Alternate Stable States in Farming System Diversification: Effects of Land Tenure, Environmental Shocks, and Subsidy Structures

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Abstract

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Introduction

Reacting largely to agricultural catastrophes like the Dust Bowl, over the last century, United States policymakers have increasingly attempted to drive more sustainable production practices on farms by offering incentives and support. With the growing preponderance of evidence that climate change both affects agricultural production, and is in-part driven by it—as well as the increasing recognition that some mainstream agricultural practices have deleterious effects on the long-term productive capacity of our soil—interest in agriecology has blossomed both in the United States and globally, and agrienvironmental policies have been enacted across multiple levels of government and within private sector supply chains.

While transitioning towards sustainable food systems is existentially critical—particularly as we face more frequent extreme weather events, soil degradation, and biodiversity loss—understanding how to effectively realize transitions to resilient management practices, while also maintaining an adequate food supply, remains an open question. A common observation is that farms tend to fall into two general categories: those small-to-medium operations that sell into local, direct markets, and take a longer view on sustainability; and those large monocropping operations that sell into the global commodities market and focus on short-term efficiency [**?**]. Several scholars have suggested that bolstering an "agriculture of the middle" may represent a possible path forward [**?**].

Critical to designing effective incentives is an understanding of the decision processes that lead farmers down the rabbit holes of these two radically-different management styles. Specifically, it is important to understand where thresholds which render a given management practice economically-viable and/or socially-acceptable to one farmer while nonviable or unacceptable to another lie. Understanding 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.

Attempts to understand the mechanisms behind both transitions from industrial commodity farming to diversified "civic" agriculture, as well as the path-dependency that leads to the observed systemic bifurcation, are not new. The International Panel of Experts on Sustainable Food Systems (IPBS) recently published a document outlining numerous case studies detailing agriecological transitions across the globe in an attempt to synthesize what we know about potential levers of change [**?**]. These case studies spanned decades, continents, and agricultural products; and found numerous mechanisms that have spurred transitions in various contexts, emphasizing the complexity of the problem.

Simultaneously, theory has explored how stylized social-environmental models can provide insight into the mechanisms of alternate equilibria and levers of transition to diversification practices [**?**]. !!Still need to add more here!!

Diversified farming systems

Here we focus on the transition to diversified farming systems (DFS) [**?**]. DFS use diversification-enhancing practices (DEPs) designed to support functional biodiversity across spatial and temporal scales and promote the ecosystem processes that provide important inputs and services to agriculture. DFS farms often adopt plot and field-scale practices like intercropping, cover cropping, and crop rotation, which enhance crop diversity in space and time, as well as landscape scale practices like planting hedgerows, buffer strips, and riparian corridors, which provide habitat for associated biodiversity. Although organic agricultural systems often draw from this same suite of practices, rules governing organic agriculture stipulate allowable and unallowable inputs rather than strategic management of biodiversity. Another distinction is that farmers can flexibly employ different combinations of DEPs that fit their situated goals and constraints, whereas organic agriculture is binary (either certified or not), even if the ways in which farmers implement organic agriculture is quite heterogeneous [**?**]. Promoting wider adoption of DEPs thus represents a process of incremental socio-ecological transition, allowing farmers embedded in monocultural agricultural systems to move stepwise toward more sustainable systems.

Bolstering biodiversity, and especially keystone ecosystem service providers through context-specific practices, can increase regulating and supporting ecosystem services in ways that reduce or eliminate the need for external inputs, reduce negative externalities, and increase positive externalities [**?**]. Yet these benefits often do not occur immediately following implementation of a given DEP. Especially if an ecosystem starts in a degraded state, for instance after decades of intensive cultivation and agrochemical inputs, restoring ecosystem processes can be a slow process. Increasing soil organic matter, crucial for nutrient and water cycling and retention, through compost application, more complex crop rotations or cover cropping often takes years to decades. Rebuilding communities of pollinators and natural enemies that underpin pollination and pest control ecosystem services through perennial plantings or intercropping similarly is slow. This lag time between implementing a DEP and realizing benefits is one challenge of transitioning, since farmers incur known costs in the short-term but benefits are less certain and in the longer-term.

Transitioning to DFS requires more than just managing biodiversity [**?**]. One example is increasing crop rotational diversity, or the number of crops grown in a place over time. Growing additional crops in rotation requires knowledge of how to do so in a particular context; reliable markets for selling additional crops; and specialized equipment and infrastructure for managing, harvesting, and transporting different crops, just to name a few requirements. Given this web of ecological, social and economic interactions that must coalesce to allow for a successful transition and its continued development, we posit that DFS occupy a different social-ecological state than simplified systems.

