

Tipping points in the adoption of agroecological diversification practices

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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 coupled natural human systems (CHANS) model representing adoption of agroecological 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 through choices of such practices. This path dependency leads to a bifurcation into either a more-simplified (conventional) or more-diversified (agroecological) 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 general pattern by dynamically coupling a simple ecosystem model with a rational decision process over time. We suggest that better understanding of such tipping points has important implications for agricultural and land use policy design across a range of domains, including land tenure and agricultural subsidies.

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

Introduction

Both ecosystems and social systems have been observed to change states abruptly as the result of crossing a critical threshold or “tipping point”. Theories of ecological multistability have long described this phenomenon (Scheffer and Carpenter 2003) and explored how ecological management impacts stability landscapes (Horan et al. 2011), with tipping points assumed to stem from complex ecological processes like population dynamics. Similarly, examples from social science suggest that tipping points may result from complex features of human systems; from the collapse of societies (Downey, Haas, and Shennan 2016), to social network dynamics such as the spread of innovations (Kuehn, Martens, and Romero 2014). 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 can be ascribed to either social process or natural phenomena.

Empirically exploring tightly coupled dynamic systems presents numerous research challenges (Kline et al. 2017). Human decisions impact ecological processes and the resultant changes create feedbacks that alter the scope and efficacy of future decisions (Ostrom 2009; Walker et al. 2004; Liu et al. 2007). Decisions can

enhance or degrade ecological services that affect the long-term productive capacity of the land base and impact future financial returns (Zhang et al. 2007). However, the temporal dynamics of ecological processes do not always align with the temporal scale of human decision-making. For example, land management to produce ecosystem services may require sequential investments over time and/or take years to accrue (Morandin, Long, and Kremen 2016; Blaauw and Isaacs 2014), meaning adoption of these practices requires decisionmakers to be forward looking, adaptive, and cognizant of environmental and economic uncertainty

Agriculture is a fundamental driver of anthropogenic ecological change (Stoate et al. 2009; Foley et al. 2005, 2011), providing a valuable context for examining how social and ecological systems interact. 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 CHANS (Liu et al. 2007; Alberti et al. 2011) .

Here we focus on Diversified Farming Systems (DFS), which use agricultural practices that promote beneficial biodiversity and bolster ecosystem services, while simultaneously enhancing farm- and landscape-scale productivity (Kremen, Iles, and Bacon 2012). While existing DFS research has increased our understanding of how diversification practices affect ecological and financial outcomes (Rosa-Schleich et al. 2019), an integrated CHANS approach requires a consideration of the feedback loop between adoption of a given practice, resultant ecological outcomes, and future investment decision factors. Such an approach to questions about sustainability provides a framework to analyze the potential synergies and tradeoffs of how diversified farming systems affect and are affected by ecosystem processes. *add something about specific practices here?*

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 or explores complex ecological processes without sufficiently considering the role of adaptive human agents (Vandermeer and Perfecto 2012). Further, those techniques that do investigate dynamic processes and responsive decision-making don't generally allow for forward looking agents (Lippe et al. 2019), ultimately misrepresenting the complex coupling of these systems.

This paper presents a stylized coupled human and natural systems model of diversification practice 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 the two systems interact. While our model necessarily simplifies individual decision-making and environmental processes, it provides a novel framework for integrating empirical findings and exploring emergent dynamics of CHANS. Additionally, we describe important implications of such tipping point dynamics 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 produce farmer. We formulate a "system state" to represent the degree of beneficial ecosystem 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 strategy for each state, based on the agent's future cumulative discounted rewards over a defined time horizon.

