Tipping points in diversified farming systems

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Abstract

The emergence and impact of tipping points have garnered significant interest in both the social and natural sciences. Despite widespread recognition of the importance of feedbacks between human and environmental systems, it is often assumed that nonlinearities in coupled social-ecological systems are the result of dynamics in either the underlying human or environmental processes, rather than their interactions. Using the adoption of diversified farming practices as a case study, we show how bistability in ecosystem states and corresponding ecosystem services can emerge purely from the temporal feedbacks between human decisions and ecological responses. Our approach to coupling ecological and human dynamics captures two obvious but often-overlooked assumptions about underlying dynamics. First, farmers' actions reflect an ability to plan for the future and not just react to current circumstances; and second, many diversified practices provide ecological benefits that accumulate gradually or with some delay. Previous work tends to ignore either planning ahead (e.g. agent-based models) or the slow timescale of ecological benefit accrual (e.g. economic models). Using a Markov Decision Process, we show that together, these two features create bistable dynamics that both explain existing patterns and show how understanding the temporal mechanisms of tipping points in social-environmental systems is critical to designing effective policy interventions for sustainable agriculture.

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

Introduction

Both ecosystems and social systems can change states abruptly as the result of crossing critical thresholds. These critical thresholds (a.k.a. "tipping points"; states of a system where small perturbations can trigger large responses), have garnered extensive academic and public attention (1; 2). Theories of ecological

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multistability have long described tipping points (3; 4) and have explored how land management impacts the stability of ecological systems (5). Tipping points in these ecological systems are generally assumed to stem from complex internal processes like population dynamics or species interactions (6; 7; 8). Similarly, examples of tipping points in social systems, ranging from the collapse of civilizations (9) to the spread of innovations through social networks (10), suggest that observed nonlinearities in social systems result from complex features of human decisions and social connections (11).

In social-ecological systems (SES), human actions impact ecological processes, and the resultant ecological changes create feedbacks that alter the scope and efficacy of future human actions (12; 13; 14). These coupled systems become increasingly complex when the dynamics of ecological processes do not align with the temporal scale of human decision-making (15). For example, in agricultural systems, ecological responses to biodiversity-promoting management practices (such as buffer strips or hedgerow restoration) happen slowly, taking years to return ecological benefits that exceed investments (16; 17).

Modeling approaches previously used to investigate dynamic ecological processes and land management choices in SES have mostly overlooked the temporal complexity of decision-making and environmental response (18). For instance, agent-based models are commonly used to explore complex emergent phenomena, but these models often use decision rules based on the static system state rather than decision strategies that maximize expected rewards over longer time horizons (18). Similarly, models that rely on equilibrium analyses, such as dynamic equations, make exploring both the time horizon of decisions and gradual response of ecological processes impossible. On the other hand, economic models, which often explicitly consider the time horizons of decisions, typically overlook ecological delays (CITE).

While variations of the above models have been used to explain and explore tipping points in numerous SES, from coral reefs to climate (19;20), we focus here on agricultural systems. Agriculture is a fundamental driver of anthropogenic ecological change (21; 22; 23), and it is closely intertwined with ecosystem processes that provide valuable ecosystem services. While adoption of sustainable farm management practices undoubtedly encompasses a continuum of actions and outcomes, suites of practices are often used together in a package, coalescing around distinct stable states or "syndromes" (24; 25; 11). To explain why these multistable patterns emerge, one must face the aformentioned issues. The mechanisms commonly used to explain complex outcomes in agroecological systems rely on the assumption that both ecological (or production) and decision (or economic) dynamics are non-monotonic. If either of these systems is approximated as monotonic in a coupled dynamic equation, the overall social-ecological system will trend toward a single stable point (or no stable point), making alternative syndromes of production impossible to explain with dynamic equations (11;

26). While non-monotonic assumptions may well be reasonable in some contexts (CITE), these equilibrium explanations overlook the temporal component of both the ecological and decision processes central to agricultural SES.

Markov Decision Processes, most often used in optimal control problems, provide a convenient mathematical framework for modeling decision making in situations where outcomes are stochastic but partly under the control of a decision maker, as well as situations where both environments change slowly and decisions are forward looking. While these methods have been widely used in a variety of environmental control problems (CITE), they have largely been ignored in modeling and exploring the dynamics of agricultural social-ecological systems. Such models provide a simple way to represent how farmers "plan for the future" and how their plans interact with a slowly evolving, stochastic ecosystem process.