In the following paper, we present a model of the decision processes behind farmers' adoption of DEPs. In brief, we suggest that a bimodal distribution of farmers, one group of whom manage farms in a relatively stable "simplified" state and one group of whom manage farms in a relatively stable "diversified" state, is likely to emerge through the temporal dynamics of !!OF WHAT?!!. Farmers in the diversified state benefit from the ecosystem services that flow from diversified farming systems, and therefore continue to invest and maintain the ecosystem service benefits despite costs. Meanwhile, farmers in the simplified state tend to be more reliant on inputs for fertility and pest control, as well as wholesale markets which do not reward diversification monetarily. Transitioning to a diversified state would require significant investment for these farmers, who would not reap rewards until they had spent years building up soil organic matter, new markets and relationships, and the knowledge to manage all of these newly diversified elements most effectively. Hence, farmers in the simplified, monocultural state tend to remain there, because of strong path dependency and the big leap needed to transition successfully to the diversified state.

Land tenure and diversification practices

One of the most significant factors impacting the degree to which farmers utilize DEPs is land tenure—the means by which they access land to farm. In the US, 39% of farmland is rented (!!USDA NASS 2016 find citation!!), with the length of the lease varying from a single year to a farmer's entire career. For tenant farmers, the length and terms of this lease, as well as their relationship to their landlord, are central to decisions about whether to invest in the ecological health of the farm.

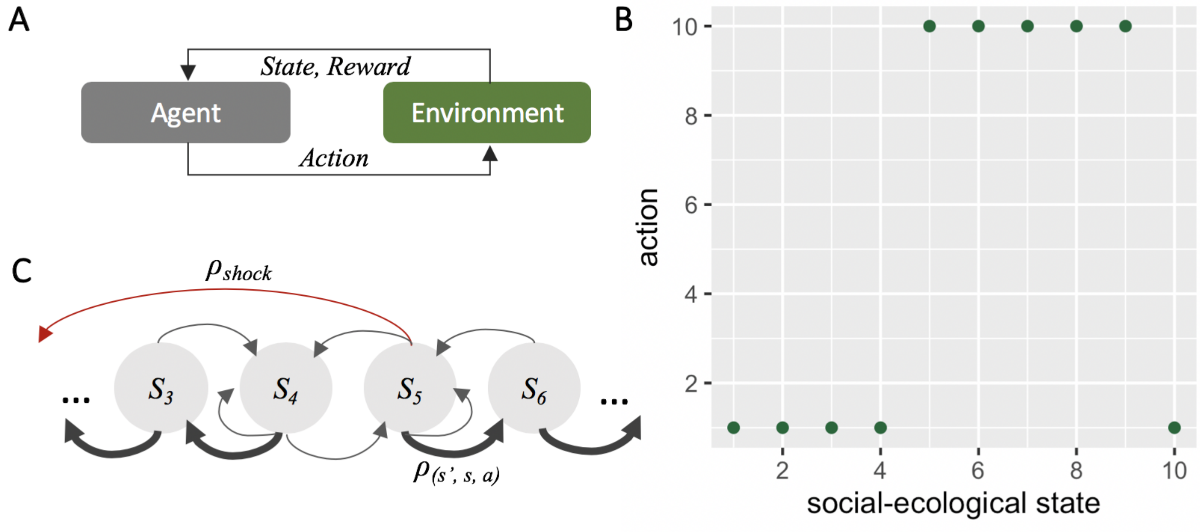

Figure 1: (A) Agent-environment interaction in an MDP. (B) PROBABLY GET RID OF THIS AS ITS SHOWN IN NEXT FIG (C) Schematic representation of our MDP model.

Because many of the ecosystem service benefits associated with diversified farming practices flow back to the farm itself, such practices often pay for themselves over time. For example, in the Sacramento Valley, researchers calculated that farmers would recoup the investment of planting a hedgerow in seven years, through increased pollination services [**?**]. For a tenant farmer, such an investment would only make sense if they had a long-term lease that ensured access to the land long enough to recoup the up-front cost. In addition, significant investments in diversified farming practices may require access to credit, which also hinges on secure land tenure as a form of collateral [**?**].

This relationship between land tenure and agricultural best management practices has been observed in numerous farming systems. 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 farmers who rented their land planted fewer perennial crops than those who owned their land [**?**]. Our own ongoing research with lettuce farmers in the Salinas Valley—discussed in more detail in the parameterization section—suggests that land tenure is an important factor in these farmers' decisions about whether to grow cover crops or utilize complex crop rotations.

