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The Ecological Insurance Trap

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Abstract

Common pool resources often insure individual livelihoods against the collapse of private endeavors. When endeavors based on private and common pool resources are interconnected, investment in one may put the other at risk. We model Senegalese pastoralists who choose whether to grow crops, a private activity, or raise livestock on common pool pastureland. Livestock can increase the likelihood of locust outbreaks via ecological processes related to grassland degradation. Locust outbreaks damage crops, but not livestock, which are used for savings and insurance. We show the incentive to self-protect (reduce grazing pressure) or self-insure (increase livestock levels) changes with various property rights schemes and levels of ecological detail. If the common pool nature of insurance exacerbates the ecological externality even fully-informed individuals may make decisions that increase the probability of catastrophe, creating an "insurance trap."

JEL Codes: Q20, Q54, Q57

Keywords: Environmental externality, common pool resources, poverty trap, endogenous risk

1. Introduction

Ecological insurance is an important ecosystem service (Baumgärtner, 2007; Baumgärtner and Strunz, 2014; Loreau et al., 2003; Naeem and Li, 1997; Quaas and Baumgartner, 2008). The ecological insurance argument is based on the idea that ecological processes stabilize ecosystems, providing an insurance effect (Loreau et al., 2003). However, not all feedbacks in ecosystems are stabilizing or welfare enhancing. Aside from providing insurance, biophysical-economic interconnections can also generate ecological externalities, for example predator control can lead to pest explosions or in some cases greater risk to endangered species (Crocker and Tschirhart, 1992; Melstrom and Horan, 2013). When people have sufficient control over the system, then management can be targeted to ensure that feedbacks produce stabilizing and welfare enhancing services (Fenichel and Horan 2016). But, institutions determine who makes decisions, and ecosystem processes that lead to benefits from the system can manifest in different ways for different people (Berkes et al., 2008; Ostrom, 1990). Without secure property rights, individuals may have little incentive to manage ecological interactions that impact the future state of the system (Horan et al., 2011), including future risks. Nevertheless, when individuals face the potential for bad events because of ecological interactions, people do what they can to avoid potential losses, which may include investing in ecological insurance. If the act of investing in ecological insurance increases the risk of bad events, then individuals may become trapped in a state of high environmental risk despite their attempts to insure.

Income traps are a common concern in economic development, and household decision makers that lack access to financial market can become “trapped” because they invest in safer assets and miss out on the higher return activity (Barrett and Carter, 2013; Zimmerman and Carter, 2003).

Natural insurance from biodiversity and other ecosystem services and financial insurance are substitutes, so that lacking access to financial insurance, individuals may invest in natural insurance instead (Quaas and Baumgartner, 2008). When exploitation of the commons does not require putting investment at risk, then people are more likely to over exploit the commons. This is the case when capital needed to exploit the commons is mobile or malleable, such as livestock. This scenario contrasts with the situation where uncertainty can lead individuals to underinvest in exploitation of a non-excludable resource in an effort to reduce risk (Libecap, 1993; Sandler et al., 1987; Sandler and Sternbenz, 1990). In this case, short run risk aversion can cause individuals to unintentionally pursue more sustainable resource use (Quaas et al., 2007). Particularly households consuming at the subsistence level are discouraged from risky investments when they lack access to insurance because they must maintain some minimal level of consumption (Dasgupta, 1997; Dercon and Christiaensen, 2011).

Poverty traps are often attributed to a lack of financial insurance or markets more generally, but incomplete property rights can also lead to poverty traps. A common motivation for a poverty trap involves risk preferences and endowments that interact to cause multistability, and impoverished individuals remain at low welfare equilibria because of lack of access to credit and financial insurance (e.g. Carter and Lybbert, 2012; Zimmerman and Carter, 2003) (Barrett and Carter, 2013). We show that when taking into account certain ecological externalities, insecure property rights can also lead to similar dynamics. In our case study, Senegalese agro-pastoralist choose between a risky investment in a cash crop subject to locust outbreaks and livestock production, which is invariant to locust outbreaks, on common pasture. We expect the agro-pastoralist to insure against outbreaks with livestock, reducing investment in the cash crop to protect wealth. However, locust outbreaks are connected to grassland degradation, which can be caused by overgrazing, creating an “insurance trap.”

The insurance trap is a result of endogenous risk and imperfect property rights regimes. Similar insurance traps can be found in the portfolios of permits held by commercial fishermen, the use of fertilizers and intensive farming practices that deplete soil nutrient content, suppression of small wildfires and increasing fuel bases, and the trade in illicit ivory where scarcity increases the financial incentive of poachers (Di Gregorio et al., 2008). In the context of institutional failure and missing property rights, we find that individuals may be particularly dependent on the common pool pasture to insure against catastrophic risk. Common pool resources are often most important to the poorest in society and resource degradation is tied to poverty traps (Dasgupta and Mäler, 1995). We define a new mechanism for resource degradation and institutional failure to lead to poverty traps – the ecological insurance trap.

1.2 Case study: Senegalese agro-pastoralists and locust outbreaks

Few environmental crises can be accurately described as biblical plagues. Locust outbreaks are such a risk (Exod. 10:15 RSV). Locust outbreaks are an important ecosystem externality associated with insuring against environmental risk with increasing livestock levels. Locust plagues result from phenotypic changes of resident grasshoppers (Pener and Simpson, 2009); locusts are not invasive pests per se. Phenotype changes can be thought of as random events, but recent research suggests a connection between the state of grassland and the probability of the phenotypic change from relatively benign grasshoppers to catastrophic locusts (Cease et al., 2015, 2012). Protein-rich grass enhances livestock production, but livestock reduce the available protein in grasslands, and low protein grasslands increase the probability of locust outbreaks (Brottem et al., 2014; Cease et al., 2012; Cease, 2017). Such locust outbreaks are associated with degraded or heavily grazed pastures that have reduced grass protein content (Cease et al., 2015, 2012; Giese et al., 2013).

Locust outbreaks threaten food production and economic activity in the African Sahel (Cheke et al., 1990; Maiga et al., 2008). As a result locust control strategies are a major expenditure in the region, with up to US $177 million spent from 1986-1992, but locusts remain a problem (Cease et al., 2015; Cheke et al., 1990). The threat of a locust plague is particularly serious in Senegal, where over 70% of the population lives on arid or semiarid land producing livestock and crops (a projected 20.3 million people by 2050 (Thornton et al., 2002)). While locust compete with livestock for grass in the pasture, they pose no direct threat to livestock. Livestock are therefore commonly used as an insurance mechanism against environmental risks including crop failure and drought (Bryan et al., 2013; Jarvis, 1974; Karanja Nganga et al., 2016; Mude et al., 2007). This insurance value and other non-market benefits have been estimated to be up to 40% of the benefits from livestock production in Kenya, Zambia, and Sri Lanka (Moll et al., 2007; Tarawali et al., 2011).

