Tipping points in sustainable agriculture adoption

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Abstract

Keywords: diversified practices, ecosystem services

Introduction

Agriculture is among the most fundamental drivers of anthropogenic ecological change [16] and a valuable system for examining core properties of the human-environment nexus. While agricultural increasingly influences both human and ecosystem well-being, practices vary in their environmental impacts, long term sustainability, 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) {cite, cite} .

However, empiracally exploring coupled dynamic processes presents numerous challenges. The temporal dynamics of ecological processes do not always align with the temporal scale of decision making of individual farm units. Further complicating, many ecosystem benefits that result from sustainable farming practices take years to realize, meaning decisions to adopt these practices require decision makers to be foreward looking, adaptive, and considerate of deep environmental and economic uncertainty. While understanding structural attributes and qualitative dynamics of coupled systems can provide valuable information on effective levers of change and important assumptions to explore empiracally, much of the existing literature stands upon simplified representations of decision making or static representations of ecological processes [17]. Those techniques that do present dynamic processes and responsive decision making don't generally allow for forward looking decision agents [8], ultimately misrepresenting the complex coupling of systems that proceed at fundementally different rates, such is the case in many coupled human and natural systems.

Diversified Farming Systems (DFS) employ practices which promote beneficial biodiversity and bolster ecosystem services, enhancing farm and landscape scale productivity and providing net benefits to production [7]. However, the additional costs required to adopt these practices on top of the stochastic nature and slow rate of benefits provided require forward thinking and consistent investments by farmers. Human decisions, such as investment in diversification practices, impact ecological processes and the resultant changes create feedbacks that alter the scope and efficacy of future decisions [11, 18, 9]. Decisions can enhance or degrade ecological services that affect the long-term productive capacity of the land base and the resultant financial returns [21]. For example, practices to reduce topsoil loss and harmful runoff such as riparian buffers and hedgerows require years to providee sufficient ecosystem benefits to offset the costs required for implementation and maintenance [12].

While increasing our understanding of how diversified farming practices affect biodiversity, ecosystem services, short-term profitability, and long-term sustainability, an integrated approach requires a consideration for how those affects alter subsequent decision making. For example, community composition of birds and soil microbes jointly influence food safety through the incidence and suppression of foodborne pathogens, and are impacted by farm level decisions about practices. An integrated CHANS approach to questions about sustainability provides an framework to increase scientific understanding of the potential synergies and tradeoffs of how diversified farming practices affect and are affected by ecosystem processes.

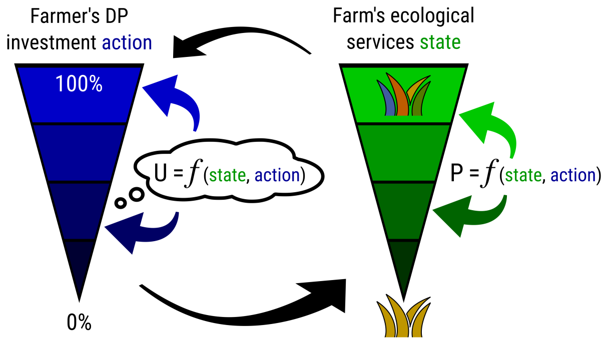

Figure 1: High level conceptual DFS-MDP figure...

We present a stylized coupled human and natural systems model, focusing on adoption of diversified farming practices as a case study. While we do not suggest that our model captures the full complexity of individual decision making nor does it address social dynamics, it does provide a novel framework for integrating empiracle work and exploring emergent dynamics of systems at the intersection of coupled human and natural systems.

Results

(this section still needs some work- I'm struggling with balancing clarity with the relevant amount of detail. . .) We explore the transition to and from diversificattion practices 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. We formulate a 'system state', s, to represent the degree of ecological services derived from an ecological, or farm, state, which provides immediate benefits to the agent At each time step the agent chooses an action from a set of available actions, described by a spectrum from 0% to 100% investment in adopting or maintaining diversified farming practices. More investment corresponds to a greater probability of transitioning to a higher (more beneficial) ecological state. Given the current state and action the environment moves to a higher or lower ecological state with some probability (1), providing the agent a reward, r. However, actions have some associated cost, which is subtracted from the benefit received from the ecological state. The agent calculates optimal action based on their future cumulative discounted rewards over a defined time horizon. The discount factor, γ informs how much the agent values current rewards relative to future rewards and the noise factor, σ represents the stochastic properties of the system.

