Tipping points in the adoption of agroecological 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 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 diversified 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

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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 processes *or* natural phenomena.

Empirically exploring tightly coupled dynamic systems presents numerous research challenges (Kline et al. 2017). In such systems, human decisions impact ecological processes, and the resultant changes create

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feedbacks that alter the scope and efficacy of future decisions (Ostrom 2009; Walker et al. 2004; Liu et al. 2007). For example, agricultural management choices can enhance or degrade ecological services that affect the long-term productive capacity of the land base, impacting future financial returns, and limiting future decision possibilites (Zhang et al. 2007). A complicating factor is that the temporal dynamics of ecological processes do not always align with the temporal scale of human decision-making. For example, land management to promote 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 to examine how social and ecological systems interact. While agriculture influences both human and ecosystem well-being, production 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) (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 agroecological research has increased our understanding of how diversification practices affect ecological and financial outcomes (Rosa-Schleich et al. 2019), an integrated approach requires a consideration of the feedback loop between adoption of a given practice, resultant ecological outcomes, and future investment decision landscapes. 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.

Computational approaches to explore structural attributes of human-environment systems can illuminate core dynamics, suggest levers of change, and highlight important assumptions to explore empirically. However, 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 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 agroecological 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 within either the human or natural system, but simply the rates at which the two systems interact over time. 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 suggest 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 farmer'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

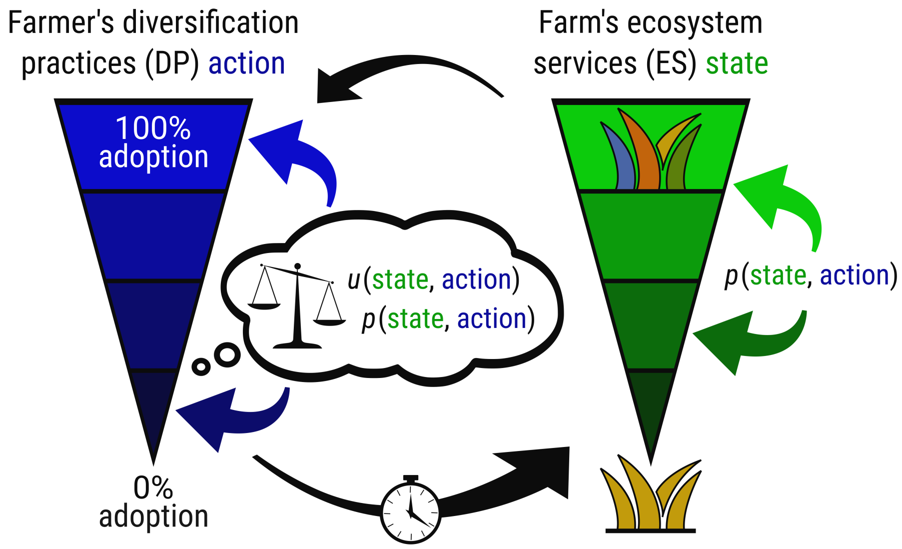

Figure 1: Conceptual diagram of the DFS-MDP model. The farmer's choice of how much to invest (time and/or money) into diversification practices (DP) adoption is shown in blue, and the resulting ecosystem services (ES) state in green, with a more diversified state at the top, and a more simplified state at bottom. Each year t, the farmer evaluates which action they judge to have the highest expected utility based on the perceived utility function (u) and the ecosystem state transition probability function (p). (p) describes how, for a given state and action at year t, the ecosystem responds stochastically at year $t+1$. The updated ecosystem state then feeds back to influence the farmer's future choices. This leads to complex tradeoffs arising from the coupling of ecological processes with the series of DP adoption decisions made by the farmer.

action strategy for each state, called π, 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. We conduct 500 runs, with agents' initial ecosystem states distributed normally around a mean of $\bar{s} = 0.5$. Fig 2 shows that, after having followed the decision strategy 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. Over time, this results in the bimodal distribution of ecosystem states 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-managment-practice adoption has been increasingly scrutinized. 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

