Tipping points in sustainable agriculture adoption

2020-02-15

**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.

**Introduction:**

Both ecosystems and social systems have been observed to abruptly change states as the result of crossing a critical threshold, or “tipping point”. Theories of ecological multistability have long described this phenomenon and explored how ecological management impacts stability landscapes , with underlying tipping points assumed to stem from ecological processes such as?. Similarly, examples from social science suggest that tipping points in human systems may result from the collapse of societies , or through social networks dynamics such as the spread of innovations . 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 processes or natural phenomena alone.

Empirically exploring tightly coupled dynamic systems to better understand the causes and consequences of regime shifts presents numerous research? challenges . Human decisions impact ecological processes and the resulting changes create feedbacks that alter the scope and efficacy of future decisions . Management decisions can enhance or degrade ecological services that affect the long-term productive capacity of the land base and impact future financial returns . 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 a fundamental driver of anthropogenic ecological change , providing a valuable context for examining how social and ecological systems interact. While agriculture influences both human and ecosystem well-being, farming practices differ 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 research? approaches which consider both human decision-making and ecology as a coupled human and natural system (CHANS) .

Here we focus on Diversified Farming Systems (DFS), which use agricultural practices that promote beneficial biodiversity and bolster ecosystem services, enhancing farm- and landscape-scale productivity . While existing DFS research has improved our understanding of how diversification practices affect ecological and financial outcomes, an integrated approach requires consideration of feedback loops between adoption of a specific practice, resulting ecological outcomes, and future investment decisions. An integrated CHANS approach provides a framework to analyze 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 variables), or explores complex ecological processes without sufficiently considering the role of adaptive human agents . Further, those techniques that do investigate dynamic processes and responsive decision-making do not generally allow for forward looking agents , ultimately misrepresenting the complex coupling of these systems.

This paper presents a stylized coupled human and natural systems model of how farmers decide to adopt diversification practices to explore the complex dynamic 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 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.

**Model Setup:**

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 (). In this case, the agent represents a single farm unit, run by a farmer or farm manager. 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, Tab1 ), 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.

***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()*

**Results:**

Using the model described above, we observe the behavior of agents’ sequential choices and resulting environmental outcomes over time. Agents’ initial ecosystem states are distributed normally with a mean at . Fig shows that, after having followed policy for nine timesteps, at 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 () state concluding in a diversified () state, and only 7% of runs initially in the diversified state transitioning to simplified.

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 \pi as shown in Fig  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 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 as shown in Fig 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 (light blue), with peaks annotated. (C) shows the observed bimodal DP adoption distribution in our survey data.

The decision policy 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 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 .

Optimal decision policy \pi as a function of ecosystem state. The upper x axis limit is the 99th percentile of observed states in our simulation results (\approx 1.23).

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

*Land tenure*

With 39% of U.S. farmland under leases , and with widely-varying rental agreements, the impact of land tenure on farming practice adoption is being increasingly examined. 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 . A study conducted in British Columbia found that tenant farmers planted fewer perennial crops than land owners . 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 .

Using the same parameters outlined above, we ran the decision model on a finite, two-year time horizon, representing the shorter window within which many tenant farmers make decisions (Fig ). 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 narrowly and farmers face strong incentives to severely limit investment into diversified practives. This results in a degradation 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 practice.

(A) Result of short land tenure on DEP adoption. The simulation is identical to that in Fig , 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 \geq 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.

**Figure 4:** (A) Result of short land tenure on DEP adoption. The simulation is identical to that in Fig , 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 at 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.

*Subsidy structure*

While land tenure status is intertwined with farming decisions, government subsidies have also become central to farming over the past half-century. Policymakers are continually called upon to weigh farm viability against food affordability and environmental sustainability when designing effective subsidy packages . Using a model run of 20 seasons, 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 (10-year) subsidy which only marginally offsets the transition cost. Formally, the cost of each subsidy package to the government is equal, and the short-term subsidy is technically more valuable if economic discounting is applied. Within the model, agents adopt their decision policy during the subsidy period, and at its conclusion they revert to subsidy free decision rules.

Fig shows that longer-running subsidies may be more beneficial to nudge behavior over a critical threshold toward more sustainable systems in the long-term. Comparing these experimental results to those in Fig , 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 influencing agent decision-making. 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 playing a major factor in any model run, as well as in? the real world, longer-term subsidy packages have a higher chance of nudging behavior beyond the critical threshold.

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.