Methods

This paper describes a Markov Decision Process (MDP) model representing a vegetable grower deciding the extent to which to adopt or invest in DEPs over time. !!SUGGEST WE NAME OUR MDP AT SOME POINT. MAYBE DFS-MDP, OR SOMETHING MORE CATCHY?!! 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 (Fig 1A).

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 1C). 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 [**?**]. 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 implementation

Our MDP was developed in R, using the MDPtoolbox library. !!ETC. . . !!

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.

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%

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.

Several possible reasons for this behavioral bifurcation emerge from the coding and analysis of interview transcripts. Farm scale appears to play a role, with the smallest and largest farms adopting fewer DEPs, and mid-scale farms adopting at higher rates. This may be explained by factors including limited capital availability of smaller growers to implement those DEPs with high up-front costs, food safety stipulations based on market outlet, risk attitude, and myopic discounting. Also, as discussed above, 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 2) 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.

To dig deeper into the causes of this bimodality, we first partition the data by farm size (in total acreage), as our observational study suggested that size—with its corresponding opportunities and limitations resulting from market outlet—may play a role in the DEP adoption decision. Figure 3A plots the density of growers at each adoption level, with the sample divided into three size quantiles. This confirms that farmers at each scale exhibit a bimodal adoption distribution, but also complicates the picture. Small farms appear to be most heavily bimodally-distributed, with peaks at zero and six DEPs. Large farms adopt zero DEPs at approximately the same rate as small farms, but, among those large growers who do adopt, they tend to adopt less heavily, perhaps only three or four DEPs. Finally, medium farms in our sample were both less likely to adopt zero DEPs, and also the most likely to adopt heavily, with seven DEPs being most common. Average adoption for each size class, shown as vertical lines on the plot, confirm that, overall, small and large growers are less likely to adopt than their mid-sized counterparts.

To investigate the high mid-size adoption dynamic further, we increase the partition granularity to six size quantiles, with the average size for each being $[2.5, 11, 26, 70, 312, 4165]$ acres. Figure 3 B plots the average adoption rate across all eight DEPs for each acreage quantile. Here we see that growers in the third quantile—around 30 acres—are most likely to adopt heavily. Growers in the largest two groups are the least likely to adopt, with the smallest growers only slightly more likely.

As discussed above, land tenure has often been shown to be a decision factor that impinges upon agri-