The dominant institutional arrangement in Senegal is a mix of grazing livestock on common property pasture and cultivating crops in private fields (e.g., nuts and millet). Common-property grazing institutions have evolved in much of the western Sahel, including Senegal, to facilitate long-distance migration between seasonal grazing sites and provide access to important pasture resources. Open access grazing "corridors" in this region allow herds to move along encampments to areas of greater seasonal forage (Brottem et al., 2014; Turner et al., 2016). These corridors connect key pastoral sites and settlements (Turner et al., 2016). These common-property arrangements allow local crop farmers to additionally invest in livestock husbandry as they wish, subject to household labor availability.

We show that the mix of private high-valued crops and common grazing that insurances against risk leads to a case where rural households over-invest in the "insuring asset" and miss out on higher returns that come from a diversified livelihood portfolio. We refer to this phenomena as an insurance trap.

2. Insurance Trap Model

A rural Senegalese pastoralist can allocate a fixed unit of labor effort to raising cash crops on private property or tending livestock herds on pastures. These pastures are commons. There are no social limitations on how many livestock an individual famer may graze; the pasture land is truly open access in the Gordon (1954) sense. There is the potential for locust outbreaks that destroy cash crops and pasture grass, but do not directly impact livestock. The probability of these outbreaks increases with livestock stocking density, which causes pasture degradation in the form of reduced plant protein – a condition favoring locusts (Cease et al., 2012).

2.1 Ecological model setup

Pastureland vegetation biomass, $x(t)$, dynamics follow

(1) $$\frac{\mathrm{dx(t)}}{\mathrm{dt}} = r * x(t) * \left(1 - \frac{x(t)}{\kappa}\right) - q\big(x(t)\big) * \sum_i z_i(t)$$

where r is the intrinsic rate of growth for vegetation, which we refer to as grass, κ is the carrying capacity of grass, $q(x(t))$ is a Holling Type II predation function (Gotelli, 2008) and $\sum_i z(t)$ is the sum of the biomass of livestock $z_i(t)$ that prey on grass and are owned by all $i = 1,2,3 \dots N$ pastoralists.[1] We assume that grass quality and abundance are correlated, so that lower quantities of grass imply lower nitrogen content, and a higher risk of locust outbreaks. The dynamics of each individual's livestock population are given by

[1] Vegetation may include forbs, sedges, rushes and other non-grasses. However, since these pasturelands are often referred to as grasslands, we adopt grass as a shorthand for vegetation. Fenichel et al. (2010) provide an economic interpretation of the Holling Type II equation.

(2) $$\frac{dz_i(t)}{dt} = q\big(x(t)\big) * z_i(t) * \eta * w_i(t) - \delta * z_i(t) - h_i(t) * z_i(t)$$

where η is the conversion efficiency of pastoralist i's livestock for converting grass biomass to livestock biomass, and δ is the natural mortality rate of livestock. In addition, there are two other terms reflecting the impact a pastoralist has on the system. An individual can harvest livestock at quantity $h_i(t)$, and he can also invest labor effort, $w_i(t)$, in managing livestock to increase the herd growth rate. Without human intervention $h_i(t) = w_i(t) = 0$. If the pastoralists spend some time tending their herds and harvest a constant proportion of their livestock this system follows a typical predator prey cycle, where livestock prey on grass (Gotelli, 2008).

2.2 Economic model setup

We are interested in two different institutional arrangements. In one situation, there is a social planner who coordinates the decisions of all users of the common pasture and chooses a level of effort $w_i(t)$ and harvest $h_i(t)$ for each individual, jointly controlling the entire stock of livestock, i.e., $z_i = z$, $w_i = w$, and $h_i = h$. This situation represents the case of well-defined property rights that internalize ecosystem externalities and risk consistent with local institutions that uphold long-term tenure security (Baland and Platteau, 1996; Ostrom, 1990), perfectly cooperative management, or private property. [2] We consider cases where the pastoralist does and does not make use of financial crop insurance that perfectly insures him against crop risk. Then, we model incomplete markets where the pastoralist chooses effort $w_i(t)$ and harvest rate $h_i(t)$, in a decentralized manner that only accounts for individual herd size, $z_i(t)$ and he take the choices made by other pastoralists, $\sum_{j\neq i} w_j(t)$ and $\sum_{j\neq i} h_j(t)$, and the overall herd size

[2] The transition to private property rights from common property is often a challenge, and in this context private property is associated with politically advantaging some groups. This is not our intent, and we do not address how privatization should occur in this paper. Rather, private property rights can also be thought of acting with collective action so that local institutions lead people to behave as if they have secure land tenure.

$z(t) = \sum_i z_i(t)$ as given. We also consider cases with and without financial crop insurance under this institutional regime.

The pastoralist has two revenue streams. First, he receives net revenues from the harvest and sale of his livestock, $R\left(h_i(t), z_i(t)\right)$. The revenues from harvest depend on the rate of harvest, and the quantity of available livestock. A larger biomass of livestock lead to stock effects either through higher quality animals available for slaughter, or a lower marginal cost of slaughtering a given quantity of meat, similar to Toth (2014). We assume grasslands are only marginally impacted by locusts, and therefore livestock are not directly affected by locust outbreaks.

Second, the pastoralist can earn income from cash crops (or gain the household production equivalent from household consumption of crops). Pastoralist i can allocate effort into farming $u_i(t) \leq 1$. This farming effort produces a harvest of cash crops $f(u_i(t))$ that are sold at price p. The pastoralist faces no other production costs aside from the opportunity cost of allocating a fraction of his unit of effort to ranching where $u_i(t) + w_i(t) = 1$.

To begin, we examine a world where the pastoralist maximizes profit without risk through effort spent on farming or ranching,

(3) $$pf(u_i(t)) + R\left(h_i(t), z_i(t)\right).$$

We may think of this scenario as one where a donor nation or agency provides costless and perfect crop insurance that protects pastoralists from the risk of locust plagues. However, locusts are a real risk in Senegal. Risk can be viewed to be endogenous or exogenous following descriptions established in the literature (Ehrlich and Becker, 1972; Kane and Shogren, 2000). In the exogenous risk case, the pastoralist is unable to directly impact the probability of the bad state, which is a locust outbreak in this case. Catastrophic locust outbreaks occur with probability $1 - \theta$, and if a locust outbreak occurs, then the entire period's crop production is consumed by the locusts. If the pastoralist acts as if locust plagues are exogenous to the state of the system and happen with fixed probability, then Eq (3) is modified to $\theta pf(u_i(t)) + R\big(h_i(t), z_i(t)\big)$. In this case, the pastoralist is restricted to reacting to the change in expected revenue from farming by shifting effort to lower risk activities, e.g., raising livestock.