This paper presents a stylized model of the adoption of diversified agricultural practices, or practices that bolster environmental health by promoting beneficial agrobiodiversity (27), to explore the ecosystem service patterns that result specifically from interactions between adaptive decision-making and an ever-changing environment. Using a Markov Decision Process model, we explore how bistability, or the tendency for the system to fall into one of two prevailing ecosystem states, can emerge without complex structural assumptions within either the human or ecological system, but rather from the rates at which the two systems interact. While our model necessarily simplifies both decision-making and environmental processes, it provides a novel framework to explore emergent properties in social-ecological systems. We use farmer interview data to inform important structural attributes of our model and to contextualize our findings. Finally, we show that our findings have important implications for agricultural policy implementation and social-ecological systems theory.

Methods

We explore the transition to and from diversified farming systems (low and high ecosystem service states) using a Markov Decision Process (MDP) in which a farmer makes a series of decisions about whether or not to employ diversified farming practices over time (Figure 1). In the context of diversified farming systems, diversification practices, such as the use of hedgerows, compost, crop rotation, intercrops, reduced tillage, and cover crops, are distinct from the concept of operational diversification (i.e., simply increasing the range of agricultural goods produced on a given farm). The model was developed through an iterative, collaborative process with an interdisciplinary team comprising plant and soil scientists, agricultural economists, ecologists, social scientists, and farmers, with the goal of capturing patterns stemming from the coupled human and natural dynamics of the modeled system.

Interview data

Between February 2018 and August 2020, we interviewed 25 lettuce growers and 17 almond growers from California using a snowball sampling method and referrals. We developed an interview guide with questions that focused on the barriers and motivations for using diversification practices such as cover cropping, planting hedgerows, and diverse crop rotations. We focused on the almonds and leafy greens/lettuce sectors because these are among the most valuable crops in California. We selected interviewees to represent a range of growers (small to large scale; organic and conventional, early to late adopters of diversification practices, family run to corporate management, and direct-to-consumer marketing to wholesale). Interviews were conducted in person or over the phone in situations where in-person interviews were not possible due to farmer schedules or the need to social distance during COVID-19 restrictions. Most interviews were audio recorded and transcribed. If recording was not possible, careful notes were taken to create a transcript. We performed coding for key themes and keyword searches of the transcripts to inform key stuctural attributes of our model and contextulize findings.

Conceptual model description

In our model at each time step the farmer takes an "action" of 0% to 100% investment in adopting or maintaining diversification practices. The "system state" corresponds to the level of benefit derived from the ecosystem services that result from those adoption decisions. While higher ecological states are beneficial, investments in diversification practices also come with higher associated costs (Figure 1 A1). Benefits may be financial, social, ideological, and/or aesthetic, and we approximate that relationship as linear (Figure 1 A2). A greater percent investment in diversification practices corresponds to a greater probability of transitioning to a higher (more beneficial) ecological state in the next decision cycle (Figure 1 A3). The rate at which that ecological response response occurs depends on parameter r, but importantly is never instaneous (Figure 1 A4). By defining parameter values for cost, benefit, transition stochasticity, ecological change rate, and future discounting (Supporting information), we can allow the optimal action strategy for the agent (farmer) to emerge based on expected rewards over either a finite (to represent short-tenure leased farms) or infinite (to represent longer-term leases and land ownership) time horizon (Figure 1 A5).