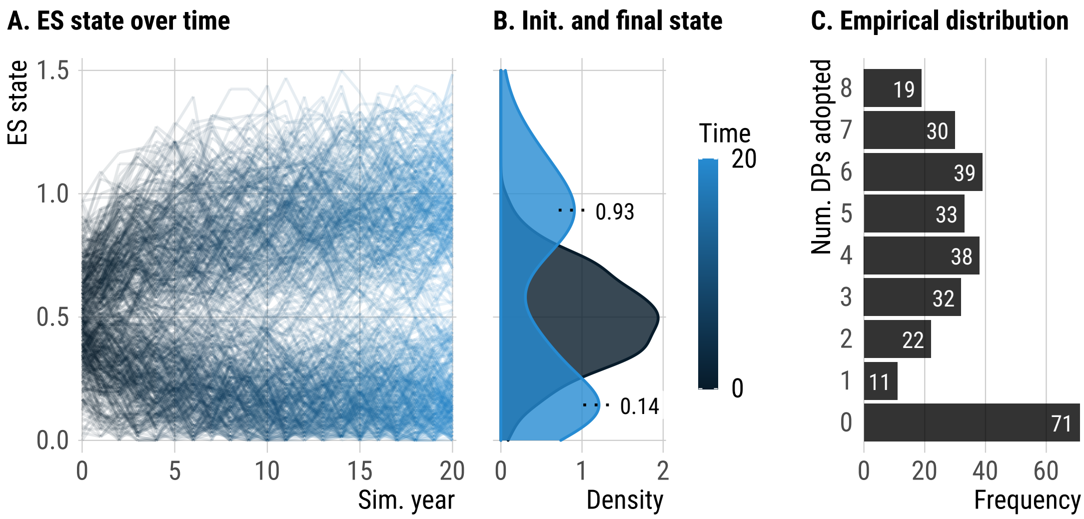

Figure 2: Simulations of 500 model agents over 20 farming seasons. Initial ES states follow a truncated normal distribution (mean = 0.5; S.D. = 0.2; truncated at [0,1]). Agents then utilize decision strategy π as shown in Fig 3 until $t = 20$. (A) State of each agent throughout each run. (B) Initial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

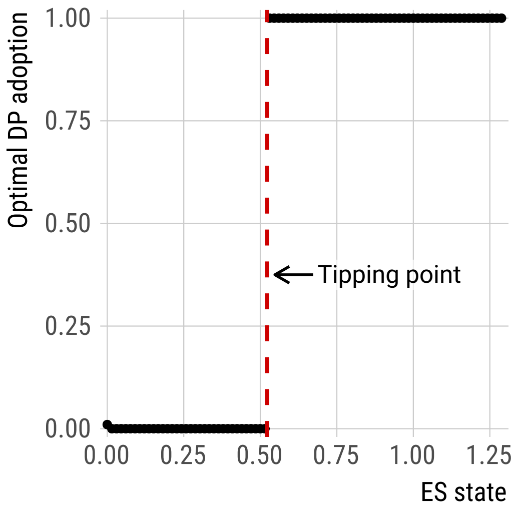

Figure 3: Optimal decision strategy π as a function of ecosystem state, showing a tipping point at $s \approx 0.52$. The upper x axis limit is the 99th percentile of observed states in our simulation results ($s \approx 1.23$).