Recent scientific discoveries (Cease et al., 2015, 2012) suggest that locust outbreaks are connected to the state of the system. Locust outbreaks are less likely when the pasture is maintained, so that $\theta'\big(x(t)\big) > 0$, and the pastoralist's expected instantaneous income is

(3′) $$\theta\big(x(t)\big)pf(u_i(t)) + R\big(h_i(t), z_i(t)\big).$$

Recognizing the connection between pasture and locust plagues makes risk endogenous to the state of the pasture (Shogren and Crocker, 1999). If society cooperates (i.e., the social planner's problem), then there are two pathways to control risk. The planner can manage livestock to affect the state of $x(t)$, changing the probability of a locust plague (self-protection or mitigation) and the social planner can shift effort away from crop production to reduce the damages from locusts should one occur (self-insurance or adaptation). However, with a common pasture the individual pastoralist cannot self-protect, and he can only self-insure by allocating effort away from crops and towards livestock. Holding more livestock insures income in the case of a locust outbreak, but increasing livestock may ultimately increase the probability of locust plagues. The decentralized pastoralist is constrained in his ability to self-insure because he is dependent on the livestock growth function. Livestock function as a capital asset (Jarvis, 1974; Zimmerman and Carter, 2003) and connect the pastoralist's decisions through time. The pastoralist's (or social planner's) objective function can be written as

$$\max_{u_i(t)\in[0,1],h_i(t)\in\mathbb{R}^{++}} \int_0^\infty \left(\theta\big(x(t)\big)pf\big(u_i(t)\big) + R\big(h_i(t),z_i(t)\big)\right) e^{-\rho t}\,dt$$ subject to (1) and (2).

(4)

where ρ is the discount rate, the social planner is assumed to manage all i pastoralists (so that i subscripts are dropped) and the probability of a locust outbreak $(1-\theta(x))$ is bounded between zero and one.[3]

2.3 Optimality conditions

To solve the pastoralist's allocation problem, we apply the Pontryagin Maximum Principle (Pontryagin and Boltyanskii, 1962) and write the current value Hamiltonian, CVH, (Conrad and Clark, 1987),

(5)

$$H_i = \theta(x)pf(u_i) + R(h_i, z_i) + \lambda(t)\left(rx\left(1-\frac{x}{\kappa}\right) - q(x)z\right) + \mu(t)(q(x)z_i\eta(1-u_i) - \delta z_i - h_i z_i)$$

where $z = \sum_i z_i$. The first two terms on the right-hand side (RHS) of the CVH are dividend or income flows, and the second two terms on the RHS are capital gains terms, where $\lambda(t)$ and $\mu(t)$ are the shadow prices of grass and livestock, respectively. They represent the marginal social worth of an additional unit of each stock.

It is useful to contrast the decentralized pastoralist's problem with the problem of a social planner who coordinates the system to internalize locust risk. The decentralized problem is the one faced by Senegalese pastoralists in reality. In the decentralized case, the number of users is large enough that each pastoralist ignores his own impact on the grass and makes decisions assuming $\frac{\partial z}{\partial z_i} \approx 0$ (Cheung, 1970; Dasgupta and Heal, 1979). Livestock remain private property,

[3] To focus on our core contribution, we assume the social planner and representative farmer have the same discount rate.

however the pastoralist loses the ability to exclude others from grazing livestock on the common pool resource. The decentralized pastoralist may somewhat endogenize risk through self-insurance by changing the value put at risk and adapting to $\theta(x)$, given that the famer can observe x and assuming $\theta'(x) \neq 0$. On the other hand, the social planner makes decisions as if $\frac{\partial z}{\partial z_i} = 1$ and replaces all z_i's with z, and can endogenize risk by adapting to $\theta(x)$ and by mitigating risk through maintaining a high value of x, thereby reducing $\theta(x)$. We also contrast the case where risk is endogenous, and agents acknowledge that the risk they face depends on x, $\theta'(x) \neq 0$, with a case where risk is assumed exogenous and agents observe the level of risk $\theta(x)$, but are unaware it depends on pastureland vegetation, so that they assume $\theta'(x) = 0$.

Whether the institutional arrangement lead pastoralists to act in a decentralized or cooperative manner, the allocation rule must satisfy four conditions, two first-order conditions and two arbitrage conditions. Regardless of the institutional arrangement the decision maker sets the marginal impact of allocating an additional unit of effort to crops on the CVH and the marginal impact of an additional unit of livestock harvest on the CVH to zero.[4]

(6) $$H_{u_i} = \theta(x)pf_{u_i}(u_i) - \mu q(x)z_i\eta = 0$$

(7) $$H_{h_i} = R_{h_i}(h_i, z_i) - \mu = 0.$$

Eq (6) states that the expected marginal net benefit of the additional unit of effort spent on farming, which consists of the marginal crop output $f_{u_i}(u_i)$ and constant price p weighted by the probability of a locust outbreak not occurring $\theta(x)$, must equal to the opportunity cost of that unit of effort. The opportunity cost of effort is the marginal increase in livestock productivity via an increase in herd growth, $q(x)z_i\eta z_i$, weighted by the shadow price of livestock μ. Effort is

[4] Subscripts that are not i or j denote partial derivatives

constrained to the unit interval. This optimality rule is not directly affected by the institutional arrangements governing pasture because livestock and crops are private assets.

The marginal impact of harvesting on the value of the current value Hamiltonian, Eq (7) states that the marginal revenue of harvesting livestock, $R_{h_i}(h_i, z_i)$, must equal the value of leaving an additional unit of livestock on the pasture, μ. The general nature of this optimality condition is also unaffected by the institutional arrangements because livestock is a private asset under both institutional arrangements.

Neither control function directly impacts pastures, which is why first order conditions, Eq (6)-(7), take the same form under the decentralized and social planner institutional arrangements.

The first-order conditions (6) and (7) can be combined to define the relationship between h_i and u_i,

(8) $$R_{h_i}(h_i, z_i) = \frac{\theta(x) p f_{u_i}(u_i)}{q(x) z_i \eta}.$$

In both problems, either when facing a sole owner or a common property resource, there is not unique control over the system (Fenichel and Horan, 2016). The only time it is possible to separate the choice of one control from the other is at a boundary solution. However, the treatment of risk impacts the relationship in Eq (8). All else equal, high levels of risk, i.e., low values of θ, reduce the expected return to time spent farming, reducing the opportunity cost of ranching. Therefore, all else equal, full costless insurance increases the expected marginal revenue from farming. The ordering of endogenous and exogenous risk is less clear because the rank order depends on the assumption about the exogenous risk.