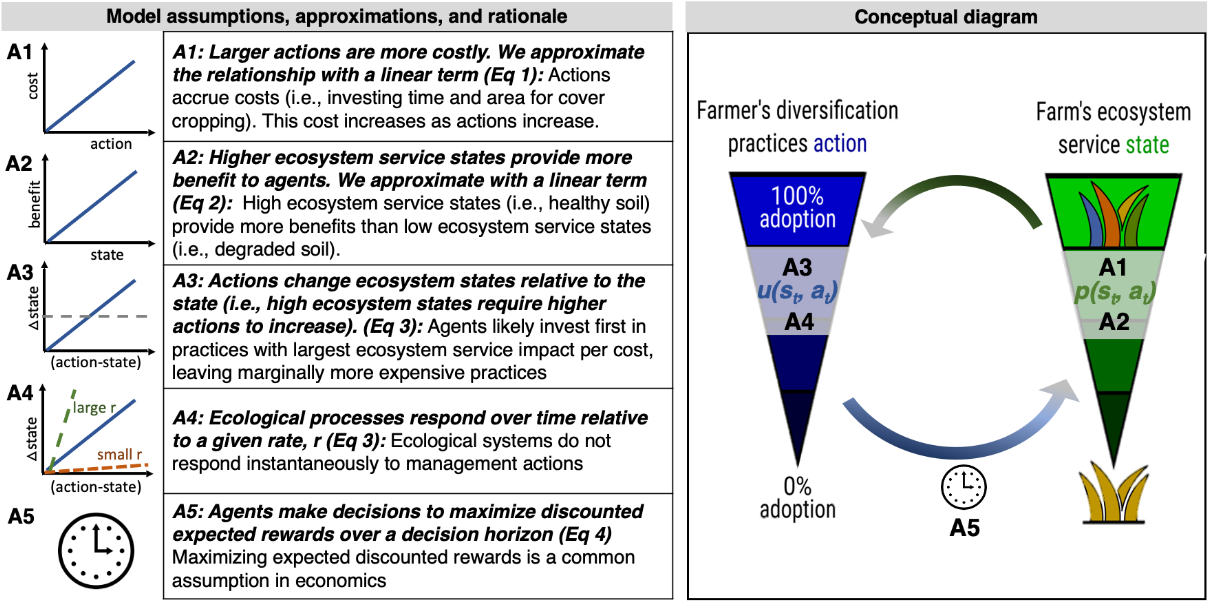


Figure 1: Conceptual diagram and model assumptions. The farmer's choice of how much to invest (time and money) into the adoption of diversification practices (blue), and the resulting ecosystem services state (green), with a more diversified ecosystem state at the top, and a more simplified ecosystem state at bottom. Each time step, the farmer chooses the optimal action for their current ecosystem service state based on the perceived utility function, u, and state transition probability function, p. For a given ecosystem service state and action at time t, p describes how the ecosystem responds stochastically to result in an updated state at t + 1. The updated ecosystem service state then feeds back to influence the farmer's future choices, leading to tradeoffs arising from the coupling of ecological processes with consecutive diversification practice adoption decisions over time. Main model assumptions (A1-A5) are outlined along with a brief rational for each approximation.

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, $\mathbb{E}$ 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, γ the myopic discount factor, and T the land tenure of the farm ($T \to \infty$ 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 difference between the cost c_a associated with diversification practice action a_t, versus expected benefits b_s derived from ecosystem state s_t, at time t, such that

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

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

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

where $\epsilon \sim N(0, \sigma)$. This provides a minimal state transition model in which the parameter r sets the natural timescale at which the ecosystem can respond to changes in land mangement decisions, and σ defines the width of the state transition probability distribution, capturing the noise inherent to ecological system change. 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 perceived utility are possible using this framework.

Parameterization

We have parameterized the model to illustrate the emergence of bistability in SES resulting from agroecological investment decision-making given stochastic ecological responses over time (Figure 1 and Figure 2; Parameter values in Supporting information). We explore a larger parameter space in the supporting information, and explain why the choice of parameters does not change the main findings.

Results

Bistability in ecosystem services

Using the described model, we observe the behavior of agents' sequential choices and the resultant environmental outcomes through time. The decision strategy, π, describes the emergent optimal course of action for a given state and is the stationary optimal state-dependent decision strategy over an infinite time horizon (Figure 2A).

Agents' initial ecosystem states were distributed normally around a mean of $s = 0.5$. We find that after following the optimal decision strategy (infinite horizon) for 20 decision cycles, agents have largely settled into two stable ecosystem states, with some farms transitioning to more simplified (lower levels of ecosystem services) farming systems, and others to more diversified (higher levels ecosystem services) systems (Figure 2B and 2C). 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 a simplified state.