The time step t corresponds to a single growing season. At each time step, the agent chooses an action a representing the intensity of investment into diversification-enhancing practices. The action space A is characterized by an integer vector from 1 (no investment) to 10 (investing everything possible).

The system state s represents the degree to which the agent derives ecosystem services (ES) such as soil productivity, water infiltration, and climate resilience from the diversification practices they have implemented on their farm at t. The state space S is an integer vector from 0 to 1, with 1 being the maximum possible level of derived ecosystem services benefit.

A probability matrix $P_a(s, s')$ describes the chance that the agent will transition from their current ES state s to some state s', given action a. s may only decrement by one, stay the same, or increment by one at each time step. Higher-investment actions yield a higher probability of transitioning to a higher (i.e. more beneficial) ES state. The shape of the probability curve can be tuned to reflect, for example, diminishing marginal increases in the probability of stepping to the next ES state with each increment in a. At the boundaries of the state space, an action cannot result in a state lower than s_{min} or higher than s_{max}. The agent's reward R is a function of the current ES state s and the chosen action a. As above, depending on

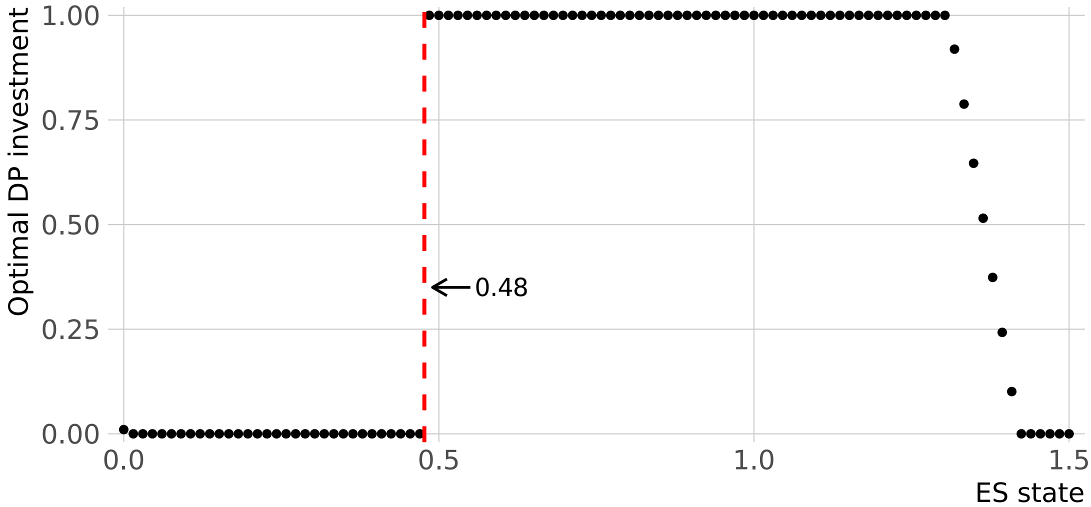

Figure 2: Optimal decision policy π as a function of ecosystem state.

underlying contexts and assumptions, the benefit accrual function can be linear ($s \propto b$), or more complex, for example if we assume diminishing benefit returns as s approaches s_{max}.

Investment in diversification practices also 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. A higher level of investment will obviously result in higher costs, but, once again, we can either assume that c scales linearly with a, or make the relationship more complex as the situation demands. Populating the reward matrix is simply a matter of subtracting costs from benefits ($R(s, a) = b(s) - c(a)$).

The action policy, π, is an optimal course of action for a given state. Fig 2 shows the policy π for an agent investing in diversification practices. We find 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 the result of transition probabilities.

Over time, ecosystem states respond to sequential decisions made by agents 3. Agents' initial ecosystem states are distributed normally with a mean at $\bar{S} = 0.5$. After having followed policy π for nine timesteps, at $t = 10$ we find that agents have largely bifurcated into two groups, with farms in the "simplified" class , and those in the "diversified" class. Further, we find strong path dependency, with only 11% of runs which started in a simplified ($S < 0.5$) state concluding in a diversified ($S > 0.5$) state, and only 7% of runs initially in the diversified state transitioning to simplified.