In addition to the first order conditions, (6)-(7), the optimal program requires adjoint or no-arbitrage conditions that govern the dynamics of the co-state variables[5]

[5] This conditions are traditionally called arbitrage conditions, but we prefer to follow Karp (2017) and call

(9) $\dot{\mu}_i = \rho\mu_i - \frac{\partial H}{\partial z} = \rho\mu_i - R_{z_i}(h_i, z_i) + \lambda q(x)\frac{\partial z}{\partial z_i} - \mu(q(x)\eta(1-u_i) - \delta - h_i)$

(10)

$$\dot{\lambda}_i = \rho\lambda_i - \frac{\partial H}{\partial x} = \lambda_i\left[\rho - \left(r - 2\frac{rx}{\kappa} - q_x(x)z(z_i, z_{-i})\right)\right] - \theta_x(x)pf(u_i) - \mu q_x(x)z_i\eta(1-u_i)$$

The institutional arrangements qualitatively affect the value and evolution of the shadow prices, λ and μ. This is because shadow prices are a function of the institutions that guide the resources are allocated (Fenichel and Abbott 2014; Horan et al. 2011). The critical difference is between the decentralized decision process and the social planner's decision process is the third RHS term in Eq (9), which is $\lambda q(x)$ in the social planner's case, but vanishes in the decentralized case. The shadow value of pasture only impacts the rate that the shadow value of livestock changes for the social planner. Specifically the relationship between the social planner and decentralized institutions is $\dot{\mu}_{social\ planner} = \dot{\mu}_{decentralizd\ commons} + \lambda q(x)$. The treatment of risk also impacts the evolution and value of the shadow price of grass. If risk is exogenous, which includes the fully and costlessly insured case, then the second RHS term in Eq (10) vanishes. This occurs because if locust risk is exogenous then the value of crop production has no impact on the shadow price of pasture. Eq (10) shows that, all else equal, the equilibrium marginal value of pasture is increased by treating risk as endogenous relative to the case where risk is exogenous. Specifically, the relationship between endogenous and exogenous risk is captured by $\dot{\lambda}_{endogenous} = \dot{\lambda}_{exogenous} - \theta_x(x)pf(u_i)$.

The no-arbitrage conditions provide insight into the value of both resources. In the most general form, Eq 9 implies

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them no-arbitrage conditions, because the conditions eliminate arbitrage opportunities.

(11) $$\frac{\dot{\lambda}}{\lambda} = \left[\rho - \left(r - 2\frac{rx}{\kappa} - q_x(x)z\right)\right] - \frac{p}{\lambda}\theta_x(x)f(u) - \frac{\mu}{\lambda}q_x(x)z\eta(1-u_i)$$

where the growth rate for the value of grass in the pasture evolves at a rate equal to the discount rate ρ less a discount for the net growth of grass, $\left(r - 2\frac{rx}{\kappa} - q_x(x)z\right)$, which includes the intrinsic rate of growth and the impact of a change in the amount of grass on the growth rate and predation function. In addition, in each instant the value of grass in the field is reduced by dividends for the higher expected return due to reduced locust outbreak risk from having more grass, where the price of output is normalized by the shadow price of grass in the field. Similarly there is a dividend associated with the change in the growth rate for livestock due to more grass in the field, where the shadow price of livestock in the pasture is normalized by the price of grass. Ceteris paribus, endogenous risk reduces the rate at which λ increases, so that the overall amount of grass optimally increases.

Rearranging Eq (9) yields

(12) $$\frac{\dot{\mu}}{\mu} = [\rho - (q(x)\eta(1-u_i) - \delta)] - \frac{R_z(h,z)}{\mu} + \frac{\lambda}{\mu}q(x)$$

where the value of livestock in the pasture must grow at a rate equal to the discount rate, less a premium for the change in net growth of livestock. In addition, in each period the value of livestock in the pasture is reduced by the change in revenue from harvest due to having more livestock, normalized by the price of livestock in the pasture and a premium for changes in the overall predation of grass.

It is possible to solve for equilibrium values of the shadow prices, stock sizes, and control levels by setting equations (1),(2),(6),(7), (10) and (9) equal to zero solving for the combination x, z, λ,μ, u_i, h_i. Analytical solutions for the optimal paths do not exist. This is because the problem is non-linear in the controls and neither control variable provides direct control over the stock of grass, x. In such under controlled setting the solution must be written in feedback form (Fenichel et al., 2010; Fenichel and Horan, 2016; Horan et al., 2011; Salau and Fenichel, 2015). The nonlinear nature of the problem in the controls means that such a feedback rule cannot be found analytically. To see this solve equations (6) and (7) for μ and take the time derivatives, which respectively yields

(13) $$\dot{\mu}_i = p\frac{\left[\theta_x \dot{x} f_{u_i}(u_i) + \theta(x) f_{u_i u_i}(u_i)\dot{u}_i\right] q(x_i) z_i \eta - \left[q_{x_i}(x_i) z \eta \dot{x} + q(x)\eta \dot{z}_i\right] \theta(x) p f_u(u)\Big]}{(q(x_i)\eta z_i)^2}$$

and

(14) $$\dot{\mu}_i = R_{h_i h_i}\dot{h}_i + R_{h_i z_i}\dot{z}_i$$

Equations (9), (13), and (14) must all be equal. Either (13) or (14) can be set equal to (9) and solved for λ. However, if one tries to take the time derivative of the resulting expression of λ with respect to time in order to set the result equal to Eq (10) the resulting time derivative contains a second derivative with respect to time for the other control variable. This means the number of unknowns will continue to exceed the number of equations. This occurs because of the one-to-one relationship in Eq (8), so that effectively there is only one control variable assuming an interior solution.

2.4 Solution Method

In order to better understand the dynamics of the system, we follow Fenichel and Horan (2016) and exploit the Hamilton-Jacobi-Bellman (HJB) identity.[6] We use numerical value function approximation techniques to recover the continuous time optimal feedback rule (Miranda and Fackler, 2004). Using the HJB identity, we rewrite Eq (5)

(15) $$\rho V(x, z_i) = \max_{\mathrm{u_i, h_i}} \theta(x) p f(u_i) + R(h_i, z_i) + V_x\left(rx\left(1 - \frac{x}{\kappa}\right) - q(x)z\right) +$$

[6] For other examples of similar approaches see (Balikcioglu et al., 2011; Fenichel et al., 2014; Marten and Moore, 2011).

$V_z(q(x)z_i\eta(1-u_i)-\delta z_i-h_i z_i)$

Then, we approximate $V(x,z) \approx \Phi(x,z) = \sum_{n=0}^{N-1} \beta_n \phi_n(x,z)$, $\Phi(x,z)$ is a two dimensional Chebyshev polynomial with N basis functions that span the state space (Miranda and Fackler, 2004).[7] β is a vector of coefficients that determine the weighting of the basis functions. We define u_i^* and h_i^* as functions of only states and co-states, using Eq (6) and (7). Fenichel and Abbott (2014) show that derivatives of Chebyshev polynomials are good approximations for the derivatives of the function that the polynomial is being used to approximate so long as appropriate derivative basis functions are used. This is because the polynomial is linear in β. Therefore, we can define an error vector on a grid of at least N nodes, which we distribute as the roots of a two-dimensional Chebyshev polynomial.

