Tipping points in sustainable agriculture adoption

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Abstract

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Introduction

Agriculture is among the most fundamental drivers of anthropogenic ecological change [13] and a critical system to examine core properties inherent to the human-environment nexus. While agriculture is increasingly influential to both human and ecosystem well-being, practices vary in their environmental impacts, long term sustainability, and climate resilience. Diversified Farming Systems (DFS), employ practices to promote beneficial biodiversity and bolster ecosystem services that enhances productivity [5]. Ecosystem functions resulting from diversification practices provide net benefits to production {CITE}. However, the tradeoffs between costs and slow enhancement of ecosystem benefits require forward thinking actions. For example, practices to reduce topsoil loss and harmful runoff such as riparian buffers and hedgerows present tradeoffs between benefits from this service and opportunity cost over time [9].

It is increasingly recognized that effective policies to address to environmental issues require interdisciplinary approaches {cite, cite} which consider both human decision-making and ecology as a coupled human and natural system (CHANS). Humans decisions, such as agricultural practices, impact the environment and the resultant environmental change creates complex feedback loops that impinge upon the scope and efficacy of future decisions [8, 15, 6]. While agriculture is often studied through a discipline-specific lens, farm management decisions have profound and complex effects on local ecology and, in aggregate, global processes. These agronomic outcomes in turn enhance ecological services (ES) that affect the long-term productive capacity of the land base and the resultant financial returns [16].

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, in turn, alter 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.

However, empiracally exploring coupled dynamic processes presents numerous challenges in the field. The temporal dynamics of ecological processes do not always align with the decision making processes of individual farmers. Further complicating, many ecosystem benefits that result from sustainable farming practices take years to realize benefits, meaning decisions to adopt these practices are require decision makers to be foreward looking, adaptive, and considerate of deep 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 that are not dynamic or static representations of ecological processes.

We present a stylized coupled human and natural systems model, focusing on adoption of diversified farming practices. (Keep working on this paragraph...)

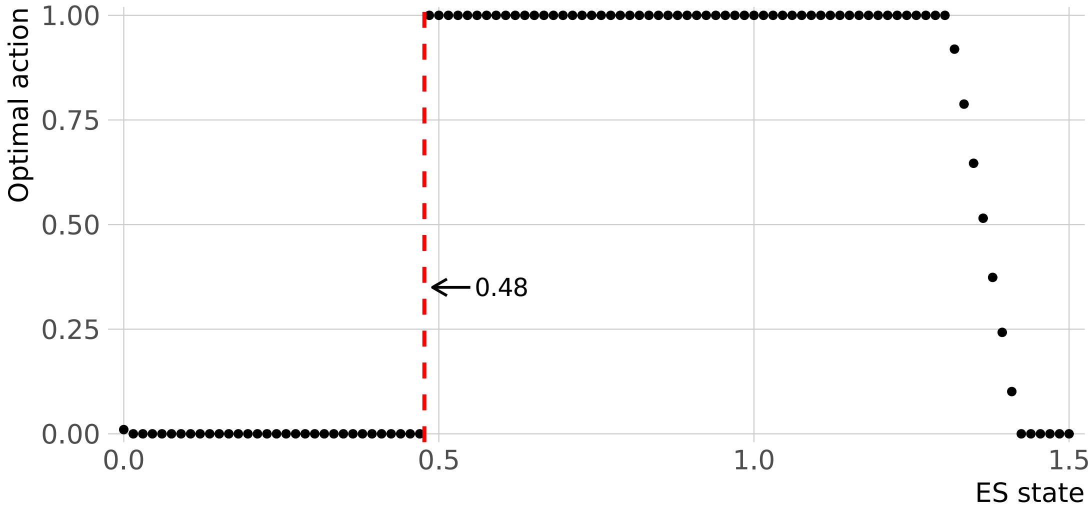

Figure 1: Optimal decision policy π as a function of ecosystem state.

Results

We explore the transition to and from DFS using a Markov Decision Process (MDP), in which an agent (farmer) makes decisions about their interactions with the environment. We formulate a 'system state' to represent the degree of benefits provided by the ecological states, which provide immediate benefits to the agent. At each time step the agent chooses an actionfrom a finite set of available actions, described by a spectrum from 0 to 100 representing a percentage investment in diversified farming practices. Higher actions correspond to a higher 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 (*reference conceptutal figure*), providing the agent a reward. However, actions have some associated cost, which is subtracted from the benefit received from the ecological state.The agent calculates optimal actions based on their future cumulative discounted rewards over a defined time horizon. The discount factor informs how much the agent values current rewards relative to about the future rewards.