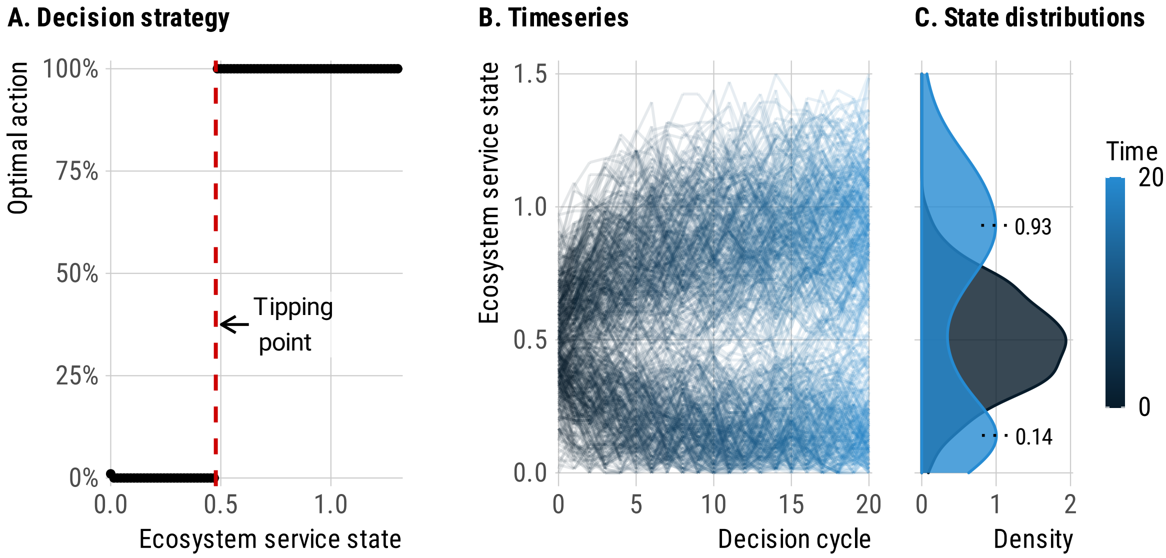


Figure 2: Initial ecosystem states are distributed normally (mean = 0.5; S.D. = 0.2; truncated at [0,1]). (A) Agents follow decision strategy π until $t = 20$. (B) Ecosystem state of each agent over time (500 simulations). (C) Initial ES distribution (dark blue) and final bimodal distribution at $t = 20$ (light blue).

Importance of temporal dynamics in coupled systems

Our baseline model shows how a simple coupling of human choices and ecological response can result in bistable landscapes of high and low diversification practice adoption and, as a result, high and low levels of ecosystem services (Figure 2). By varying the time horizon of the decision process, the rate of the ecological response, and the cost/benefit ratio, we find that this tipping point disappears when the speed of response of either the ecological system or decision-making process overwhelms the coupling (a proxy for decoupling).

Figure 3A shows that with temporal human/environment interactions, there exists a region of cost/benefit ratio within which various bimodal ecosystem state distributions exist (this region is exemplified in Figure 2). However, when ecological processes become fast enough that the ecosystem responds almost immediately to farmer actions ($r = 0.95$), alternate stable states do not emerge, regardless of cost-benefit ratios (Figure 3C). Similarly, as decisions become temporally myopic (in this case, with a time horizon of 2 decision cycles), the potential for bistability in adoption trajectories disappears (Fig 3B). Only when both a gradually changing environment and a forward-looking decision-maker (i.e. a farmer who takes into account potential benefits over the long term) are coupled do tipping point phenomena emerge in the decision strategy (without non-monotonic assumptions), leading to two predominant ecosystem service states (Figure 3). As we observe from our interview data (Figure 4), as well as in extensive farmer decision-making and agroecosystem research, this is often the case in the real world.