(16) $\epsilon = \rho\Phi(x,z_i) - \theta(x)pf(u_i^*) - R(h_i^*,z_i) - \Phi_x(x,z_i)\left(rx\left(1-\frac{x}{\kappa}\right)-q(x)z\right) -$

$\Phi_z(x,z_i)(q(x)z_i\eta(1-u_i)-\delta z_i-h_i^* z_i)$

The function Φ is solely a function on observed state variables and unknown Chebyshev coefficients. Therefore, the vector of coefficients, β, that minimizes $\epsilon'\epsilon$ provides a good approximation for V, $V_x=\lambda$, and $V_z=\mu$ enabling us to approximate the optimal dynamics. By using a vector of nodes the same length of β we are able to solve the system exactly, a process known as collocation (Miranda and Fackler).

3. Numerical Example

Due to the complexity of analytical analysis, a numerical example is included to display results. The parameter values and functional forms are shown in Table I.

3.1 Ecological model

[7] Two dimensional Chebyshev polynomials can be built as the tensor product of one dimensional Chebyshev polynomials. The combination of Chebyshev nodes and polynomials distributes the error between the approximating and unknown true function evenly, resulting in the best polynomial specification for functional approximation (Press et al., 2007).

We begin by plotting the stable limit cycle when the system is allowed to exist in a semi-natural state consisting only of "wild" livestock and grass – a world without people. In this system, livestock are not harvested, but all pastoralist effort is dedicated to maximizing livestock growth rate – this is the equivalent of "wild" animals that are able to fend for themselves without human intervention. Livestock act as predators of grass, and the dynamics are shown in the phase plane in Fig 1. Livestock is on the vertical axis, and grass on the horizontal axis and both are measured in units of kg/ha. Livestock are measured in wet weights while grass is measured in dry weights. Wet weight is used for livestock because this is typically the more interesting number when selling for meat consumption. We plot the null-cline for livestock ($\dot{z} = 0$) and a null-cline for grass ($\dot{x} = 0$) as well as trajectories that shows the direction of movement at any point in the state space. The system follows a counter-clockwise stable limit cycle, demonstrating classic predator prey dynamics (Gotelli, 2008). The stability and size of the cycle is dependent on the choice of parameters for the Holling Type II predation function and mortality and growth rates; however this general pattern is repeated for various parameter choices. Fenichel and Horan (2016) show that the Hessian matrix for this common predator-prey system is not strictly definite negative. Therefore, an optimal management problem for this system will not satisfy the Mangasarian sufficiency conditions for a unique maximum (Caputo, 2005).

3.2 Bioeconomic model

We now analyze the bioeconomic model and summarize our numerical results in Table II with welfare and probability calculations. While it is straightforward to Pareto rank equilibria conditional on starting at an equilibrium, the common pool pasture scenario lacks a stable equilibrium and instead features a stable limit cycle. Welfare therefore depends on the expected value of income received over the duration of the cycle into the future. Our numerical approach enables us to compute the optimal path at any point in state space, including over the stable limit cycle.

3.2.1 Farming only

We begin the bioeconomic analysis by considering the production decision of an individual restricted to only farming. The pastoralist faces the profit function

(17) $$p_c\left(u-\frac{1}{2}u^2\right)\left(0.3+\left[\frac{2.5x}{5000+x}\right]^2\right)$$

Without the option to invest in cattle, the pastoralist faces a probability of a catastrophe equal to $1-\left(0.3+\left[\frac{2.5x}{5000+x}\right]^2\right)$ and the production function for agricultural products $\left(u-\frac{1}{2}u^2\right)$, which the pastoralist maximizes by setting $u=1$ with expected income equal to Eq (17). This yields an expected instantaneous welfare at equilibrium equal to the price of the produced crops, p_c, weighted by the probability the crop survives, $\left(0.3+\left[\frac{2.5x}{5000+x}\right]^2\right)$. If individuals are only able to farm, lacking access to financial insurance we assume they are unable to mitigate locust risk.

3.2.2 Livestock only

Next, we consider the choice of pastoralists who are restricted to ranching, and face the revenue function

(18) $$p_r h^{0.75} z^{0.25}$$

which does not depend on the probability of a locust outbreak. Livestock and harvests are modelled as substitutes in production because of stock effects, these stock effects enable the same payoff to be earned with lower harvest if the herd itself is larger. This is because the unit cost of management can be less and because of animal products like milk. The price of livestock p_r is multiplied by net production, $h^{0.75}z^{0.25}$, to find the revenue from harvests. Effort invested in raising livestock does not directly impact the revenue function, but instead indirectly impacts it through reduced livestock mortality. This reduced mortality leads to a larger overall stock, greater revenue for the pastoralist, and is maximized when $u = 0$, assuming no opportunity cost of labor time.

We solve the pastoralist's problem for scenarios when the pasture is a common pool resource and when pasture is private property using the dynamic programming method outlined in section 2.4. The feedback control diagram shown in Fig 2 displays the solutions to these problems. The left panel shows the optimal strategy from each point in state space for the private grassland, and the right panel shows the optimal strategy at each point in the state space when the grassland is a common pool resource.

There is a single universally optimal steady state when pasture is privately owned. This equilibrium can be found analytically and is well approximated by our solution technique. If we introduce humans into the natural system, they harvest livestock at a rate high enough to reduce the population and allow the stock of forage to reach relatively pristine conditions. People with private property rights act as stewards that increase the quality of available pasture. Contrary to the ecological insurance hypothesis (Loreau et al., 2003), it is people, not ecological feedbacks, that stabilize the system in this case.

If the pasture is a common pool resource, the story is analogous to private property rights, however individual pastoralists are never able to achieve a steady state. Humans introduced into the system slow the recovery of depleted livestock populations at low levels of grass. By slowing the growth rate of livestock populations, the pasture is allowed to recover more than when animals go uncontrolled. However, because pastoralists cannot prevent others from grazing their animals on the common pool resource the pasture is eventually depleted. This leads to an unsustainable population of livestock, to farmers harvesting the surplus animals, and ultimately to a stable limit cycle.

3.3.3 Farming and Ranching with Insurance

Next, consider a pastoralist who “settles down” and can allocate effort to ranching and farming. We assume at first this individual is perfectly insured against crop failure, either through a government program or non-government organization (NGO). This program provides him with the full market value of his expected crop, regardless of locust outbreak status (the equivalent of $\theta(x) = 1$). The feedback control diagrams (Fig 3) show the optimal choice at every point under this scenario with private property (left panel) and common property pasture (right panel). We plot the optimal null-clines for grass and livestock. We find one globally optimal steady state when pastoralists have private property rights to pasture.

By evaluating the Hamiltonian at the steady state our welfare calculations show that when they compare “naïve” welfare, which assumes they face no risk of collapse, pastoralists do better by performing both activities relative to only farming or only ranching (Table II). The same pattern holds in the common property cases, as farmers would face risk of locust outbreaks from the ranching activities of other pastoralists, and performing both activities provides greater welfare than only ranching.