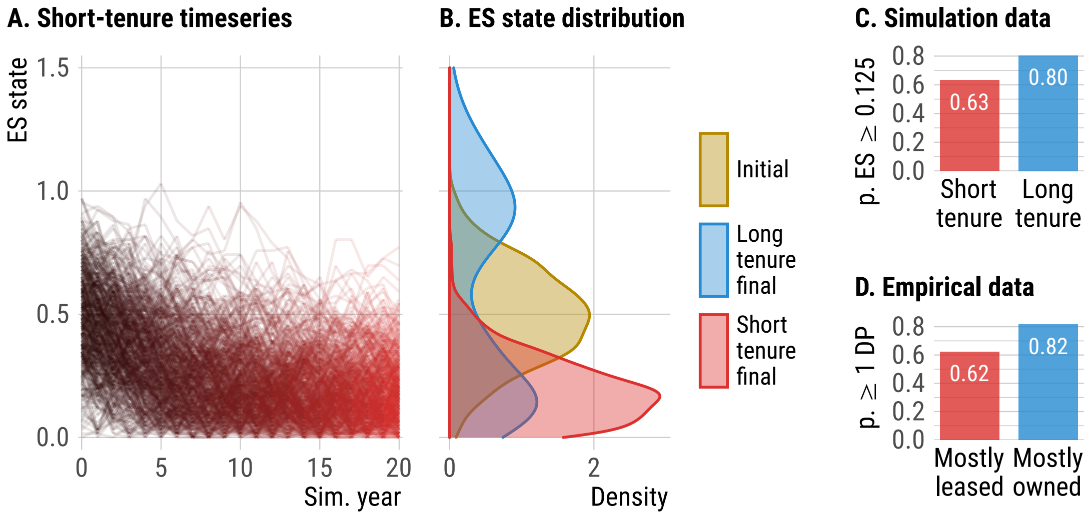

Figure 4: (A) Result of short land tenure on DEP adoption. The simulation is identical to that in Fig 2, but the MDP is solved under a finite, two-year time horizon. (B) Comparison between final state distribution of short- vs. long-tenure model runs. (C) Probability of ecosystem services state being ≥ 0.125 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.

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 produce 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 (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, it becomes optimal to curtail investment into diversified practives. 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 results echo empirical findings from a recent large-scale survey of U.S. west coast produce growers, which show that farmers who lease land are roughly 20% less likely to invest in at least one diversification practice.

Agroecological incentives

While land tenure is intertwined with land use decisions, agricultural incentives 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 incentives and subsidies have a range of goals, one of which is the promotion of sustainable management practices. We explore the impact of incentive duration on policy efficacy by implementing 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 offests the transition cost. Within the model, agents adapt their decision strategy 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 5 shows that longer, more sustained incentive programs may be more effective at nudging behavior over the critical threshold toward more sustainable systems. Comparing the subsidy simulations to the base

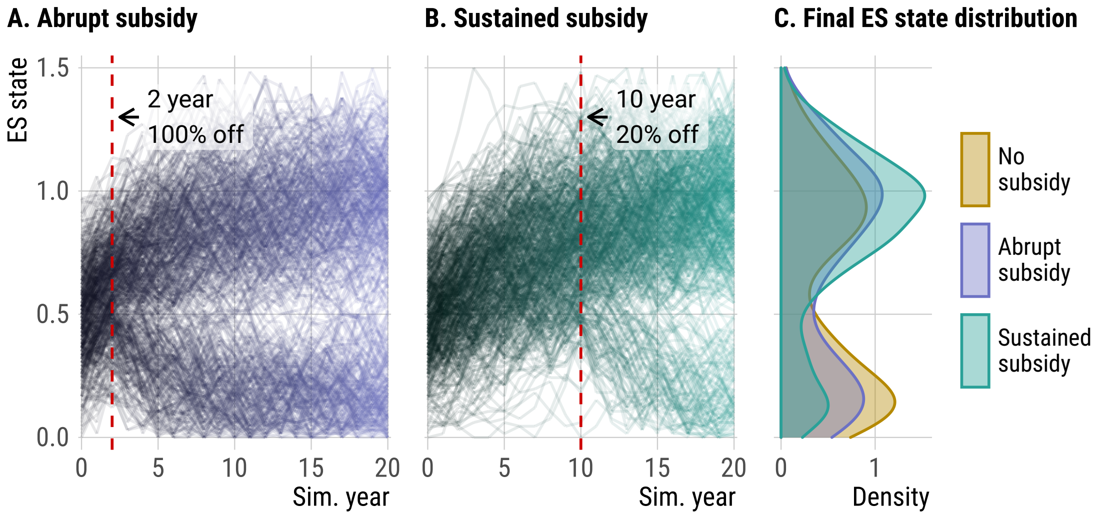

Figure 5: Replicate simulations from 500 normally-distributed starting states (mean = 0.5; S.D. = 0.2; truncated at [0,1]) over 20 timesteps. (A) Large, abrupt subsidy (100% of adoption expenses are covered during the initial two years). (B) Smaller, more sustained subsidy (adoption cost is 80% of baseline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

case, non-subsidy results, we find that, while both incentive packages worked to some extent, the sustained incentive was much more effective at moving the needle. Due to the tipping point dynamic, 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. Since ecosystem state change in the model is somewhat stochastic, as it is in real-world ecosystems, it may take a series of investent actions over several years before the ecosystem reacts. Due to this time delay, longer-term subsidy packages have a higher chance of nudging behavior beyond the critical threshold, ultimately resulting in more agroecological practice adoption.