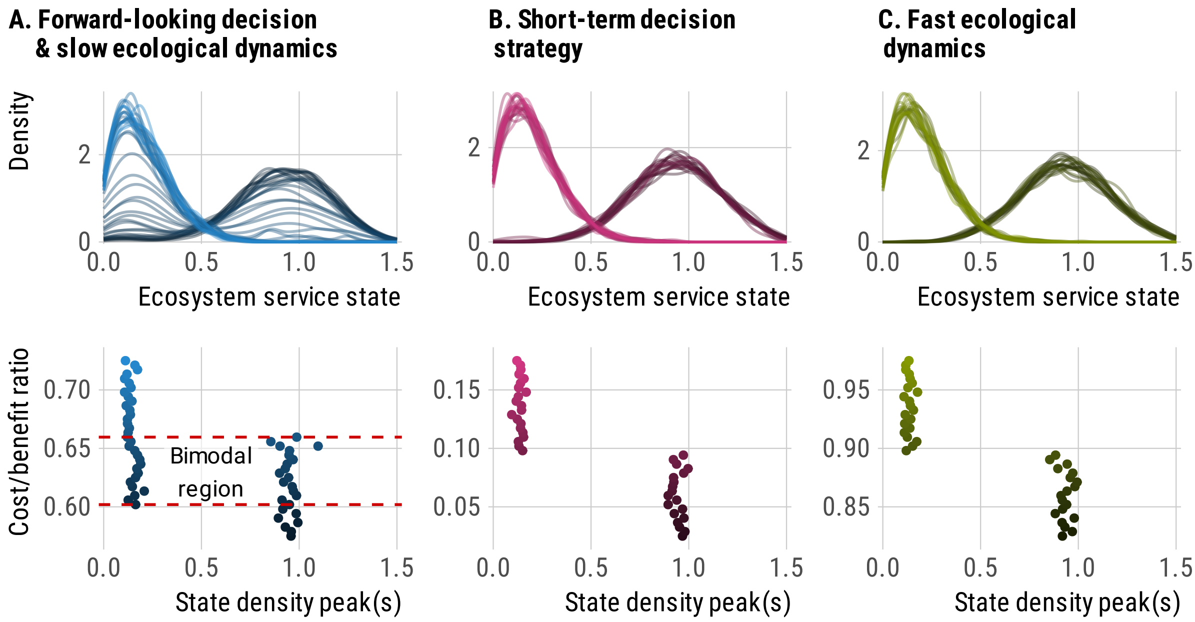


Figure 3: For three scenarios (coupled human/natural system, overly-myopic decision maker, and overly-fast ecological change), cost/benefit ratio was varied incrementally over 40 values, indicated by color shade, across a $c : b$ range of width 0.15, encompassing the transition between a "never invest" to an "always invest" policy. For each $c : b$, 500 replicate simulations were conducted as in Fig 2. Upper plots show distribution of ES state at $t = 20$ for each $c : b$. Lower plots show density curve peak(s). (A) By coupling a forward-looking decision-maker and a slowly-adapting environment, complex dynamics like alternate stable states can emerge. However, with (B) a short-term decision strategy (solving the MDP over a 2-year time horizon), or (C) a fast ecological change rate ($r = 0.95$), no bimodality is observed.

Implications for land tenure policy

While alternative mechanisms to explain a given phenomenon may seem inconsequntial to policy design, we suggest that in the contest of agricultural land tenure this is not the case. Given that long- vs. short-term benefits were central themes emerging from our interview data about adoption patterns (Figure 4), and that approximately 39% of U.S. farmland is leased rather than owned, the impact of land tenure on farmer decision making is important for understanding agricultural management more broadly. For example, U.S. corn farmers who lease land are significantly less likely than landowners to implement grassed waterways, strip cropping, contour farming, and conservation tillage (28).

To investigate this, we solve the MDP on a constrained time horizon (20-decision cycles, in comparison to an infinite time horizon in Fig 2), representing the shorter horizon on which tenant farmers would make economically-rational decisions (Fig 5). Comparing the final state distribution of the long-tenure (baseline) versus the short-tenure model shows that, as a farmer's expected land tenure duration decreases, it becomes optimal to reduce diversification adoption across a wider range of ecosystem states. This results in ecosystem state degradation even among farm sites with an initially high ecosystem service value, with 94% of farmers ending up in the simplified state at $t = 20$. It's worth noting that land tenure itself does not necessarily

Figure 4: Key quotes from farmers suggest that the temporal horizons of decision making and the rate at which farmers recieve ecosystem benefits as a results of those decisions are important factors in the adoption of diversification practices

define decision horizons, since there are numerous factors (i.e. cultural, economic) that might also impact decision criteria (Figure 4).