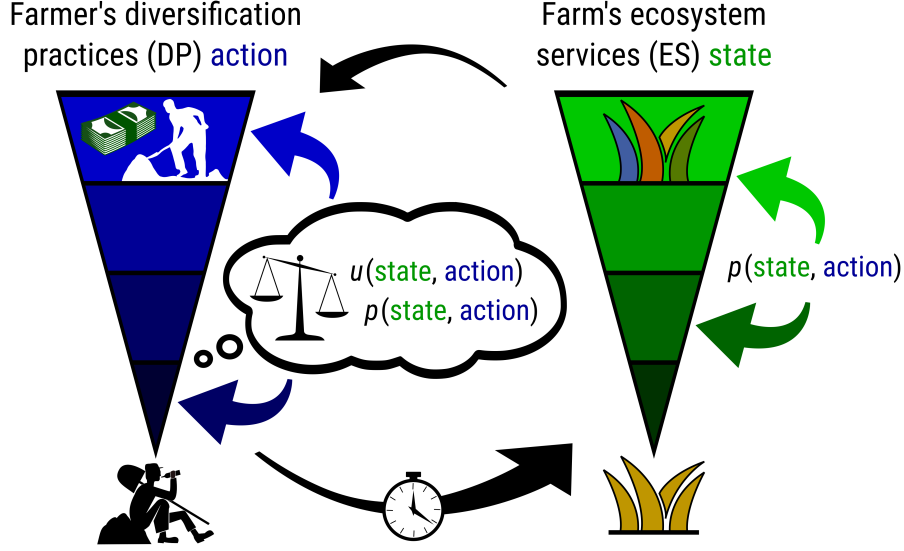


Figure 1: Conceptual diagram of the DFS-MDP model. The farmer’s choice of how much to invest (time and/or money) into diversification practices (DP) is shown in blue, and the resulting ecosystem services (ES) state in green. Each year, the farmer evaluates which action they judge to have the highest expected utility, based on the transition probability function (p) and perceived utility function (u). The ecosystem responds stochastically over time, influencing the farmer’s future choices. This leads to complex tradeoffs arising from the coupling of ecological processes with the series of DP investment decisions made by the farmer.

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 the decision strategy π for nine timesteps, at $t = 20$ agents have largely settled 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 17% of agents who started in a simplified ($s < 0.5$) state concluding in a diversified ($s > 0.5$) state, and only 7% initially in the diversified state transitioning to simplified.

Optimal decision strategy

The decision strategy π describes the optimal course of action for a given state, with each agent in the simulation above using this strategy to guide their choices over time. Fig 3 reveals that there is a critical bifurcation, or tipping point, at a specific ecosystem state, below which the highest expected value is derived by investing little to nothing into diversified farming systems, and above which the optimum action becomes near-full investment into DPs. 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 (Service 2016), and with widely-varying rental agreements, the impact of land tenure on best-management-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 (Soule, Tegene, and Wiebe 2000). A study conducted in British Columbia found that tenant farmers planted fewer perennial crops than land owners (Fraser 2004). 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.

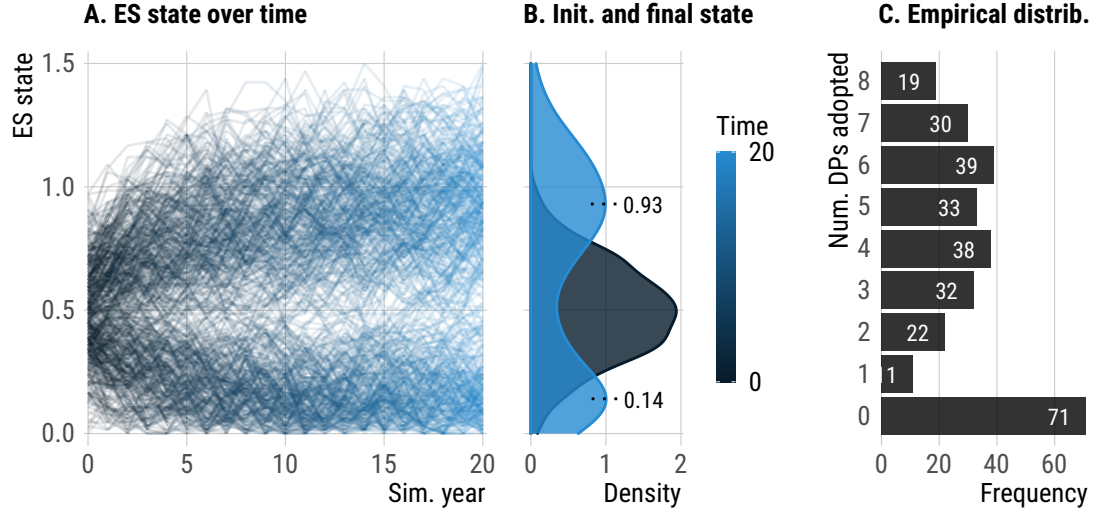


Figure 2: Simulations of 500 model agents over 20 farming seasons. Initial ES states follow a truncated normal distribution (mean = 0.5; S.D. = 0.2; truncated at [0,1]). Agents then utilize decision strategy π as shown in Fig 3 until $t = 20$. (A) shows the state of each agent throughout each run. (B) shows the initial ES distribution (dark blue) and bimodal density distribution at $t = 20$ (light blue), with peaks annotated. (C) shows the observed bimodal DP adoption distribution in our survey data.