Land tenure

With 39% of U.S. farmland under lease (USDA NASS 2016 find citation), and with widely-varying rental agreements, the impact of land tenure on best-managment-practice adoption has been increasingly examined in agricultural lands. For example, a study of U.S. corn producers found that cash renters were less likely than land owners to implement grassed waterways, strip cropping, contour farming, or conservation tillage [15]. A study conducted in British Columbia found that tenant farmers planted fewer perennial crops than land owners [4]. 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 [13].

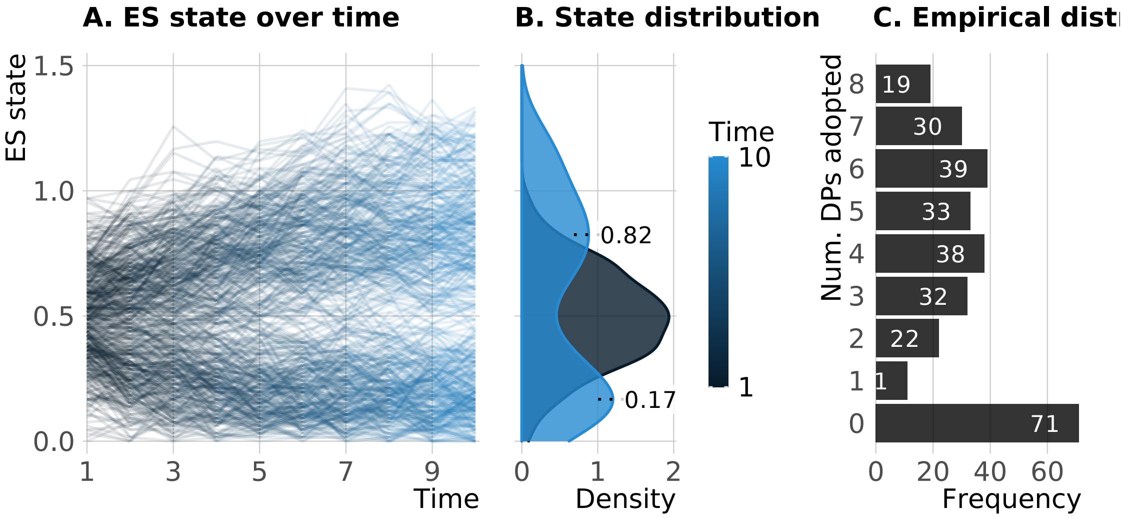

Figure 3: Simulations of 500 model agents over ten farming seasons. Initial ES states follow a truncated normal distribution (mean = 0.5; S.D. = 0.2; truncated at [0,1]). Agents utilize decision policy π as shown in Fig 2 for nine timesteps. (A) shows the state of each agent throughout each run. (B) 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.

Using the same simulation methods and parameters outlined we solve the decision process on a finite, two-year time horizon, representing the shorter window within which many tenant farmers may make decisions. Comparing Fig 4 to Fig 3 above shows that, as length of land tenure or stability of lease agreements decline, optimal decisions are calculated more myopically and farmers are incentivized to severely limit investment into diversified practives. This results in a degredation of ecosystem state even among those plots with an initially high value, with 92% of farmers ending up in the simplified state.

Subsidy structures

While land tenure is intertwined with land use decisions, agricultural subsidies have also become an integral part of farming over the past half-century, and policymakers are continually called upon to weigh farm viability against food affordability and environmental sustainability {>>cite farm bill, etc.<<}. In recent years, climate change, soil degradation, and water use/quality considerations have increasingly pressured agricultural policy optimization {>>cite<<}. Some have suggested that large, short-term subsidies may be more efficacious in nudging farmers toward management systems that effectively weigh these tradeoffs, while others are proponents of long-term, yet smaller subsidies {>>cite<<}. The capacity to explore the impacts of policy in the framework of a sequentially decisions that impact ecological systems allows us to investigate this question in silico.