The pastoralist expends more effort on ranching when the pasture is a private resource relative to when it is common property, as they can capture positive growth externalities with a smaller, faster growing herd due to higher quality pasture. When pasture is common property, the pastoralist maintains a considerably larger stock of livestock, harvests a larger amount of animals, and degrades the pasture to a lower level. This behavior is in response to pastoralists’ inability to capture rents from a healthy pasture via livestock growth. The degraded pasture leads to a greater probability of locust outbreak, but the pastoralists ignore this risk because they are fully insured against plagues.

3.3.4 Farming and Ranching with Exogenous Risk but No Insurance

In our next two cases the pastoralist is not insured against locust plagues (Fig 4). We assume the state of science or political will is such that individuals treat locust outbreaks as a curse from the heavens and beyond human control. When pastoralists have private property rights over the pasture, a stable focus prevails. Pastoralists reduce their farming effort relative to when they are fully insured, and increase their efforts to grow their livestock herds. Their efforts to increase livestock growth lead to larger harvests, and only marginally impact the pasture and risk of a locust plague compared to when they were fully insured. This is because pastoralists are still able to capture rents from a well-managed pasture via faster livestock growth.

In contrast, when pastoralists lack property rights a stable limit cycle prevails and they drastically increase their livestock herd and reduce their farming effort relative to when they were insured. They harvest a lower proportion of their cattle, and rely on livestock to insure against catastrophe. They trade off potential income in a world where a locust plague dos not occur, or their “naïve” welfare, for a higher expected welfare. When they believe locust plagues likely and beyond their control, pastoralists self-insure against the locust plagues by reducing the asset they have at risk (crops) and increasing their investment in the “safe” asset, livestock.

Pastoralists have the option to abandon farming entirely. A pastoralist with property rights facing an exogenous locust threat (and sufficiently undisturbed pasture) would be better off abandoning ranching and only farming. As performing both activities is the most profitable outcome, an international agency is faced with an interesting conundrum. They could pay pastoralists in reaction to outbreaks, however the expected welfare of pastoralists before the transfer payment is the same as if they did nothing. In this case, pastoralists are no more productive when they know about the payments ahead of time.

3.3.5 Farming and Ranching with Endogenous Risk but No Insurance

When the pastoralist identifies the link between his (and his neighbors') actions and the risk of locust plagues he expends more effort on agriculture relative to the exogenous risk case, but less than when he is fully insured. The solutions to the dynamic programming problem and null-clines are shown in the feedback control diagrams in Fig 5. When pastoralists have private property rights they prefer to self-protect rather than self-insure, and holds a significantly smaller herd leading to a healthier pasture and lower locust plague risk. When pasture is common property, pastoralists maintains smaller average stock of livestock than when risk was exogenous with a slightly lower risk of locust outbreaks. Pastoralists also spend slightly more effort on farming.

This divergence is a result of the property rights regime – when pasture is private property, the pastoralist attempts to protect himself from the bad outcome (locust plague) by reducing the probability of an outbreak through higher quality pasture. When pasture is a common property the pastoralist knows that larger herds will degrade the pasture and cause locust outbreaks, but he is unable to reduce this probability more than a nominal amount because any grass left in the field will be consumed by the livestock of a rival.[8] Instead the pastoralist invests in self-insurance (livestock). This self-insurance exacerbates the risk of an outbreak, and can act as an insurance trap.

[8] Large wildlife populations could also lead to this result, but we abstract from wildlife interactions in this paper.

The lack of private property rights causes the risk-aware pastoralist to prefer abandoning farming entirely, even though on its own it is the more profitable activity. If a pastoralist facing common pool pasture had to choose which activity to give up while in the stable limit cycle, the expected value of only ranching is always higher than the expected value of farming. This is because in a common pool pasture situation, the individual pastoralist is only choosing his own activity. In addition even if one pastoralist abandoned ranching his neighbors would continue to degrade the pasture.

4. Discussion

There are justifiably large concerns about the role of risk and uncertainty in environmental decision making, but ultimately risk may be second-order relative to institutional arrangements. Scientific understanding of an environmental externality is a necessary but not sufficient condition for managing the risk as institutional failures cause agents to knowingly invest in insurance mechanisms that increase the probability of catastrophe. Thus common pool property regimes remain a problem even when ecological relationships are well understood.

The impact of risk on the amount of grass and livestock pastoralists choose to hold involves two different effects, self-protection and self-insurance (Shogren and Crocker, 1999). Faced with common property pasture, pastoralists are unable to self-protect by reducing the probability of catastrophe and instead “bet the farm” on self-insurance, increasing the overall risk. Facing a lack of property rights, individuals can count on others exacerbating the risk by self-insuring, and therefore find themselves in a tragedy of the insurance commons. This divergence; a move from self-protection (conserving the pasture) towards self-insurance (holding more cattle and degrading the pasture) is the insurance trap.

The escape from the insurance trap comes in the form of institutional reform to ensure more secure land tenure and to increase cooperation between individuals so that ecological externalities can be internalized. This approximates private property rights in our model, which increase welfare even when risk is treated as exogenous or fully insured. While it seems straightforward to transition to a scenario with property rights, limiting access to the common pool pasture to benefit pastoralists may be a difficult political proposition. While some individuals would win from lower locust risk and more productive agriculture, others would lose traditional access to valuable resources. Responding to this problem by providing perfect insurance fails to solve the underlying problem. Financial insurance provided without cost by an outside organization simply acts as a transfer from the donating agency to the pastoralist.

Without reform, over investment in self-insurance can lead to a poverty trap that is difficult to escape. Poorer households may partake in asset smoothing to protect their minimal wealth and maintain at least a subsistence level of consumption (Carter and Lybbert, 2012; Dercon and Christiaensen, 2011). Our findings that individuals become trapped in less productive activities mirrors the result in the literature where risk causes individuals to do the same (Barrett and Carter, 2013; Zimmerman and Carter, 2003). Our analysis argues that attempting to solve these problems by providing crop insurance will still leave individuals over invested in “safe” activities, unless underlying property rights or collective action problems are also addressed. Efforts to be egalitarian and maintain traditional access to commons and rights regimes are often at the heart of environmental risk, exposing people that policy most intends to protect.

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Tables

Table I. Parameter values for numerical simulations.

Parameter	Definition	Value
ρ	Discount rate	.05/365
β	Livestock half-saturation (1000 kg/ha)	1600
r	Grass growth rate	0.06
ϕ	Max livestock uptake of grass (1000 kg/ha)	0.047
δ	Livestock mortality	.0032
η	Grass to livestock conversion	0.7
κ	Grass carrying capacity (1000 kg/ha)	2500
$q(x)$	Holling Type II function	$\frac{\theta x(t)}{\beta + x(t)}$
p_c	Price of crops	2.5
p_r	Price for sold cattle	1.95
$\theta(x(t))$	Effective risk	$0.3 + \left(2.5 \frac{x}{\beta + x}\right)^2$
$f(u(t))$	Crop production function	$0.5\left(u - \frac{1}{2}u^2\right)$
$R(h,z)$	Cattle harvest revenue	$p_r(h^{0.75} z^{0.25})$

Table II. Numerical results of different risk and property rights regimes when individual are able to spend time either ranching or farming. The first column denotes the stead state discussed and the second column denotes the risk regime. “Naïve Welfare” is the expected value of the system omitting risk, “Welfare” is the expected value net of locust outbreak risk.