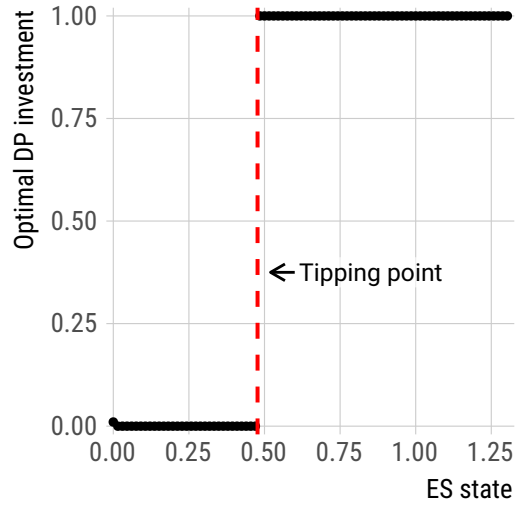


Figure 3: Optimal decision strategy π as a function of ecosystem state, showing a tipping point at $s \approx 0.48$. The upper x axis limit is the 99th percentile of observed states in our simulation results ($s \approx 1.23$).

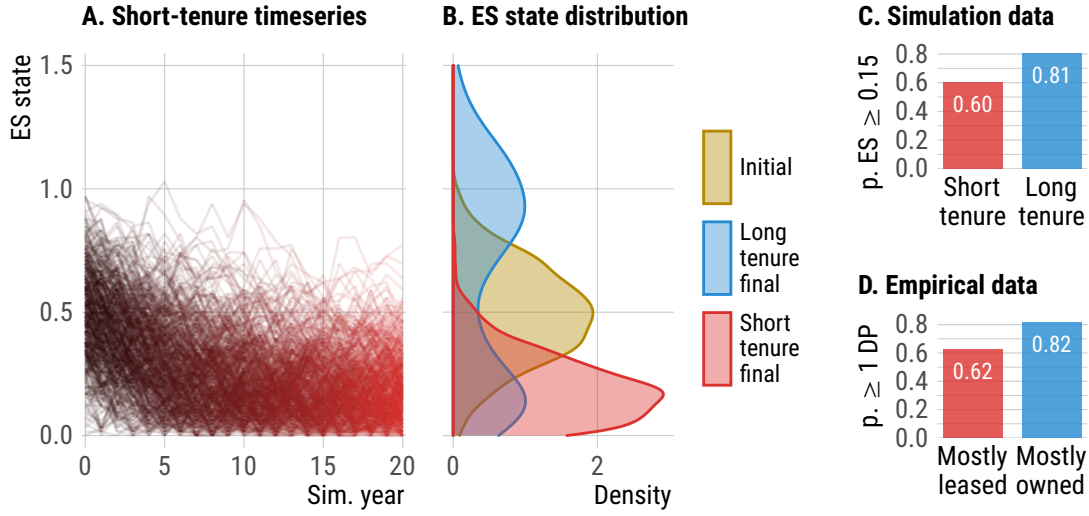


Figure 4: (A) Result of short land tenure on DEP adoption. The simulation is identical to that in Fig 2, but the MDP is solved under a finite, two-year time horizon. (B) Comparison between final state distribution of short- vs. long-tenure model runs. (C) Probability of ecosystem services state being ≥ 0.15 at $t = 20$ 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.

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 (Richardson Jr 2015).

Using the same simulation methods and 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 practices. This results in degradation of ecosystem state even among farm sites 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 lease land are roughly 80% less likely to invest in any diversification practices.

Agroenvironmental subsidies

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 viability against food affordability and environmental sustainability to design effective incentive packages (Graddy-Lovelace and Diamond 2017). Agricultural subsidies have a range of goals, one of which is the promotion of sustainable management practices. We implement two competing incentive structures: a short-term (two-year) incentive which completely covers the cost of diversification practice adoption, versus a longer-term (ten-year) incentive which only marginally offsets the transition cost. Within the model, agents adapt their decision strategy π during the subsidy period, and at its conclusion they revert to the subsidy-free strategy. Formally, the cost of each incentive package to the taxpayer is equal, and in fact the short-term subsidy is technically more valuable if economic discounting is applied.