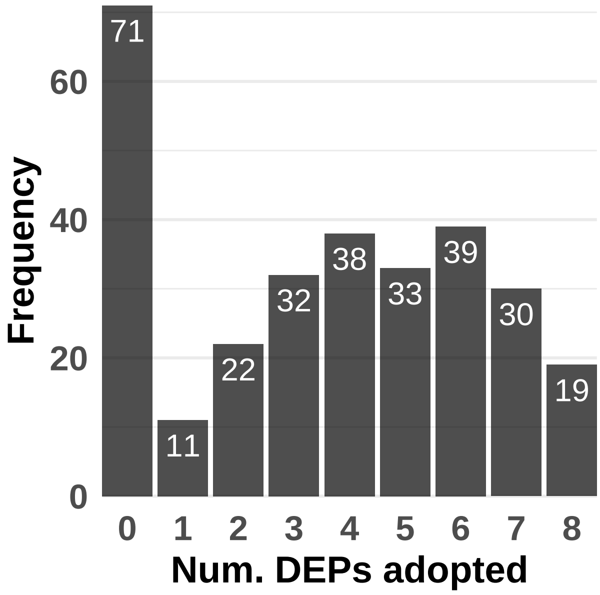

Figure 2: Distribution of DEP adoption in the sample

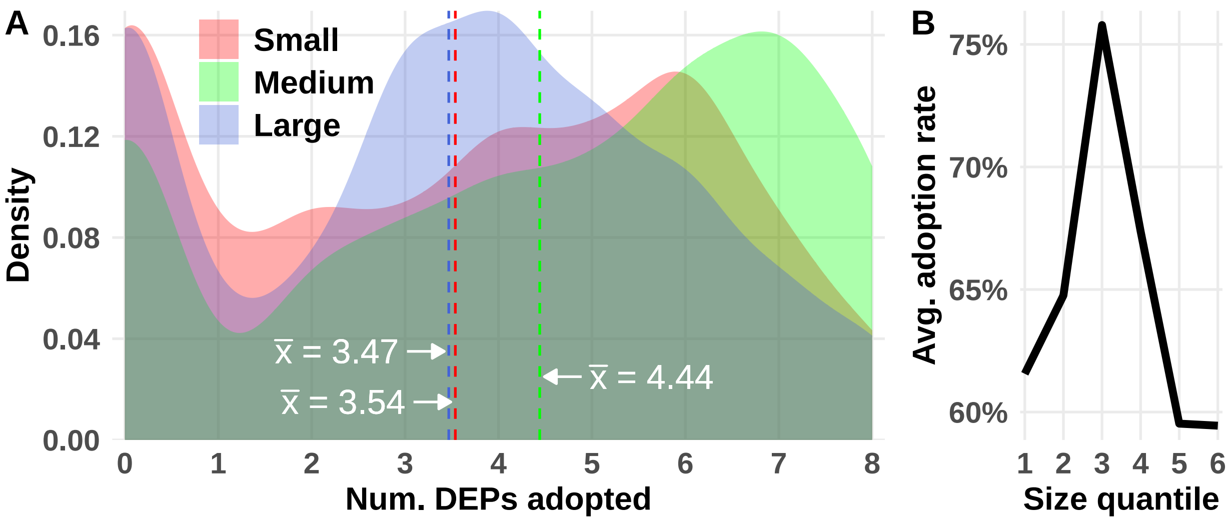

Figure 3: Impact of farm size on DEP adoption in the survey data. (A) shows the density of number of DEPs adopted by the smallest, middle, and largest third of growers. Dashed vertical lines show the average number of DEPs adopted for each size quantile. (B) shows the overall average adoption rate—across all DEPs—for growers classified into six size quantiles.

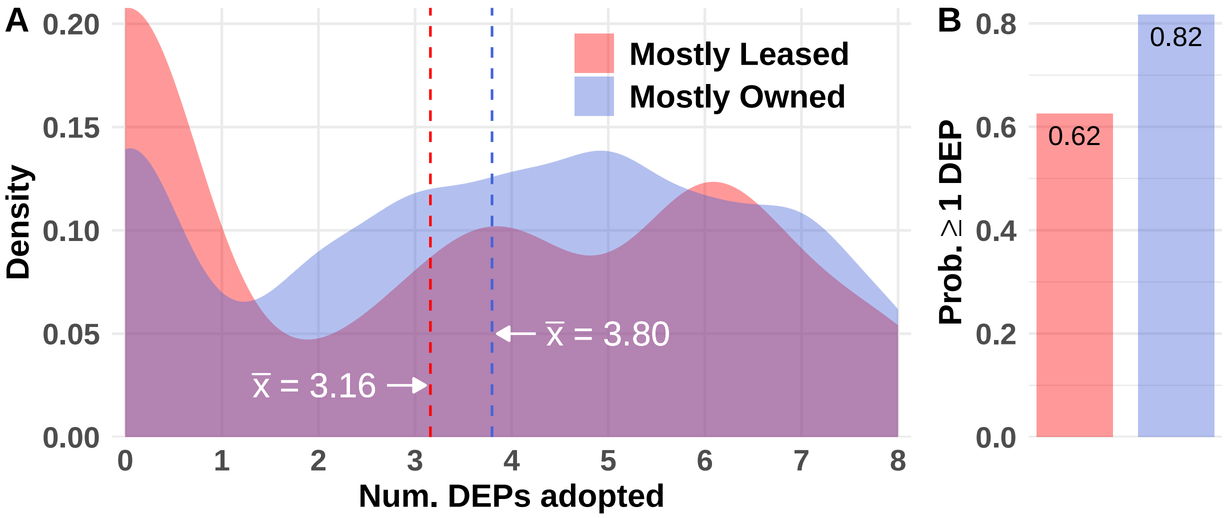

Figure 4: Impact of land tenure on DEP adoption in the survey data. (A) shows the density of the number of DEPs adopted by growers who primarily own their land (blue) vs. those who primarily lease (red). Dashed vertical lines show the average number of DEPs adopted for each land tenure classification. (B) gives the probability of a farmer in each group adopting at least one DEP.

cultural management practice adoption [? ? ? ?]. 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 4A shows that owners are more likely than leasers to invest in DEPs at all, and also that the average number of DEPs in use is somewhat greater for owners than leasers. Plot B confirms the effect of land tenure on DEP adoption, with owners being 20% more likely to adopt at least one DEP than their leasing counterparts.

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!!

Experimental design

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

Results and Discussion

Bimodal DEP adoption distribution

. . . model shows bimodal distribution like we hypothesized (Fig 5). . .