Temporal dynamics and incentive structures

One benefit of understanding mechanisms of bistability in coupled systems is the capacity to explore how incentives that shift cost-benefit calculations influence management practices. We explore the impact of incentive duration on the efficacy of policies to promote adoption of diversification practices by implementing two competing publicly funded incentive schemes: a short-term (two-time step) incentive which fully covers the cost of adoption, versus a longer-term (ten-time step) incentive which spreads the cost offset of adoption over a longer timeframe. Formally, the cost of each incentive package is equal. In these the model runs, agents adapt their decision strategy based on the cost-benefit ratio during the incentive period, and at its conclusion they revert to the baseline strategy (i.e. without payments).

While one may assume that the 100% cost offset of the short-term scenario would be a stronger incentive, we find that longer, more sustained incentive programs may be more effective at encouraging diversified practice adoption in light of the tipping-point dynamics at play (Fig 5). Due to ecosystem response time, it takes several cycles of investment for a farmer to cross the ecosystem state threshold that makes diversified systems viable, after which it becomes less likely that they will return to simplified systems, even after

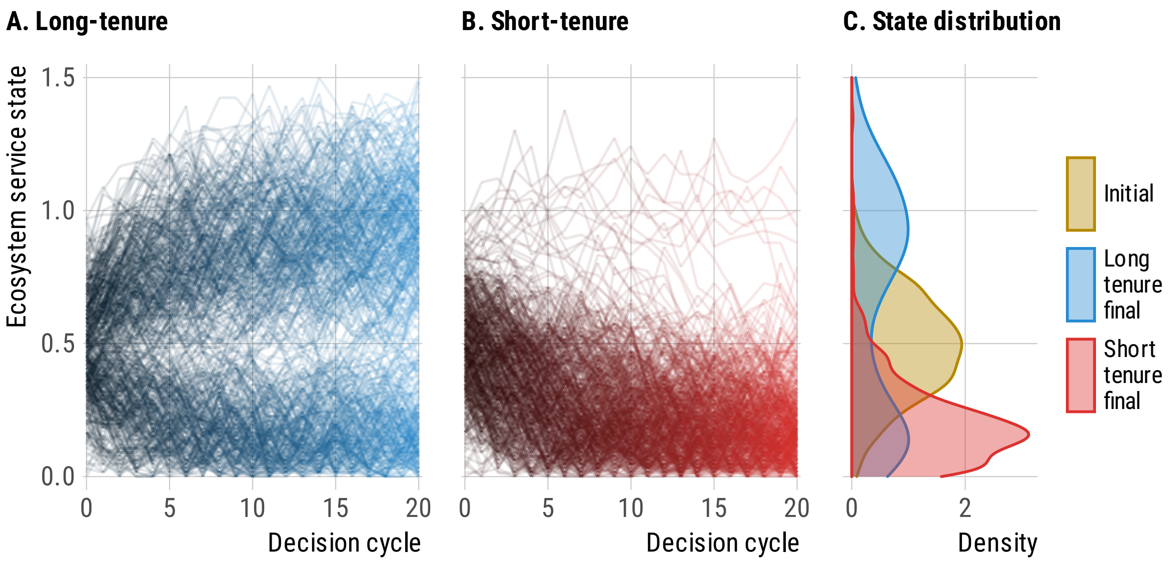


Figure 5: The simulation is identical to that in Fig 2, but the MDP is solved under a finite, 20-year time horizon. (A) Result of short land tenure on ES state over time. (B) Comparison between final state distribution of short- vs. long-tenure model runs.