**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 .

**Discussion:**

Recent research in complexity theory highlights the importance of understanding nonlinear behaviors within dynamical systems. For example, when pushed beyond some threshold, a system may suddenly shift to a different state, potentially irreversibly. This can occur even if human decision-makers take powerful countervailing actions to manage the system. Systems may also be capable of shifting to multiple alternative states that are all stable; but which particular state actually materializes may not be easily predicted. Such dynamics have been observed empirically across a wide variety of coupled human and natural systems. The identification of effective policy measures to manage change in these systems has been described as a “wicked problem” that often confounds traditional analytical methods because the change happens unpredictably .

While much agricultural management research continues to rely on traditional disciplinary approaches (e.g. sociological and agronomic fields), researchers are increasingly experimenting with novel computational methods like agent-based modeling, network analytics, and machine learning to try to capture this systems behavior . Yet these tools still often rely on predefined and fixed decision rules, removing the dynamic and responsive nature of agent decision-making, and thus limiting the capacity to explore levers of change that stem from interactions between adaptive agents and a changing environment. Our work attempts to model agent decision-making as interactive… [fill in].

In 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 tipping points inherent in the ecological dynamics themselves, or in the cognitive/social predispositions of human agents. The model we present here represents a simplified and stylized version of feedbacks between human decision-making and ecological processes, but shows that complex dynamics can arise as a direct result of human-environment interaction. While the concepts of alternate stable states and tipping points within agricultural SESs has been previously explored , our experimental 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.

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 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 . 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 incentives is a better understanding of how these thresholds come into play.

Because agroecological practice adoption is often characterized by uncertainty and a time delay before beneficial effects are realized , we find a broad threshold 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 that 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.]

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.

In this context, certifications like the organic standard, which offer market benefits from higher food prices, may be critiqued as being binary in nature, leading to unintended consequences. Organic certification stipulates allowable inputs rather than strategic management of soil health; and producers are either (1) certified or (2) not certified, even if the ways in which they can implement organic agriculture is heterogeneous . Our work suggests that emphasizing policies that reward adoption of individual sustainable practices and gradually encourage their combination together, rather than a fixed 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 status is an often-cited decision factor that influences the likelihood of diversified agricultural practice adoption . Land owners or holders of long-term lease agreements have a personal stake in the productive quality of their soil ecology, and they are more likely to invest in practices that will benefit them years down the line. Inversely, growers who are uncertain whether they will 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 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 that might reduce their production output and income in the short term. 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 for farm purchases, or promoting stable farm succession plans, may therefore be a key intervention to nudge farmers toward diversified systems.

Subsidies are a fundamental part of modern agricultural policy, through direct payments, or, under more recent farm bills, heavy subsidization of crop insurance premiums . We show that a given quantity of taxpayer funding will more effectively move farmers toward DFS if it is guaranteed over a long period rather than being offered as a lump sum over a short period. 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 program 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, farmers will be incentivized to simply continue in their simplified state. With U.S. farm bills being reworked every five years or so, a farmer may have limited confidence that a critical subsidy program will be sufficiently long-lived, adequately funded, or accessible. This suggests that a policy intervention is to make decade-long grants available for diversified farming practices that extend between successive farm 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 is a vector with a lower bound of 0, and a soft upper bound of 1, with the system state representing the degree to which the agent derives ecosystem services benefits 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 defining the rate at which the ecosystem responds to change. While agents may stochastically transition to , investments into diversification practices do not positively correlate with the probability of upward state transitions beyond .

The action space is a continuous vector from 0 to 1, with representing no investment of resources into DP adoption and maintenance and representing the highest conceivable level of investment. Investment in diversification practices incurs costs , 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 corresponds to a single growing season. At each time step, the agent chooses an action based on their current state by following decision policy . is calculated by maximizing expected utility for each state/action pair over the full time horizon using a Stochastic Dynamic Programming (SDP) approach , with the discount rate determining how much the agent values current rewards relative to future rewards.

***Model mathematical description***

The farmer’s decision model can be expressed as

where is the set of available actions to be taken at each point in time , is the discount rate, the expectation operator, and the utility which the farmer associates with being in state and taking action at time . is the land tenure of the farm ( 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 as a combination of the costs associated with the diversification practice investment action and the benefits derived from the ecosystem state (which is in turn influenced by the practices adopted)

The ecosystem state is also dynamic, evolving according to the transition probability function :

This provides a minimal state transition model in which the parameter sets the natural timescale at which the ecosystem can respond to a change in mangement practice, and 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 ) 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 not showing up…)

***Field observation 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 small sample. We then test hypotheses using results from a large-scale survey.

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.

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 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 B) 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 B shows that owners in our sample are about 20% more likely than leasers to invest in at least one diversification practice.