Fig \ref{fig:res_subsidy} shows that longer, more sustained incentive programs may be more effective at nudging behavior over the critical threshold toward more sustainable systems. Comparing these subsidy simulations to the non-subsidy results in Fig 2, we find that both incentive packages were effective in shifting farmers to higher ecosystem-services states. However, the sustained incentive was much more effective at moving the needle. Due to the previously-discussed tipping point dynamic, once an agent has crossed the

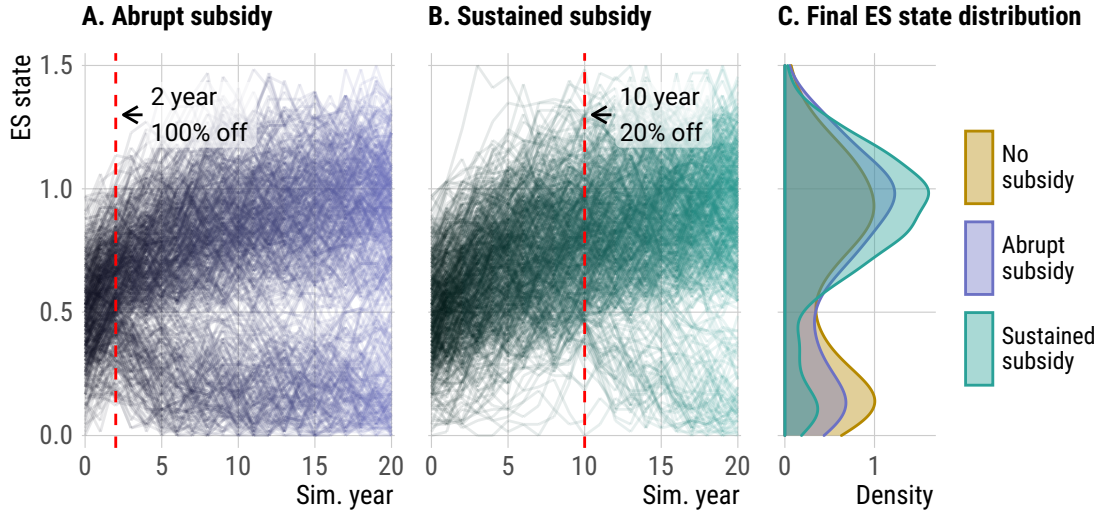


Figure 5: Replicate simulations from 500 normally-distributed starting states (mean = 0.5; S.D. = 0.2; truncated at [0,1]) over 20 timesteps. (A) shows the effects of a large, abrupt subsidy (100% of adoption expenses are covered during the initial two years). (B) simulates a smaller, yet more sustained subsidy (adoption cost is 80% of baseline during the first 10 years). Ignoring 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 $t = 20$.

threshold to the diversified state, it becomes much less likely that they will fall back toward the “simplified” state. Since ecosystem state change stochasticity is a major factor in a given model run, similar to real-world ecological dynamics, longer-term subsidy packages have a higher chance of nudging behavior beyond the critical threshold, resulting in more agroecological practice adoption.

Importance of coupling human and natural system dynamics

As we have shown, a stylized model of agroecological decision-making over time can produce complex results like tipping points if the human and natural system are analyzed as one. However, this bistability vanishes when the ecological process becomes “fast” or the decision strategy becomes temporally myopic.

Discussion

Recent research in complexity theory reveals 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 (Bar-Yam 2019). 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 (Head and others 2008).

While much of the research on agricultural management has continued to revolve around traditional unidisciplinary approaches (Francis et al. 2008), novel computational methods like agent-based modeling, network analytics, and machine learning have increasingly provided important insights into the complexities of CHANS (Lippe et al. 2019; Wiltshire 2018; Wiltshire et al. 2019). 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.