Land tenure

Using the same framework as outlined in the previous section, we solve the MDP on a finite horizon, representing shorter time horizons. At large horizons, the policy is equal to that of the infinite horizon above (Fig 6A). As land tenure decreases, and optimal decisions are calculated on a shorter time horizon, the investment in diversified practices become less optimal and ultimately infeasible (Fig 6B)

Also present Fig 7

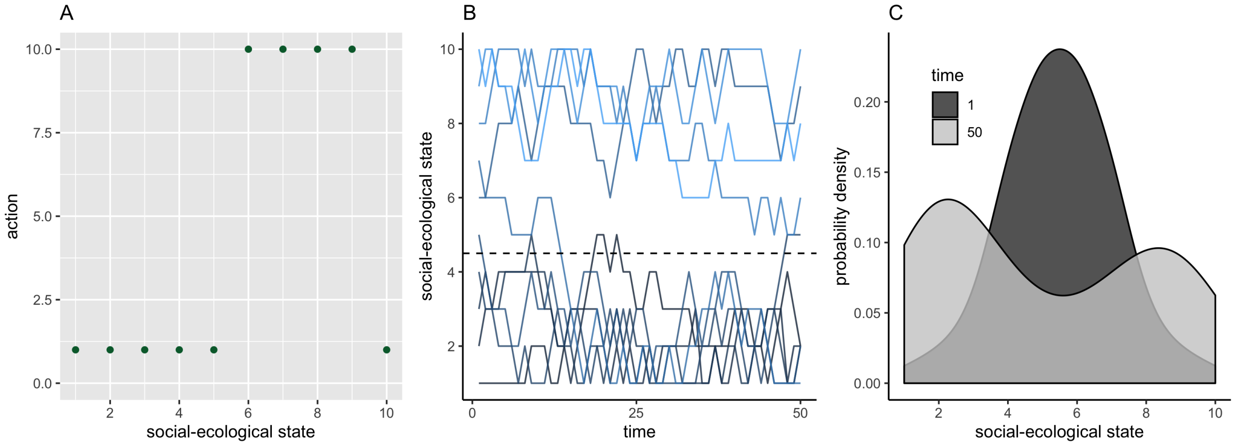

Figure 5: (A) optimal strategy as a function of the system state, showing only boundary strategies are optimal, with a tipping point at which an optimal solution of minimizing DP switches to favor an optimal solution of maximum DP once the ecosystem services reach a critical threshold. (B) Bistability based on initial state. (C) Bimodal probability distribution of ecosystem states at time T= 100.