Bimodal DEP adoption distribution

Fig 1 shows the policy π, or optimal course of action, for an agent. We find a critical bifurcation, or tipping point, at an specific ecosystem state, below which the highest expected value is derived by investing virtually-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.

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 centered around $S = 0.17$, and those in the "diversified" class around $S = 0.82$. 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

Many agrienvironmental practices require upfront investment, but can pay for themselves over time through accrued ecosystem services. For example, in California's Sacramento Valley, researchers calculated that an average farmer would recoup the investment of planting a hedgerow in seven years due to increased pollination services [7]. However, such an investment is only wise if the grower is confident they will

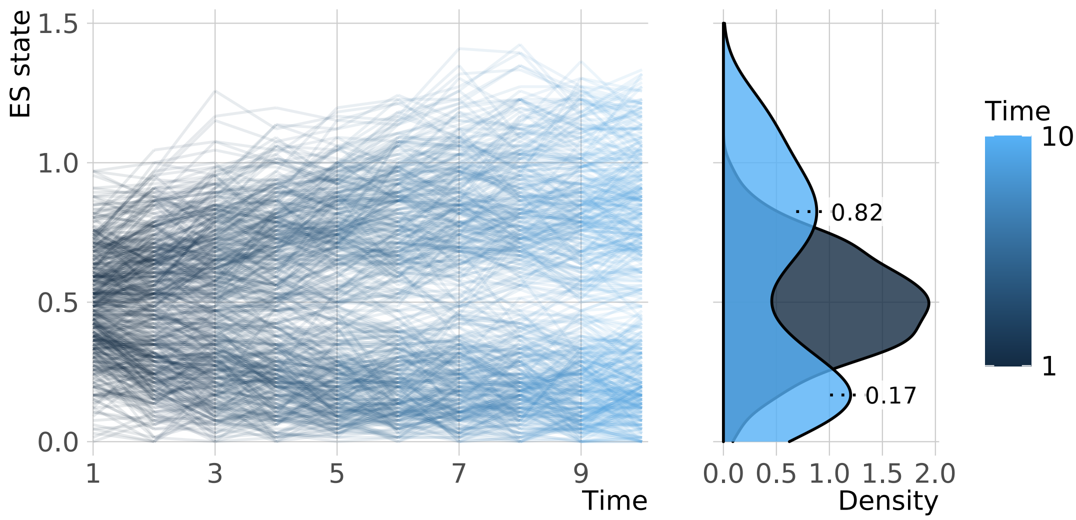

Figure 2: Simulations of 500 model agents over ten farming seasons. Initial ES states follow a truncated normal distribution (mean = 0.5; S.D. = 0.2; truncated at [0,1]). Agents utilize decision policy π as shown in Fig 1 for nine timesteps. Right plot shows initial distribution (dark blue) and bimodal density distribution at $t = 10$ (light blue), with peaks annotated.

continue farming at their present location, for example if they own the land or have a sufficiently long-term lease. 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. 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 [12]. A study conducted in British Columbia found that tenant farmers planted fewer perennial crops than land owners [3]. 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 [10].

Using the same simulation parameters as outlined in the previous section, 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 3 to Fig 2 above shows that, as length of land tenure or stability of lease agreements declines 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

Agricultural subsidies have become an integral part of farming over the past half-century, and policy-makers 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<<}. Here we apply the DFS-MDP model 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 (i.e. the government or taxpayer) is equal, and in fact the short-term subsidy is technically more valuable if economic discounting is applied {>>cite the concept