Importance of temporal dynamics in coupled system trajectories

Our model shows how a simple coupling of human choices and ecological response can result in bistable landscapes of high and low diversification practice adoption. Importantly, these bistable dynamics disappear when the human and natural systems are decoupled. To explore this, we incrementally sweep through different cost/benefit ratios and examine the effect on final ecosystem state distributions. We chose the baseline cost/benefit ratio value to highlight the bistability dynamics that can emerge in the model. As the ratio grows, at some point the decision strategy favors full investment into DPs, and conversely, a sufficienly low ratio will result in no DP adoption.

Fig 6 shows that, with human/environment interaction, there exists a region of cost/benefit space within which various bimodal ecosystem state distributions emerge. However, when ecological processes become fast enough that the ecosystem esentially responds immediately to farmer actions, it becomes impossible to parameterize the model's cost-benefit ratio to result in alternate stable states. Similarly, as decisions become temporally-myopic, the potential for bistability within the model also disappears. Only when both a gradually changing environment and a forward-looking decision making agent are coupled do tipping point phenomena emerge in decision strategy, leading to alternate stable diversification states.

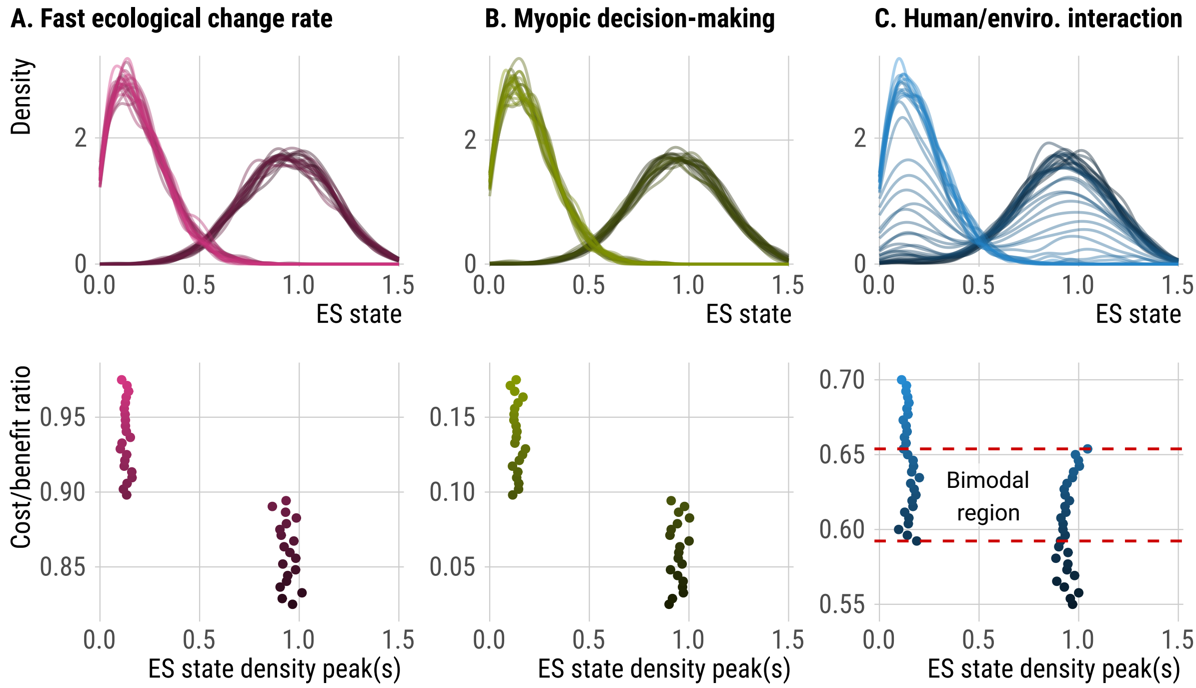

Figure 6: For each scenario (fast ecological process, temporally-myopic decisions, and coupled system), cost/benefit ratio was varied incrementally over 40 values, indicated by color shade, across a range of width 0.15 encompassing the transition between a "never invest" to an "always invest" policy. For each $c : b$, replicate simulations were conducted from 500 normally-distributed starting states (mean = 0.5; S.D. = 0.2; truncated at [0,1]) over 20 timesteps. Upper plots show density curves of ES state at $t = 20$ for each $c : b$. Lower plots show values of density curve peak(s) for each $c : b$. (A) With fast ecological change rate ($r = 0.95$), no bimodality is seen. (B) With a short-term decision strategy (solving the MDP over a 2-year time horizon), no bimodality is seen. (C) Only when both forward-looking decision making and a slowly-adapting environment are included do complex features such as bimodality emerge.