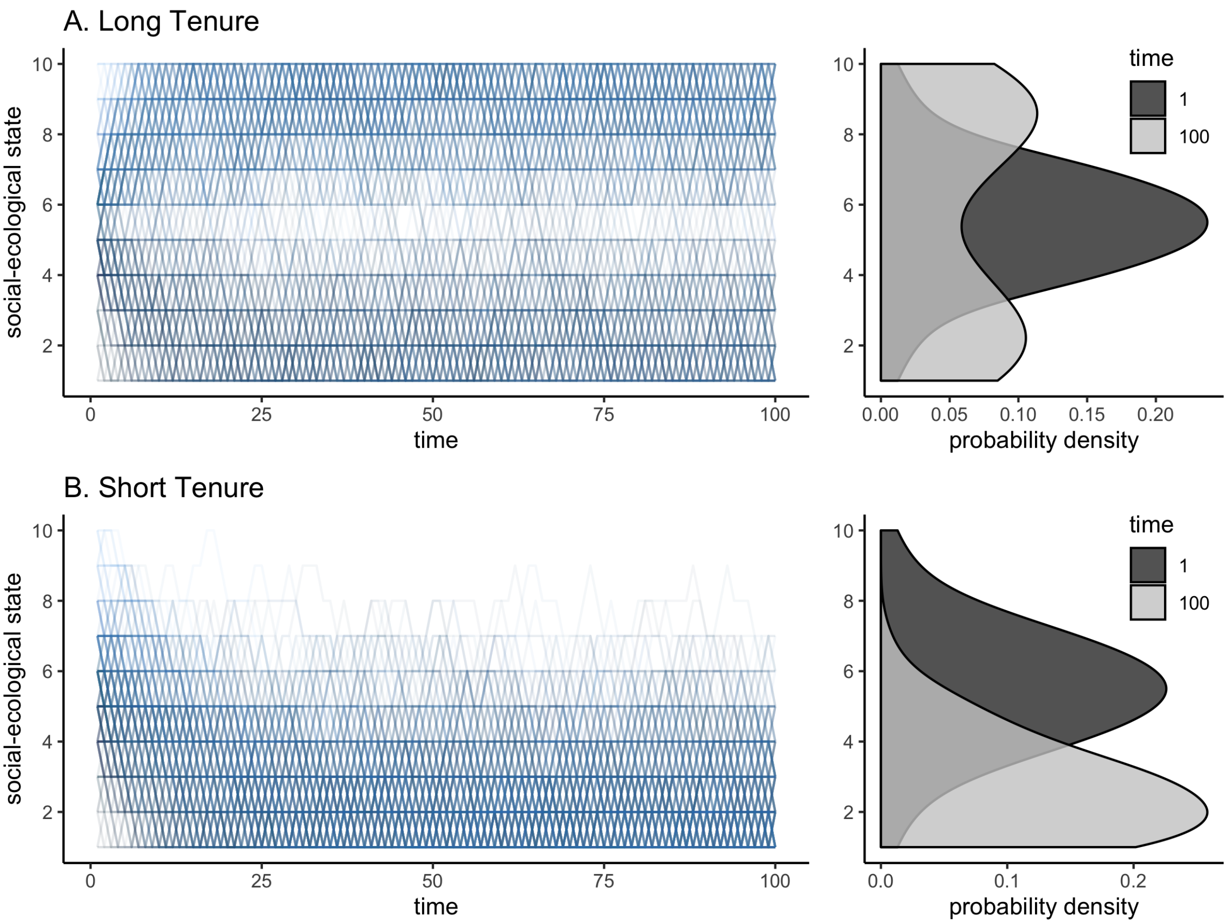

Figure 6: (A) captiony caption. (B) another one cool.

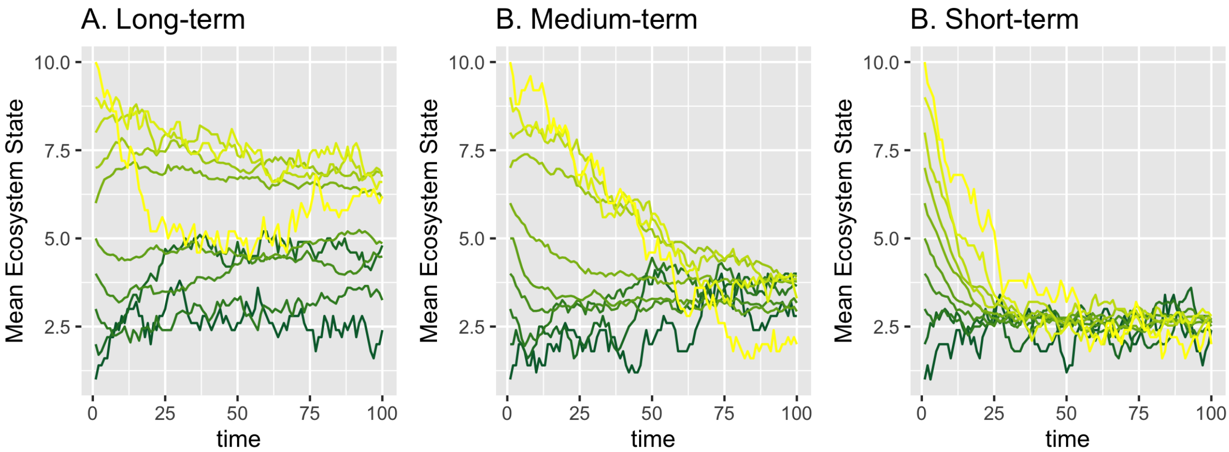

Figure 7: Tenure impacts the location of tipping point to high ecosystem states...

System shocks

Empirical system suggest that farmers' response to perceived risk of shocks may have a bimodal distribution as well: that is, diversified farmers will invest more in biodiversity to buffer against shocks because they see this as a less risky strategy, while farmers in the simplified state may actually see transition to diversification as a more risky approach if they perceive a possibility of shocks like drought or market disruptions along the path that they cannot adapt to. (Fig 8)

- fear or belief in shock as in the case of food bourne illness can lead to loss of diversified farming states and can have am even large effect than the shock itself. This suggest long-term, long lasting, lock-ins to low diversity states, despite benefits and increase resistance to shocks.

!!Say something about (Fig 9)...!!

Conclusions

Levers of change:

- long lasting impacts of shocks
- policy duration vs intensity: really depends on policy design and how it targets investments
- policy targeting to change cost structures of DF practices (qualitative impacts of convex vs concave cost functions)

Novelty:

Alt stable states and tipping points in agriculture is not really a new idea + temporal dynamics and non-instantaneous build up of ecosystem services is what leads to the lock-in dynamics and tipping points + changing cost structures, etc. so long as they are sequential can alter this?

Significance: + Different levers of change that previous papers because different mechanism

Other thoughts:

+ Does not suggest that ecosystem services are the only mechanism for lock-in, but allows for incorporation of different decision criteria and price-yield dynamics, which could further reinforce bimodality, or maybe reduce it? + we dont explore feedbacks between individual production and market systems– this is important (obviously..) on a large scale but with little mechanistic understanding of transitions on an even smaller scale it seems like maybe not the utmost important bit..