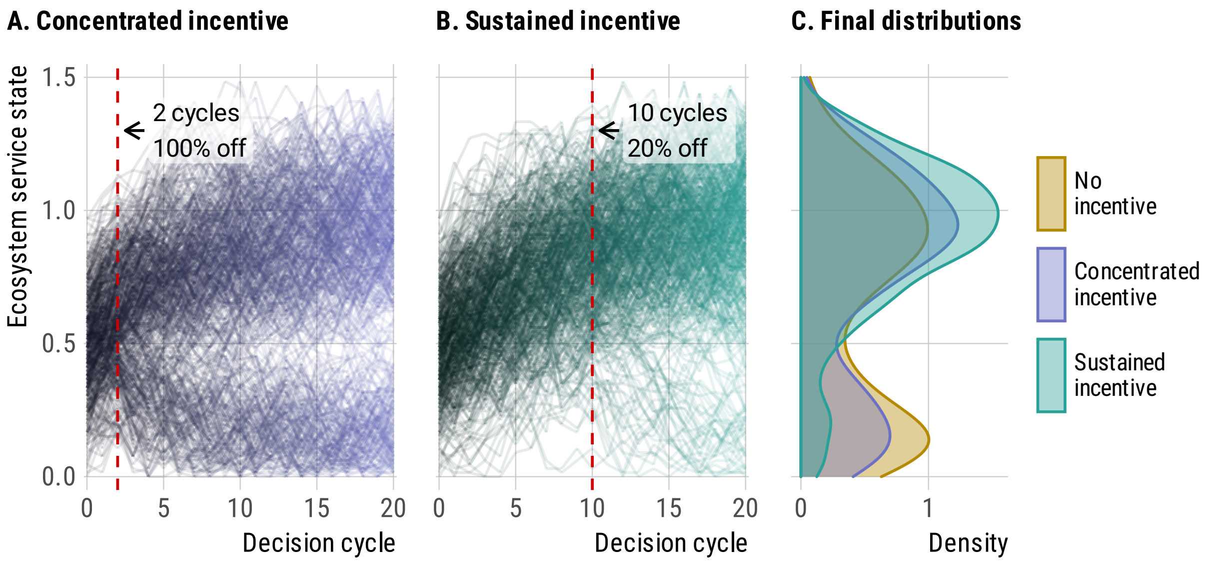


Figure 6: Starting from the same initial states as Fig 2, ES state timeseries are shown for (A) a large, abrupt incentive (100% of adoption expenses are covered for two years) vs. (B) a smaller, more sustained incentive (adoption cost is 80% of baseline for 10 years). Ignoring discounting, both packages have the same total cost to the funder (the equivalent of 2 years' worth of full adoption cost offsets). After the incentive period, agents adjust their decision rules to that of the base case (i.e. no incentive) until $t = 20$. (C) Shows that the sustained incentive ultimately drove more DP adoption.

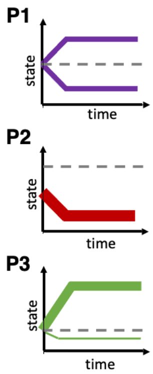
incentives are removed. Because of this time lag, we find that longer-term incentives ultimately result in more diversification practice adoption.

Discussion

Our analysis suggests a mechanism for bistability in social-ecological systems that is the result of temporal interactions between forward-looking decisions and gradual ecological processes rather than complex structural assumptions about either system alone. While alternate stable states within social ecological systems, and farming systems in particular, have been previously explored and observed (29; 30; 31), our results shed light specifically on how temporal feedbacks might contribute to this pattern (Figure 6). We show how path dependency can result in self perpetuating low ecosystem states and low adoption of diversification practives (Figure 2), and why this provides novel insights not only for social-ecological research (Figure 3), but also for agricultural policy (Fig 4 and Fig 5).

In contrast to equilibrium models (31), our model (Figure 1) reflects the delay between adopting a diversified practice and seeing the ecological benefits. For example, soil organic matter and fungal-plant-soil relationships take time to build following investment in the use of compost and cover crop mulch (CITE). This fact was often brought up in our interviews with farmers. One farmer explains: *"Cover crops cost money. And [there is resistance at our company because] some people don't believe they see the benefit right away. That's an internal discussion we try to have [at our company]. I'm for the cover crop. It takes time. It takes time".* The time required to see these benefits influences the adoption patterns seen across short and long term tenants. As another farmer explains, *"We do have hedgerows on several of the ranches, more where we have long-term leases."* Our findings help to show why secure land tenure can impact decision strategies and consequently is integral to increasing the adoption of diversified farming practices. Farmers who hold shorter leases are less likely to decide investing in diversified practices will benefit them, since they may lose their land access, or may have insufficient time to learn how to implement practices on the particular conditions of their farm. This finding complements a larger body of sociological research documenting how security and length of land tenure affects adoption of sustainable agricultural practices (32; 33; 34; 28). Policies that increase land tenure duration, such as regulating lease agreement terms, providing low interest loans, or promoting stable farm succession plans, may represent a key lever to enable farmers to adopt more diversified agroecological practices.