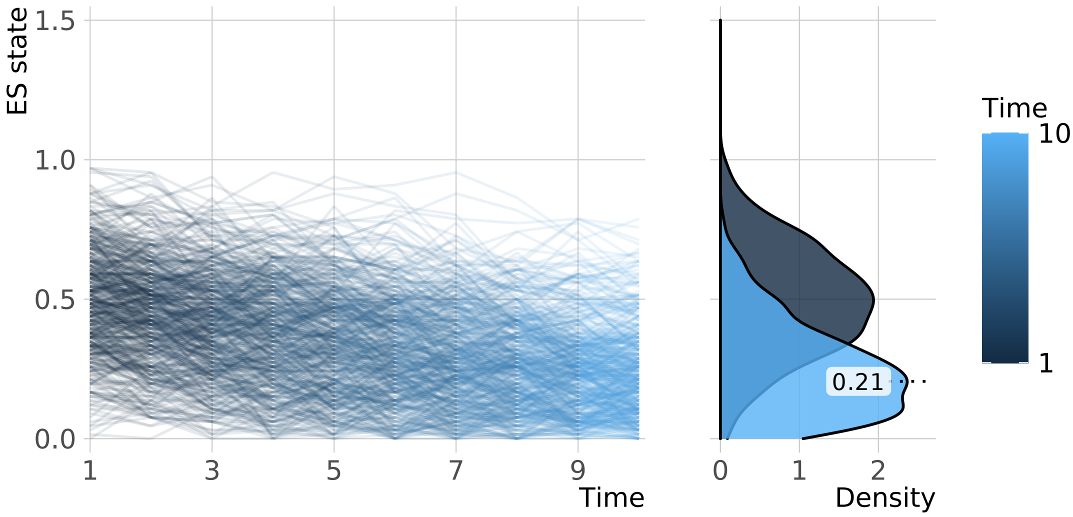

Figure 3: Result of short land tenure on DEP adoption. The simulation is identical to that in Fig 2, but the MDP is solved under a finite, two-year time horizon.

of discounting<<}. Within the model, agents adapt their decision policy π during the subsidy period, and at its conclusion they revent to base case (i.e. subsidy-free) decision rules.

Fig 4 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 2, 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 (as it is in the real world), longer-term subsidy packages have a higher chance of nudging behavior beyond the critical threshold.

Discussion

describe model more in conceptual terms - leave mention of MDP for the methods "conceptual model to represent optimal sequential decisions, or something…"

third paragraph - more general discussion of DFS, how it fits into CHANS then explain the concept of ES

in intro - mention that this model is intended to inform survey design and sampling and to better understand the impact of ES on farms - for the interdisciplinary team; iterative process, companion modeling, will later lead to refinements of the model itself - also, mention that this is a decision of an individual farmer

move the discussion of existing evidence for bimodality to discussion

fourth para - focus more on qualitative patterns that emerge

complexity and chans modeling section - can move most of that to discussion, more reflective than as a theoretical motivation motivation is more that this type of model allows us to integrate social and ecological elements

The DFS-MDP we present here represents a simplified and stylized version of the coupled human decision factors and ecological ramifications of diversification practice adoption among California produce growers. While the concept of alternate stable states—or basins of attraction—and tipping points within agricultural SESs has been previously explored [14], our experimental results cast light on several core mechanisms that help to explain these complex dynamical behaviors, suggesting novel considerations as policymakers work to enhance the sustanability and resilience of agricultural production systems.

