single growing season. At each time step, the agent chooses an action based on their current state by following decision policy π. π is calculated by maximizing expected utility for each state/action pair over the full time horizon using a Stochastic Dynamic Programming (SDP) approach [17], with the discount rate γ determining how much the agent values current rewards relative to future rewards.

Model mathematical description

The farmer's decision model can be expressed as

$$\max_{\{a_t\}} \mathbb{E}\left[\sum_t^T u(s_t, a_t)\gamma^t\right]$$

where $\{a_t\}$ is the set of available actions to be taken at each point in time t, γ is the discount rate, $\mathbb{E}$ the expectation operator, and $u(s_t, a_t)$ the utility which the farmer associates with being in state s_t and taking action a_t at time t. T is the land tenure of the farm ($T = \infty$ if the farmer owns the land or otherwise expects to be able to farm the same land and thus benefit from the ecosystem services established there indefinitely).

We assume a simple model for the farmer's utility $u(s_t, a_t)$ as a combination of the costs c associated with the diversification practice investment action a and the benefits b derived from the ecosystem state s (which is in turn influenced by the practices adopted)

$$u(s_t, a_t) = bs_t - ca_t$$

The ecosystem state is also dynamic, evolving according to the transition probability function $p(s_t, a_t)$:

$$s_{t+1} = p(s_t, a_t) := s_t + r\,(a_t - s_t) + \sigma$$

This provides a minimal state transition model in which the parameter r sets the natural timescale at which the ecosystem can respond to a change in mangement practice, and σ defines the spread of the state transition probability distribution, capturing stochastic noise inherent to the ecological system's change over time. While we have assumed very basic transition and utility functions for this stylized model, in general more complicated nonlinear functions of both the ecosystem state transition and derived utility are possible in this framework.

Model parameters

We have chosen parameters for illustrative purposes (Table 1) and the results should be interpreted as numerical examples of bistability in CHANS resulting from optimal decision making under uncertainty in ranges of ecological dynamic rates and decision making scales.

Table 1: Table 1: Parameter values

Parameter	Value
b	1.57
c	1.00
σ	0.1
r	0.1
γ	0.97

Table 2: Diversification practices in the survey data

DP Name	Adoption rate
Crop Rotation (3 or more)	63%
Cover Cropping	68%
Intercropping	52%
Insectary Plantings	61%
Riparian Buffers	84%
Border Plantings	45%
Compost or Manure	75%
Reduced Tillage	69%

Field observations and empirical data

To ground-truth our modeling work, our interdisciplinary research team began by exploring empirical evidence about the real-world drivers and distributions of farmers' adoption of diversification-enhancing practices using qualitative observations of trends within a relatively-small sample. We then test hypotheses using results from a large-scale survey.

Original interviews

We conducted interviews and on-farm observational studies of 20 organic lettuce growers and 8 technical assistance providers based in the California central coast region. The sample was stratified to include growers across the spectrum of scale and market outlet. Based on these studies, several important trends emerge. Echoing previous research in this area, we find that adoption of diversification practices tends to be bimodal; that is, growers are likely to either intensively-adopt many diversification practices, or to adopt these practices minimally. This may be explained by factors including limited capital availability to implement practices with high up-front costs, food safety stipulations based on market outlet, risk attitude, and myopic discounting. Both length of time on the land, and whether land is leased versus owned also emerged as a salient decision factor.

Survey dataset

To evaluate the extent to which these observed adoption distributions hold quantitatively, we leverage a dataset of survey responses from 295 vegetable growers in Washington, Oregon, and California *CITE DATA SOURCE*. Table 2 shows the set of DPs queried in the survey, with their adoption rates across the entire sample. A histogram plotting the number of diversification practices used by each grower (Fig 2B) shows a bimodal distribution, with growers generally tending to either adopt zero DPs—the most likely case—or else to adopt many, with six practices being the next-most-likely. To investigate the effect of land tenure on DEP adoption, we partition the dataset into growers who primarily own their land versus those who primarily lease it. Figure 4B shows that owners in our sample are about 20% more likely than leasers to invest in at least one diversification practice.

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