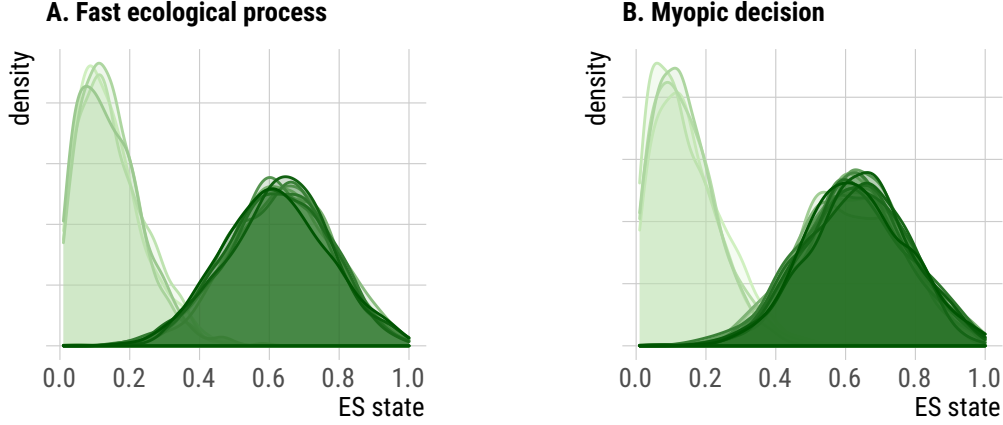


Figure 6: Replicate simulations from 500 normally-distributed starting states (mean = 0.5; S.D. = 0.2; truncated at $[0,1]$) over 20 timesteps. Color of the density corresponds to cost-benefit ratio. (A) shows the effects of fast ecological process simulated through cost-benefit space. No bimodality is seen in any single parameter cases. However, both low and high states are possible under different cost-benefit ratios. (B) Similar results are seen in the case of decision-making that is not forward looking.

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 (Vandermeer and Perfecto 2012), our experimental results cast light on several core mechanisms that help to explain this phenomenon, suggesting novel considerations as policymakers work to enhance the sustainability 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 (IPES-Food 2018). 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 (Carlisle 2014; Long et al. 2017), we find a threshold such that farmers on each side of a tipping point are drawn to alternate stable states, one being more simplified 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 (Shennan et al. 2017). 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 (Soule, Tegene, and Wiebe 2000; Fraser 2004; Richardson Jr 2015; Long et al. 2017). 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 (Graddy-Lovelace and Diamond 2017). 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 28% 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 sunset 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 model’s state space 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 service benefits b_s from the diversification practices they have implemented on their farm. Actions to increase investments in diversification practices probabilistically 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 is a continuous vector from 0 to 1, with $a = 0$ representing no investment of resources into DP adoption or 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 strategy π . This strategy is calculated by maximizing expected utility for each state/action pair over the full time horizon using a Stochastic Dynamic Programming (SDP) approach (Marescot et al. 2013), 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 , \mathbb{E} the expected utility operator, $u(s_t, a_t)$ the utility which the farmer associates with being in state s_t and taking action a_t at time t , and γ the myopic discount factor. T is the land tenure of the farm ($T \rightarrow \infty$ if the farmer owns the land or has a long lease).

We assume a simple model of the farmer’s perceived utility, $u(s_t, a_t)$, as a function of the costs c associated with diversification practice investment action a , versus benefits b derived from achieved ecosystem state s :

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

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

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

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 land management and σ defines the spread of the state transition probability distribution, capturing the noise inherent to ecological system change over time. While we have assumed very basic transition and utility functions for this stylized model, in general more complicated nonlinear functions for both the ecosystem state transition and derived utility are possible using this framework.

We have parameterized the model to illustrate bistability in CHANS resulting from optimal agroenvironmental investment decision-making given stochastic ecological responses over time. Parameter values appear in Table 1.

Field observations and empirical data

To ground-truth this modeling work, our interdisciplinary research team began by investigating real-world drivers of farmers’ management practices using qualitative observations of trends within a relatively-small sample. We then test hypotheses using data from a larger-scale survey.

Table 1: Baseline parameter values

Parameter	Value
Benefit b	1.57
Cost c	1.00
State transition noise σ	0.1
State response rate r	0.1
Discount factor 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%

Original interviews

We conducted interviews and on-farm observational studies of 20 organic lettuce growers and 8 technical assistance providers in California’s Salinas Valley. The sample was stratified to include growers across the spectrum of scale and market outlet. 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 DPs, or to adopt them minimally. Participants cited decision factors including limited capital availability to implement practices with high up-front costs, food safety stipulations based on market outlet, risk attitude, and economic discounting. Both length of time on the land and whether land is leased versus owned also emerged as salient decision criteria.

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 2C) 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. Figure 4D 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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