Using the same initial setup as described above, we implement two competing subsidy structures: a short-term (two-year) subsidy which completely covers the cost of transitioning to a more diversified state, versus a longer-term (ten-year) subsidy which only marginally offests the transition cost. Formally, the cost of each subsidy package to the issuing organization is equal, and in fact the short-term subsidy is technically more valuable if economic discounting is applied. Within the model, agents adapt their decision policy π during the subsidy period, and at its conclusion they revert to base case (i.e. subsidy-free) decision rules.
Fig 5 shows that longer, more sustained subsidies may be more beneficial to nudge behavior over the critical threshold toward more sustainable systems in the long term. Comparing these experimental results to those in Fig 3, we find that both subsidy packages were effective in shifting farmers to a sustained higher ecosystem-services state. However, the sustained subsidy was much more effective at moving the needle. Due to the previously-discussed “tipping point” dynamic inherent in the model, once an agent has crossed the threshold to the diversified state, it becomes much less likely that they will fall back toward the “simplified” state, at least in the short term. With state-transition stochasticity a major factor in a given model run

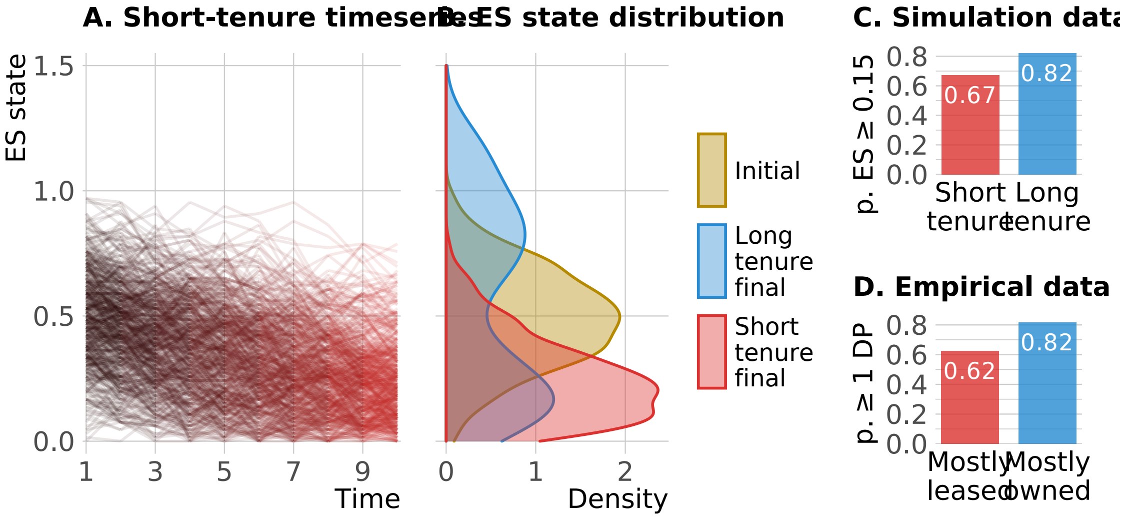

Figure 4: (A) Result of short land tenure on DEP adoption. The simulation is identical to that in Fig 3, but the MDP is solved under a finite, two-year time horizon. (B) Comparison between final state distribution of short- vs. long-tenure model runs. (C) Probability of ecosystem services state being ≥ 0.15 at $t = 10$ for the short-tenure simulation vs. the base-case simulation. (D) Impact of land tenure on the probability of a farmer in our survey dataset adopting at least one DP.

(as it is in the real world), longer-term subsidy packages have a higher chance of nudging behavior beyond the critical threshold. However, as the ecological dynamics increase in rate, which is relevant in analagous contexts of sequentially controlled ecological systems, this effect decreases (create figure for this?).

Discussion

Recent research in complexity theory reveals the importance of understanding nonlinear behaviors within dynamical systems. For example, when pushed beyond some threshold, a system may enter a virtually-irreversible state, driving its behavior into divergent basins of attraction, even given potent countervailing actions on the part of a decision-maker [1]. These types of complex dynamics have been observed empirically across a wide variety of SESs, such that the identification of effective policy measures to effect change in these areas have been described as "wicked problems" that often confound traditional methods of analysis [5].

While much of the research on agriculture has continued to revolve around unidisciplinary approaches, [3], computational methods like agent-based modeling, network analytics, and machine learning have been employed and provided important insights [8, 20, 19]. However, these tools often rely on predefined decision rules, removing the dynamic and responsive nature of agent decision making and planning and with that the capacity to explore different levers of change, such as subsidies, insurance, and land tenure, to those decisions in varying ecological environments.