Policies designed to promote agricultural sustainability and ecosystem services by reducing the costs of practice adoption have become an integral part of farming over the past half-century (35; 36). Incentive



Model predictions	Evidence in support of pattern	Value of MDP method
Bistability in ecosystem states (ecosystem services) can emerge without structural assumptions about non-monotonic cost structures and ecological dynamics (Fig 2)	Syndromes of production, or bistable patterns in adoption of agricultural practices, have been both empirically documented and theoretically described (Vandermeer et al., 2012)	The temporal mechanism for bistability leads to different suggested intervention strategies than mechanisms that require nonmonotonic assumptions about individual system dynamics
Decision making over short time horizons decreases investment in ecosystem service promoting activities (Fig 4) and removes bistability as decision horizons become infinitely short (Fig 3B)	U.S. corn farmers who rent land are less likely than landowners to implement grassed waterways, strip cropping, contour farming, and conservation tillage (Soule et al, 2000)	Decision horizons are less intuitive to explore in equilibrium models. Including these attributes of decision making important for understanding the impact of tenure systems.
Longer, more sustained incentive programs are more effective than short term policies at encouraging adoption of practices for which benefits accrue slowly (Fig 5)	***model prediction***	Tradeoffs between incentive duration and magnitude remain unresolved. MDPs allows us to explore these policy scenarios unlike equilibrium models.

Figure 7: Table of the main model predictions, evidence in support of the pattern, value added from the temporal mechanism and minimal assumptions.

policies are particularly interesting to explore with a Markov Decision Process due to their often sequential, but time limited, nature. Incentive policies rolled out over a given time frame are difficult to study with equilibrium analyses or with simple decision rules. Our results suggest that long-term, *sustained* incentives, even when only partially covering the cost of adoption, may be more effective in shifting farmers toward more beneficial diversified ecological states than concentrated short-term incentives (Figure 6 P4). We show that the cost of interventions and the social-environmental benefit of those interventions are not necessarily equivalent. Rather, perceived stability of incentive programs over time may be an important driver of adoption, which would be overlooked if the temporal rates of coupled dynamics in social-environmental systems were not considered. In other words, if farmers expect a stable source of support over a significant time period, they may decide it is worthwhile to experiment and persist with a new practice. Unstable support, by contrast, may lead to farmers abandoning practices after a short time, or even not even trying them out. This finding is particularly relevant to the design of government payment programs and suggests that payments can be highly effective in encouraging adoption of diversification practices (or other ecosystem service promoting practices) when implemented over long time horizons. While policy discontinuation may contribute to the lack of impact for short-term incentives, it is also possible that reduced transaction costs that come with farmers making a longer-term commitment may partially explain the greater impact of sustained incentives as compared to concentrated incentives.

[another paragraph?]

By centering temporal dynamics in a social ecological system model, we offer insights into important agriecological patterns and their implications for policy. We present a flexible model framework that can be built on to address numerous questions in social-ecological systems research and policy design. Expanding the boundaries of the model to include the effect of factors such as agricultural regulations and network structures would expand the scope of questions explored.

[ideally don't end on the limitations, but on the summary. would move limitations up a bit.-sw]

Model implementation

The model was developed in the *R* programming language[37]. The *MDPtoolbox* library was used to set up and solve the MDP[38], *tidyverse* for data analysis[39], and *ggplot2* to generate all figures[40]. Code for our model and the experiments conducted in this paper is available freely at https://github.com/boettiger-lab/dfs-mdp.

Author Contributions:

Conceptualization CB, MC, SW, PB, TB, LC, FC, KE, SG, AI, DK, CK, JL, EO, JO, MR, AS, JT, HW; Data curation: MC, SW, CB; Formal Analysis: MC, SW, CB; Funding acquisition: TB, AI, CK, DK, CB; Methodology: CB, MC, SW, PB, TB, LC, FC, KE, AI, DK, CK, EO, JT, HW; Code: MC, SW, CB; Visualization: MC, SW, CB; Writing – original draft: MC, SW, CB, LC; Writing – review & editing: CB, MC, SW, PB, TB, LC, FC, KE, SG, AI, DK, CK, JL, EO, JO, MR, AS, JT, HW

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