			Grass (dry kg/ha)	Livestock (wet kg/ha)	Outbreak Probability	Farming Effort (% of effort)	Harvest	Cycle Length	"naïve" Welfare (USD)	Welfare (USD)
Farming Only			2500.0	0.0	0.56%	100%	0.0000%	N/A	$4,563	$4,537
Private	Ranching Only		1749.1	1284.2	28.02%	0.0%	1.3982%		$3,465	$3,465
	Fully Insured		1879.6	1102.4	23.35%	54.6%	0.4863%		$5,134	$4,288
	Exogenous Risk		1830.2	1173.2	25.12%	43.8%	0.6663%		$5,065	$4,281
	Endogenous Risk		2374.6	254.6	5.20%	62.1%	0.4257%		$4,853	$4,650
Common	Ranching Only	min	44.7	2066.5	69.95%	0.0%	0.2366%	456	$1,003	$1,003
		avg	293.6	2057.3	68.08%		0.2287%			
		max	1007.0	1986.4	52.44%		0.2662%			
	Fully Insured	min	69.1	2069.0	69.88%	92.9%	0.0518%	488	$4,317	$1,746
		avg	513.1	2033.7	64.59%	64.3%	0.0534%			
		max	1383.5	1697.4	40.64%	25.5%	0.0560%			
	Exogenous Risk	min	158.1	2100.5	69.41%	65.1%	0.2327%	370	$3,493	$1,883
		avg	477.4	2106.2	65.25%	32.2%	0.2341%			
		max	945.2	2026.0	54.20%	6.9%	0.2556%			
	Endogenous Risk	min	158.1	2100.5	69.41%	65.1%	0.2327%	400	$3,611	$1,911
		avg	456.6	2078.7	65.62%	34.2%	0.2334%			
		max	945.2	2026.0	54.20%	6.9%	0.2556%			

Figures

Figure 1. Without human interference, the livestock and grass dynamics follow a stable limit cycle (SLC) reflecting a predator prey system. Units are in thousands of kg/ha.

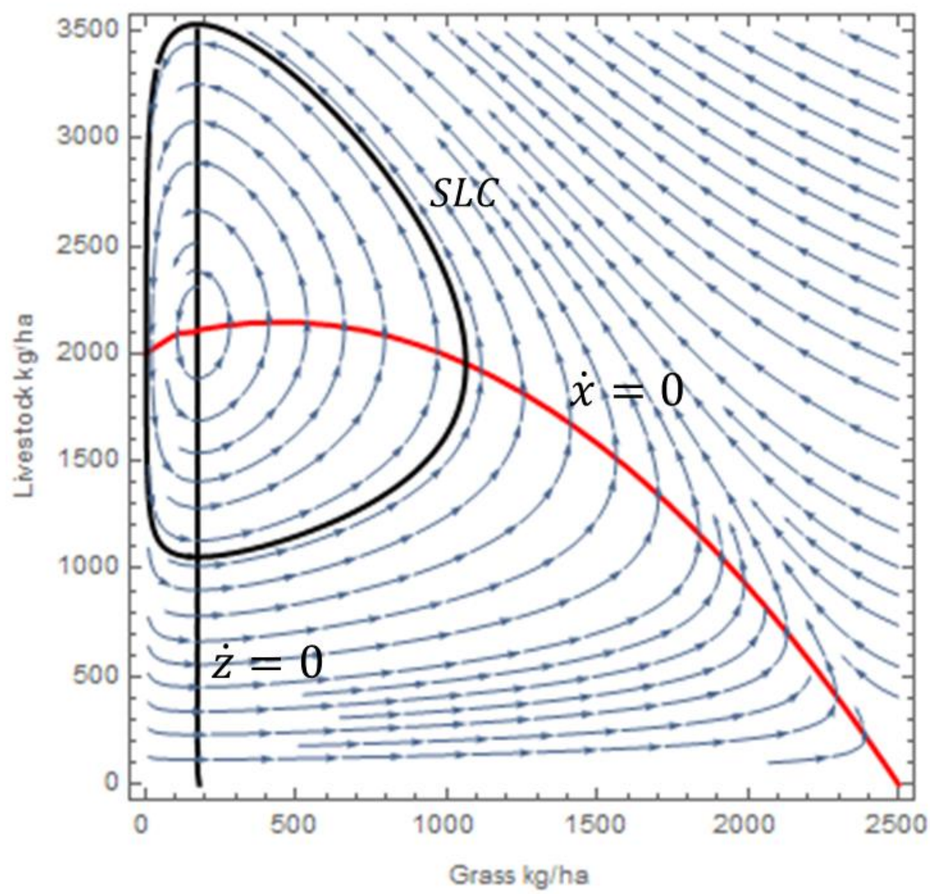

Figure 2. The optimal mixture of grass and livestock when pastoralists are only able to spend time ranching. The left panel is when pastoralists have private property rights over pasture, and a steady state level of livestock and grass is maintained (SS), which is both solved for analytically and approximated numerically by our solution method. On the right, the pasture is common pool property and a stable limit cycle occurs (SLC). The approximation areas for our solution method are highlighted in blue, with optimal trajectories plotted within.