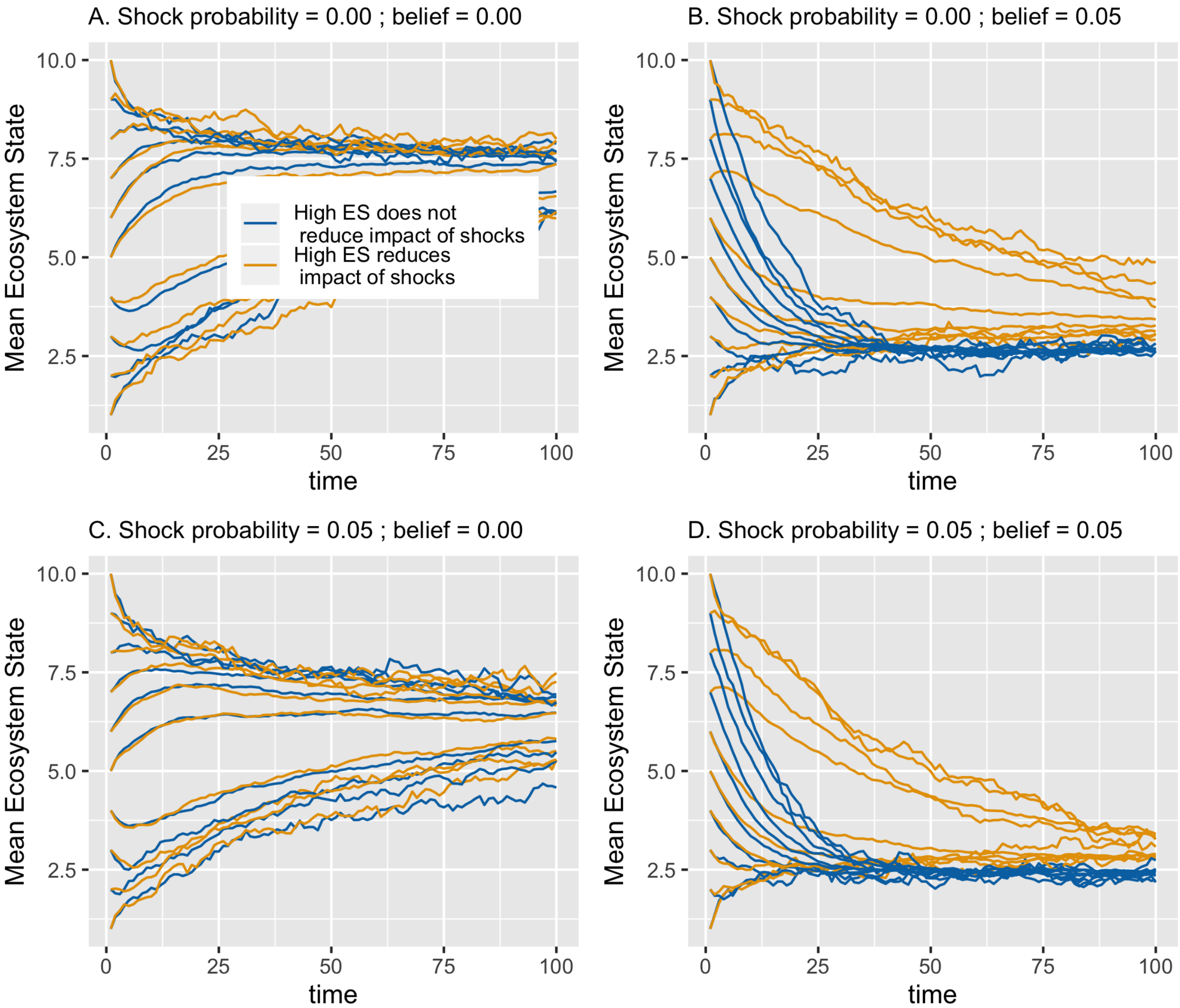

Figure 8: Impact of shocks to mean system dynamics and bistability (A) Both shock probability and belief in that probability are set equal. In the case where high ecosystem states increase resilience to shocks (or decrease the intensity of state shift due to shock) bistability remains. Otherwise, system state degrades to lower ecosystem state. It may be reasonable to assume Farmers that believe that diversified practice do not reduce the impact of shocks (or even increase risk of certain shocks, such as pathogen outbreak, may follow the trajectory as is a high ecosystem state does not reduce impacts. The bistability is not an artifact of the shock itself, but rather the belief of shocks and their corresponding risk factors and probabilities, which impact the optimal policy.