Representing the coupled human-environmental system as a controlled dynamic system we find that the empirically-observed bistability in the adoption of diversification practices adoption may be the result of tipping points in optimal sequential control, rather than inherent tipping points in the ecological dynamics themselves. The model we present here represents a simplified and stylized version of the feedbacks between human decision making and ecological processes of diversification practice adoption. While the concept of alternate stable states and tipping points within agricultural SESs has been previously explored [17], our experimental results cast light on several core mechanisms that help to explain these behaviors, suggesting novel considerations as policymakers work to enhance the sustanability and resilience of agricultural production systems.

In light of historical agricultural catastrophes like the dust bowl, both scholars and society have called for swift action around stressors like climate change, soil degradation, water quality, and biodiversity loss.

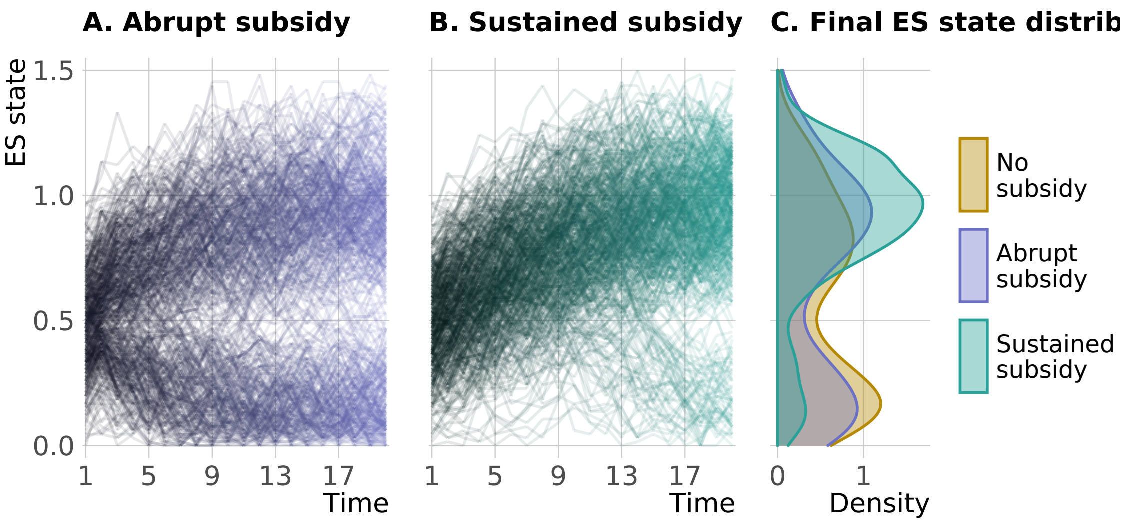

Figure 5: Replicate simulations from 500 normally-distributed starting states (mean = 0.5; S.D. = 0.2; truncated at [0,1]) over 20 timesteps. (A) shows the effects of a large, abrupt subsidy (100% of adoption expenses are covered during the initial two years). (B) simulates a smaller, yet more sustained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

Policymakers have responded by developing programs which offer incentives and support for agriecological practice adoption, yet designing effective policies has proven challenging. Recent case studis emphasize that policy mechanisms designed to promote agricultural sustainability have complex ramifications across various contexts [6]. Critical to designing incentives is an understanding of the thresholds which render a given management practice viable to one farmer while nonviable to another.

While it is well known that many practices that increase ecosystem services can take several years before significant beneficial effects are realized [2, 10]. We find a threshold such that agents on each side of a tipping point are drawn to alternate stable states, one being more simplfied and the other more diversified. This leads to path dependency, whereby a farmer who begins with degraded land is incentivized to transition even more toward the simplified state while a farmer who begins with well-cared-for, fertile land is incentivized to adopt management practices that maintain and improve functional diversification. Given this finding, we suggest that a key lever of change for policymakers interested in promoting adoption of agrienvironmental practices may be to increasingly focus on supporting farmers' transitions within the critical window from the simplified to the diversified state by opening space for viable intermediate states. Given this, binary certifications like the organic standard may be critiqued in some for some of their unintended consequences. Although organic systems often use diversification practices, rules governing organic agriculture stipulate allowable inputs rather than strategic management of biodiversity; and producers are either certified or not, even if the ways in which farmers implement organic agriculture is quite heterogeneous [14]. An increasing focus on adoption of individual practices, rather than a cut and dried standard, may allow for a process of incremental transition, with farmers embedded in monocultural agricultural systems able to move stepwise toward the adoption of diversification practice.