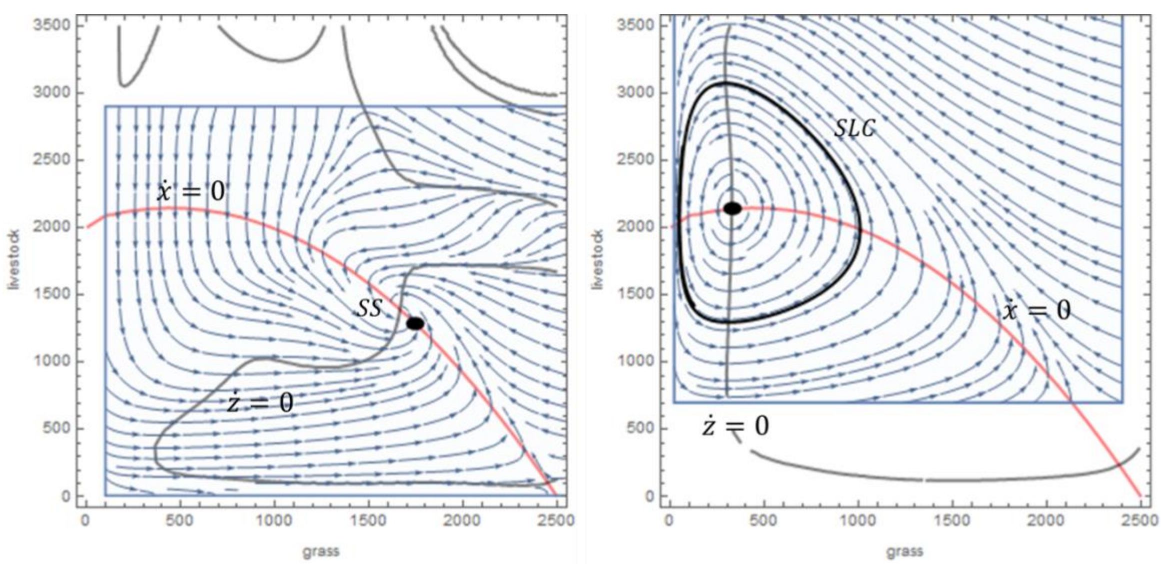

Figure 3. The optimal mixture of grass and livestock when pastoralists are fully insured for locust risk. The left panel is when pastoralists have private property rights over pasture, and we solve analytically for a steady state level of livestock and grass (SS) as well as numerically approximating this point at the intersection of the $\dot{y} = 0$ and $\dot{x} = 0$ nullclimes. On the right, the pasture is common pool property and a stable limit cycle occurs (SLC). The approximation areas for our solution method are highlighted in blue, with optimal trajectories plotted within.

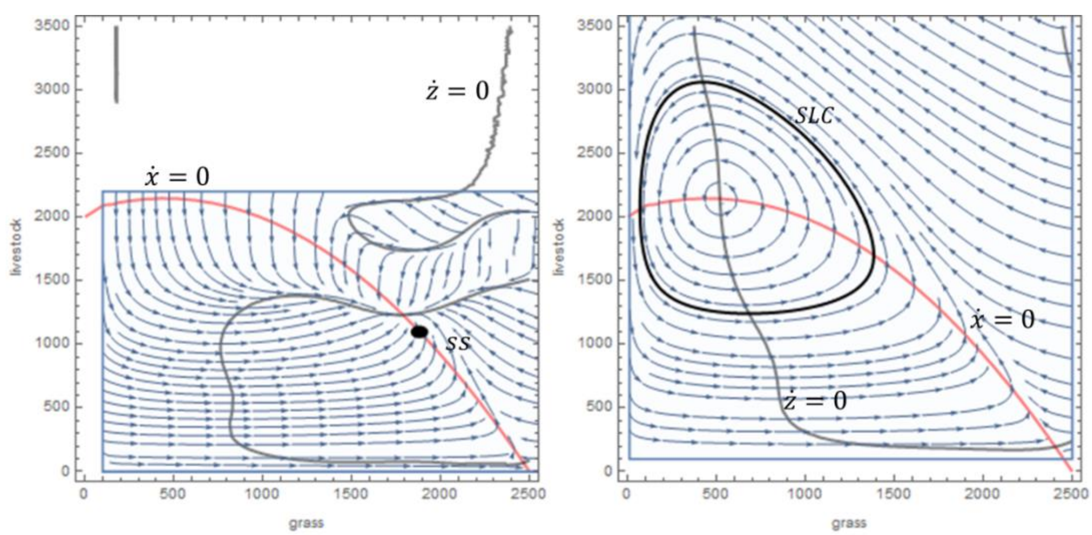

Figure 4. The optimal mixture of grass and livestock when locust risk is exogenous and pastoralists are not perfectly insured. The left panel is when pastoralists have private property rights over pasture, and a steady state level of livestock and grass is maintained (SS), and this point is solved for analytically and approximated by our solution method. On the right, the pasture is common pool property and a stable limit cycle occurs (SLC). The approximation areas for our solution method are highlighted in blue, with optimal trajectories plotted within.

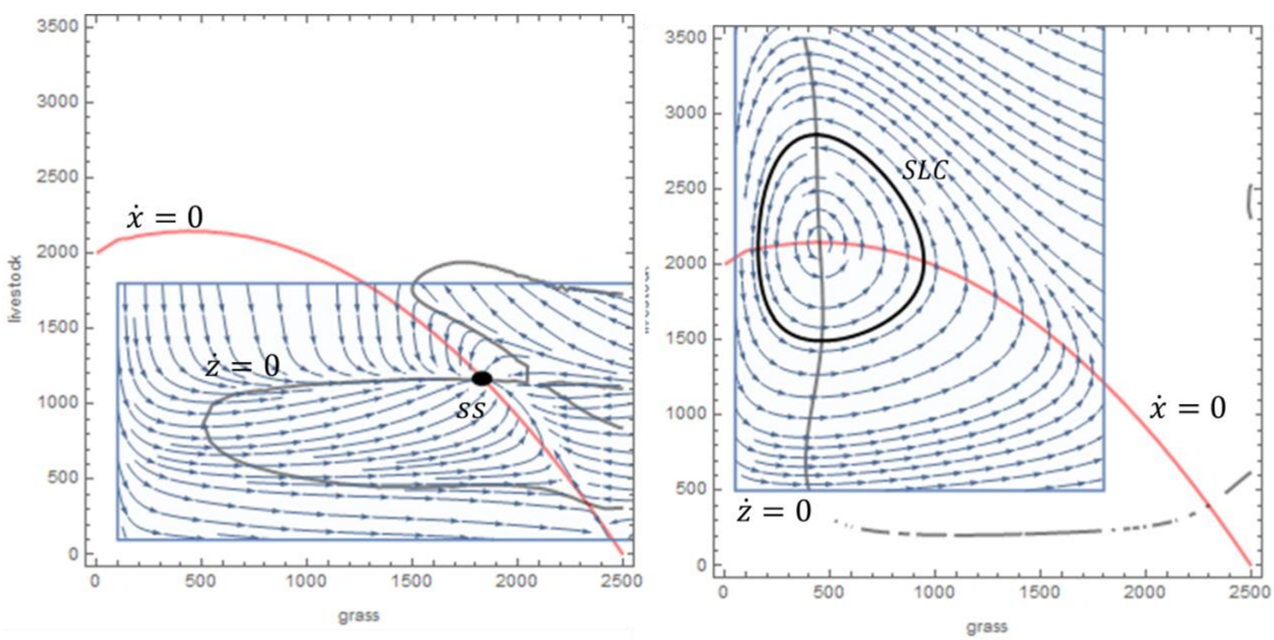

Figure 5. The optimal mixture of grass and livestock when locust risk is endogenous and pastoralists are not perfectly insured. The left panel is when pastoralists have private property rights over pasture, and a steady state level of livestock and grass is maintained (SS). This steady state is solved for analytically and approximated numerically by our solution method. On the right, the pasture is common pool property and a stable limit cycle occurs (SLC). The approximation areas for our solution method are highlighted in blue, with optimal trajectories plotted within. Estimates of the $\dot{z}$ nullcline outside the approximation area may be approximation error.