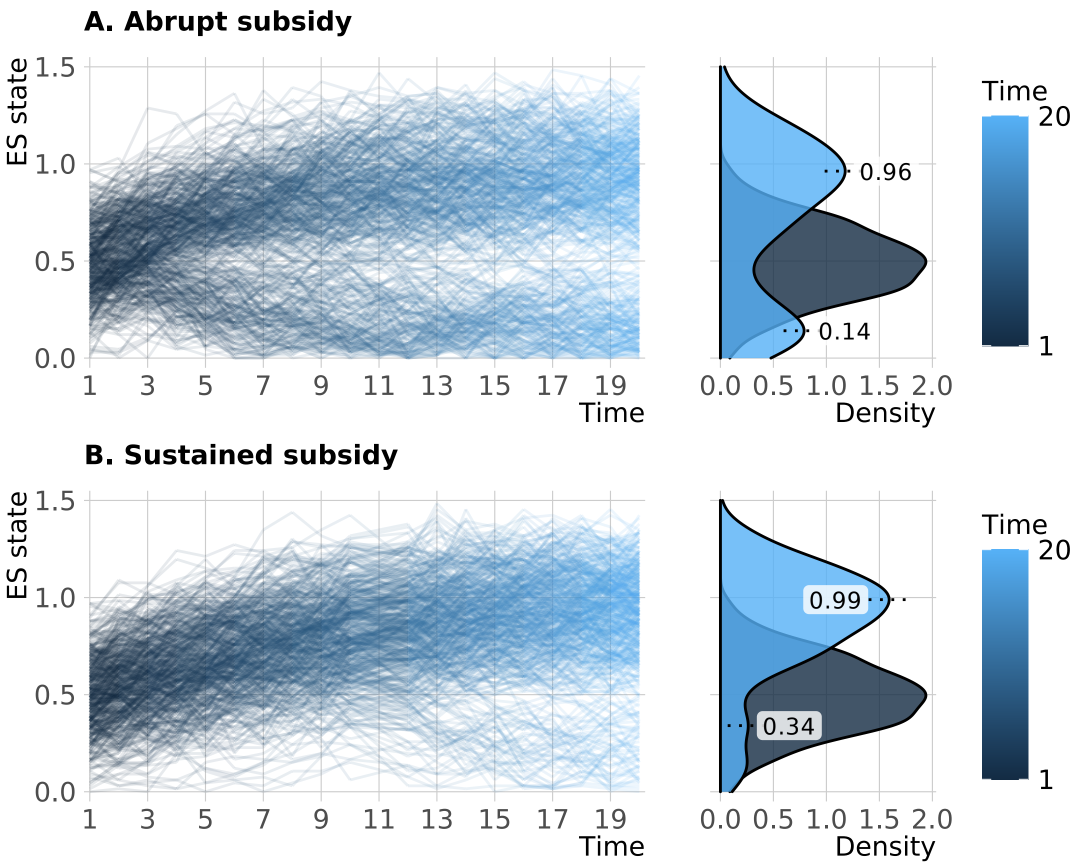

Figure 4: Replicate simulations from 500 normally-distributed starting states (mean = 0.5; S.D. = 0.2; truncated at [0,1]) over 20 timesteps. Panel A shows the effects of a large, abrupt subsidy (no direct cost to adoption during the initial two years). Panel B simulates a smaller, yet more sustained subsidy (adoption cost = 0.9 during the first 10 years). Ingoring discounting, subsidies have the same total cost to the issuing organization. After subsidy is removed, agents adjust their decision rule to that of the base case (i.e. no subsidy).

In light of historical agricultural catastrophes like the dust bowl, scholars have increasingly called for swift action around modern-day stressors like climate change, soil degradation, water quality, and biodiversity loss. Policymakers have responded by developing programs which offer incentives and support for agriecological practice adoption, yet designing efective policies has proven challenging. Recent case studies—spanning decades, continents, and agricultural products—emphasize that policy mechanisms designed to promote agricultural sustainability have complex ramifications across various contexts [4]. Understanding how to realize transitions to resilient management practices, while also maintaining an adequate food supply, remains an active area of study. Critical to designing incentives is an understanding of the thresholds which render a given management practice viable to one farmer while nonviable to another. Studying the decision factors that give rise to these thresholds is the only way for policymakers to develop effective levers to nudge management choices toward a model that is both financially and environmentally sustainable.

While it is often assumed that farmers who adopt pro-environmental practices are motivated primarily by ethical beliefs about the long-term health of our planet, we present a model within which ecological benefits are accrued at the level of the individual farmer. We find that, even where farmers are acting out of self-interest, investment in diversification practices can pay off. However, it is well known that many practices that increase functional ecosystem services can take several years before significant beneficial effects are realized [2, 7]. Within the model, we find a threshold such that agents on each side of a tipping point tend to be drawn to one of two 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, whereas 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.

Under this view, binary certifications like the organic standard may be critiqued in some respects. 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 [11]. 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 DFS adoption.

To drill deeper into potential policy implications, we model the potential impact of land tenure on the adoption choice. 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. Experimentation with DFS-MDP shows that, 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 DEPs. Whereas in the long-tenure base case 48% of farmers end up in a low ecosystem-services state, under the short land tenure scenario 92% of farmers end up in this simplified state. This suggests that a focus on expanding financing for new farmers to purchase land and/or legislating minimum lease durations for agricultural land rentals may be possible levers by which to increase adoption of agriecological practices. Another related consideration is farmers' succession plans: with the average age of landholding farmers continuing to increase, and with succession plans often uncertain {>>cite<<}, it is likely that even more agricultural land may be leased in the coming years if this issue is not addressed.

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.

{>>probably a short conclusion paragraph<<}

Methods

We have developed a Markov Decision Process model (DFS-MDP) to simulate the decision factors faced by vegetable growers choosing the extent to which to adopt or invest in DEPs over time. An MDP is an appropriate tool here because the scenario can be represented by an agent-environment pair in which the agent exists in a given state, interacts with the environment through consecutive actions, transitions probabilistically between states, and derives some reward therefrom.