Discussion

In light of historical agricultural catastrophes like the Dust Bowl, the importance of swift policy 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 diversification practice adoption, yet designing effective policies has proved challenging [CITE]. Existing case studies emphasize that policy mechanisms designed to promote agricultural sustainability have complex ramifications across various contexts (IPES-Food 2018). Policies must take into account the possibility that farmers might vary in their management capacity and decision-making behavior in part because they encounter thresholds at which particular farming practices become more or less viable. Critical to designing effective incentives is a better understanding of how these thresholds emerge.

Because agroecological practice adoption is often characterized by uncertainty and a time delay before beneficial effects are realized (Carlisle 2014; Long et al. 2017), thresholds such that farmers on one side of this tipping point are drawn to more simplified agriculture, and farmers on the other side are attracted to more diversified agriculture. These are alternate stable states can lead to strong path dependency. For example, a farmer who begins with degraded land is more likely to transition even more toward relying on simplified management practices, while a farmer who begins with well-cared-for, fertile land is more likely to be able to adopt management practices that maintain and improve functional diversification. Nonetheless there may be a critical period during the tipping point where farmers could still find ways to move across the threshold in either direction, by acquiring (or losing) resources to help them change their state.

Our analysis suggests a mechanism for bistability in the adoption of agroecologiical practices that is not the result of complex structural assumptions about either the ecological and human system. In representing agriculture management as a dynamic coupled human and natural system, we find that the empirically-observed bistability in diversification practice adoption may be the result of tipping points in the optimal sequential decisions of forward looking agents in systems with slow ecological dynamics, rather than tipping points inherent in the ecological dynamics themselves, or in the cognitive/social predispositions of human agents. While the concepts of alternate stable states and tipping points within agricultural systems has been previously explored (Vandermeer and Perfecto 2012), our results cast light on several core mechanisms that help to explain this phenomenon, suggesting novel considerations for policymakers as they strive to enhance the sustainability and resilience of agricultural production systems.

Given this finding, we suggest that a key intervention that policymakers interested in promoting adoption of diversified practices can take is to focus on supporting farmers' transitions within the critical window from the simplified to the diversified state by opening space for viable intermediate states that enable farmers to accrete enough resources to "stick" on to the diversifying pathway.

Incentive programs can reduce costs or change cost structures, however our model suggests that the temporal component of decision making is imporant for shifting diversified practice adoption. In our simulations, a ten-year subsidy was more successful in moving farmers who started in the simplified ecological state to the diversified state, compared to 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 barrier between the two stable states represents a precarious economic position, if a subsidy is not guaranteed for a long enough period to get significant benefits from the ecological feedbacks, the farmer may be incentivized to simply continue in their simplified state. With U.S. Farm Bills being overhauled every five years, 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 (Jackson 2009).

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). For example, land owners or long-term lease holders have a larger 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 may be 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. If farmers maximize their expected utility on a short time horizon, there is a strong incentive to disinvest in diversification practices. Further,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 interest loans, or promoting stable farm succession plans, may therefore represent a key lever to nudge farmers toward more agroecological systems.

Several limitations of this model should be considered. We do not draw distinctions between diversification practices that have different cost structures. Additionally, our model does not capture market dynamics resulting from feedbacks between production and consumption, amd 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 or deleterious environmental effects that spillover from neighboring farms. However, we feel these can all be integrated into the current framework and offer potential avenues for future research.

Importantly, our analysis suggests a novel approach to studying diversified farming as a coupled human and natural system. Specifically, we show that complex system behaviors like tipping points can emerge purely from the temporal rate of feedbacks between human decisions and corresponding ecological processes. 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 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 ($T \to \infty$ if the farmer owns the land or has a long lease).

Table 1: Baseline parameter values

Parameter	Value
Benefit b	1.56
Cost c	1.00
State transition noise σ	0.1
State response rate r	0.1
Discount factor γ	0.97

We assume a simple model of the farmer's perceived utility, $u(s_t, a_t)$, as a function of the costs c_a associated with diversification practice investment action a_t at time t, versus benefits b_s derived from ecosystem state s_t at time t:

$$u(s_t, a_t) = b_s s_t - c_a a_t$$

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 mangement 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.

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

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%

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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