While certification and therefore cost structures are important for adoption tajectories, the impact of secure land tenure is integral to adoption diversification practices. Growers who either own land or have a long lease agreement are incentivized to invest more in the long-term productive capacity of their land, which can result in adoption of agrienvironmental practices that have an upfront cost, yet pay out over longer time horizons. If farmers maximize their expected value on only a two-year time horizon, there is a strong incentive to maximize short-term profits by disinvesting in diversification practices.

Subsidies are a fundamental part of modern U.S. agricultural policy, be it through direct payments, or, under more recent farm bills, heavy subsidization of crop insurance premiums. Our subsidy experiment shows that—all else being equal—a given quantity of taxpayer funding devoted to diversification practices will more-effectively move the needle if it is guaranteed over a longer period rather than being offered as a lump sum. Specifically, we find that a sustained subsidy was successful in moving 43% of farmers who started in the simplified state to the diversified state, whereas the figure was only 24% for the abrupt subsidy. A ramification of this finding is that the perceived stability of suibsidy programs may be important in promoting agrienvironmental practice adoption. Since, as we have seen, the transitional "hump" between the two stable states represents a precarious economic position, if a subsidy is not guaranteed for a long enough period to get over the hump toward DFS, the rational farmer will be incentivized to simply continue in their simplified state. With U.S. farm bills being completely overhauled every five years or so, a farmer may have limited confidence that a critical subsidy program will be sufficiently long-lived, suggesting that a policy lever may be to prolong the sunsetting of any new agrienvironmental subsidy.

Several limitations of this study must 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 farmers' practices. Each of these areas remains a potential avenue for future research.

** CONCLUSION PARAGRAPH** Despite these simplifications, our analysis provides a novel approach to

Methods

Model mathematical description

Mathematically, the farmer's decision model can be expressed as

$$\max_{\{a_t\}} \mathbb{E} \left[\sum_t^T U(x_t, a_t) \delta^t \right]$$

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

We assume a simple model for the farmer's utility $U(x_t, a_t)$ as combination of the costs associated with adopting the diversified practice and the benefits derived from the ecosystem state (which is in turn influenced by the diversified practices or non-diversified practices adopted),

$$U(x_t, a_t) = bx_t - ca_t$$

Where x_t is the ecosystem state, b the benefit associated, and ca_t the cost of taking action a_t. In general, more complicated nonlinear functions of both the ecosystem state and action are possible in this framework.

The ecosystem state is also dynamic, evolving according to the transition function $f(x_t, a_t)$

$$x_{t+1} = f(x_t, a_t) := x_t + r\,(a_t - x_t)$$

This provides a minimal, one-parameter model in which the parameter r sets the natural timescale at which the ecosystem can respond to a change in mangement practice.

Model implementation

Our MDP was developed in R, using the MDPtoolbox library. {>>ETC. . . <<}

Table 1: 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%

Parameterization from field observations and empirical data

To establish the general parameters of our MDP model, our interdisciplinary research team began by exploring empirical evidence about the real-world drivers and distributions of farmers' adoption of diversification-enhancing practices. We take a twofold approach, beginning with qualitative observations of trends within a relatively-small sample, and then testing hypotheses using results from a large-scale survey.

Original interviews

Members of our team 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 DEPs tends to be bimodal; that is, growers are likely to either intensively-adopt many DEPs, or to adopt these practices minimally or not-at-all. This may be explained by factors including limited capital availability to implement those DEPs with high up-front costs, food safety stipulations based on market outlet, risk attitude, and myopic discounting. Land tenure—in terms of both length of time on the land, and whether land is leased versus owned—also appears to be a salient decision factor.

Survey dataset

To evaluate the extent to which these observed adoption distributions hold quantitatively, we leverage a dataset of survey responses from 295 vegetable growers in Washington, Oregon, and California (!!CITE DATA SOURCE!!). Table 1 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 3B) 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.

As discussed above, land tenure has often been shown to be a decision factor that impinges upon agricultural management practice adoption [15, 4, 13, 10]. Growers who have a long-term personal stake in the productive quality of their soil ecology are more likely to 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 be farming a given parcel of land in future seasons may be less likely to adopt practices whose positive effects will not come to fruition in the short term. To investigate the effect of land tenure on DEP adoption, we partition the dataset into growers who primarily own their land versus those who primarily lease it. Figure 4B shows that owners in our sample are about 20% more likely than leasers to invest in at least one diversification practice.

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