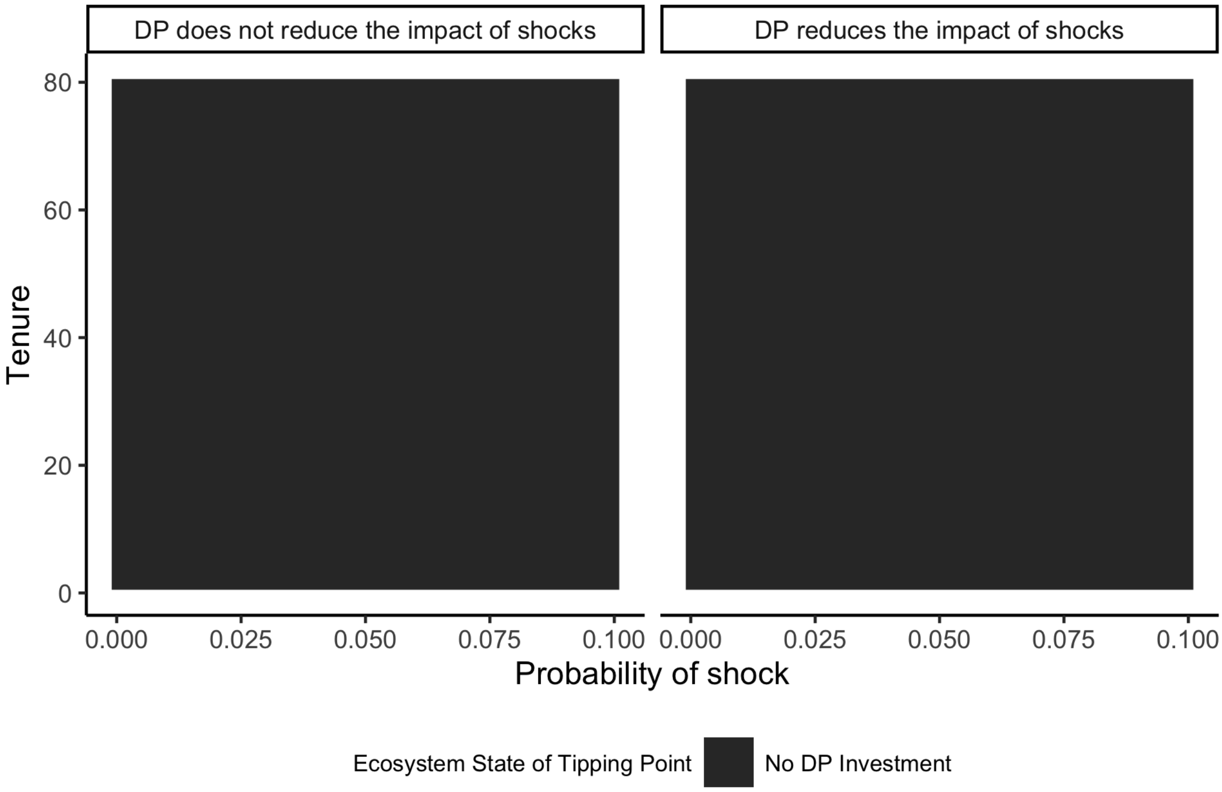

Figure 9: !!!Figure is not showing up correctly. Need to investigate this!!! Diminishing returns can provide mechanisms for reducing biomaditly and adoption of DP to the point where they become self sustaining. This could be in the form of providing technical assistance etc. However, would need to be provided for a significant amount of time to be worth it, and runs the risk of reducing the upper lock-in. Synergistic policies may create a quicker option for decreasing the barrier to entry, however, still provide mechanisms for bistability and may not support farmers are the lowest ecosystem states. However, synergistic solutions may not have unintended consequences of decreasing the upper optimal equilibrium point. .

Given this bimodal distribution, we suggest that a key role for policy and supply chain initiatives lies in supporting farmers' transitions from the simplified to the diversified state, by creating viable intermediate states through which these farmers can transition. While we believe the diversified state can self-sustain to some extent, we caution against the assumption that farmers may find their own way there in the face of shocks like climate change and market disruptions that act to force change. We suggest that farmers response to perceived risk of shocks may have a bimodal distribution as well: that is, diversified farmers will invest more in biodiversity to buffer against shocks, while farmers in the simplified state may actually see transition to diversification as more risky if they perceive a possibility of shocks like drought or market disruptions along the path.

!!policies that encourage stable transitions between generations of farmers may positively impact sustainable decision-making by encouraging longer-term thinking… i.e. encourage more long-term tenure, more reason to invest (in DEPs). succession plans!!

References