{>>NEW METHODS FIGURE HERE?<<}

The overarching goal of the model is to provide a mechanism for exploring the drivers behind DEP adoption, including the impact of ecosystem shocks, land tenure, and other decision factors. Using a model-based approach, we aim to identify potential levers of change without relying on assumptions surrounding non-monotonic dynamics of prices or decisions. While the model assumes that price is not a decreasing function of yield, we assume that at the state of the individual this does not qualitatively change. Here we provide an overview of model elements and functions; full implementation details are provided in Appendix 1.

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). We assume that $A_s = A$ for all states.

The system state s represents the degree to which the agent derives ecosystem services (ES)—such as soil productivity, water infiltration, climate resilience, etc.—from the DEPs they have implemented on their farm at t. The state space S is an integer vector from 1 to 10, with 10 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. In our model, 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. Systems in higher ES states receive additional benefits b_s from the ecosystem services provided by the DEPs they have adopted. As above, depending on 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 $s \to s_{max}$.

Investment in DEPs 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 ($R(s, a) = b_s - c_a$).

System shocks

We assume that the DEP investment choice can only increase or decrease an agent's ES state by—at most—one level at each time step. However, stochastic environmental shocks—such as drought, flood, and disease—can decrease the derived ecosystem services benefit by a larger amount (Fig **??**C). We assume that the degree of ES state disruption when a shock occurs is proportional to the agent's current state (i.e. higher states are more resilient to shocks).

Solving the MDP

To solve the MDP, we employ the value iteration—or backward induction—algorithm [1]. This yields policy π, which codifies the optimal course of action for the agent given the initially-imposed environmental conditions. In addition to the state transition matrix P and reward matrix R, the algorithm also incorporates a myopic discounting factor $0 \leq \gamma \leq 1$, which describes the rate at which the agent's expected utility becomes less salient with each future time step, with $\gamma = 1$ representing no discounting. For example, a vegetable grower would, in most cases, derive much more utility from high expected profits on next-year's crop than on the crop ten years in the future.

Model mathematical description (from Carl - needs to be integrated into the section)

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),

$$U(x_t, a_t) = b x_t - c a_t$$

Where x_t is the ecosystem state, b the benefit associated, and $c a_t$ 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-enhancing practices in the survey data

DEP 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 DEPs queried in the survey, with their adoption rates across the entire sample. A histogram plotting the number of diversified practices used by each grower (Fig 5A) confirms a bimodal distribution, with growers generally tending to either adopt zero DEPs—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 [12, 3, 10, 7]. 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 5B shows that owners are about 20% more likely than leasers to invest in at least one DEP.

Model parameters

!!PROBABLY INCLUDE A BIT ABOUT HOW WE USED THE DATA TO PARAMETERIZE THE MODEL, INCLUDING A TABLE WITH THE FINAL PARAMETER VALUES WE DECIDED UPON. THIS COULD ALSO BE LEFT FOR THE APPENDIX!!

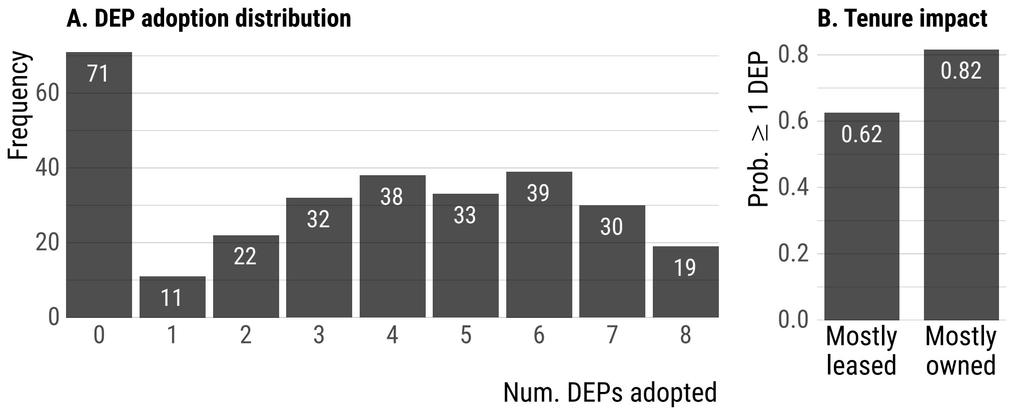

Figure 5: A. Bimodal distribution of DEP adoption in the sample. B. Impact of land tenure on the probability of adopting at least one DEP.

Experimental design

!!MILLIE - DESCRIBE EXPERIMENTS WE CONDUCTED WITH THE MODEL IN DETAIL HERE!!

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