Journal of Environmental Economics and Management 98 (2019) 102251

Contents lists available at ScienceDirect

Journal of Environmental Economics and Management

journal homepage: www.elsevier.com/locate/jeem

The ecological insurance trap

Kevin Berry [a,*], Eli P. Fenichel [b], Brian E. Robinson [c]

[a] University of Alaska Anchorage, 3211 Providence Drive, Anchorage AK, 99501, United States
[b] Yale School of Forestry & Environmental Studies, 120 Kroon Hall, New Haven CT, 06510, United States
[c] McGill University, 805 Sherbrooke St West, Canada

ARTICLE INFO

Article history:
Received 12 January 2018
Received in revised form 30 May 2019
Accepted 7 August 2019
Available online 9 August 2019

JEL classification:
Q20
Q54
Q57

Keywords:
Environmental externality
Common pool resources
Poverty trap
Endogenous risk

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 can 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 risk management decisions that increase the probability of catastrophe, creating an "insurance trap."

1. Introduction

Insurance is often portrayed as an important ecosystem service (Baumgärtner, 2007; Baumgärtner and Strunz, 2014; Loreau et al., 2003; Naeem and Li, 1997; Quaas and Baumgärtner, 2008). The ecological insurance argument is based on the idea that ecological processes stabilize ecosystems, providing an insurance effect (Loreau et al., 2003). However, these ecological processes may be more of a self-protection effect, reducing the probability of bad events, rather than an insurance effect that redistributes income from a good state to a bad state of the world (Ehrlich and Becker, 1972; Shogren and Crocker, 1999). Furthermore, 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; Horan et al., 2018b). But institutions determine who makes decisions and whether there is sufficient coordinated control (Berkes et al., 2008; Ostrom, 1990). Without secure property rights or other mechanisms that lead to cooperation, individuals can 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, people do what they can to avoid potential losses. This includes engaging

* Corresponding author.
E-mail addresses: Kberry13@alaska.edu (K. Berry), eli.fenichel@yale.edu (E.P. Fenichel), brian.e.robinson@mcgill.ca (B.E. Robinson).

https://doi.org/10.1016/j.jeem.2019.102251
0095-0696/

in self-insurance that could involve ecological production. If the act of investing in self-insurance uses ecological production, then it is possible that the act of self-insuring increases the risk of bad events. If this happens individuals may become trapped in a state of high risk despite their attempts to insure.

Income traps are a common concern in the economic development literature, and household decision makers that lack access to financial markets 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) or are simply unable to finance higher yielding, non-marginal fixed capital investments (Fenichel et al., 2019). Ecological and financial insurance can act as substitutes, so that lacking access to financial insurance, individuals may use ecological production to generate a self-insurance asset instead (Quaas and Baumgärtner, 2008). Such behavior follows the broader literature that market insurance and self-insurance are substitutes (Ehrlich and Becker, 1972).

Poverty traps are often attributed to a lack of financial insurance or markets, 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 multi-stability, and impoverished individuals remain at low welfare equilibria because of lack of access to credit and financial insurance (Barrett and Carter, 2013; Carter and Lybbert, 2012; Zimmerman and Carter, 2003). We show that when considering ecological externalities, insecure property rights can lead to similar dynamics. In the case study, Senegalese agro-pastoralists choose between a risky investment of scarce labor resources in a cash crop subject to locust outbreaks and livestock production, which is invariant to locust outbreaks. Therefore, livestock are an insurance asset. However, livestock production takes place on common pasture. We expect the agro-pastoralist to use livestock to insure against locust outbreaks to protect income, reducing investment in the cash crop. Locust outbreaks are connected to grassland degradation (Cease et al., 2015, 2012), which can be caused by overgrazing, creating an "insurance trap."

The insurance trap results from an interaction between the endogenous nature of risk and imperfect property rights. If the capital used to harvest in the commons also provides self-insurance with respect to other income streams, then this insurance benefit can lead to even greater exploitation of commons. Yet commons are often complex ecosystems, so greater exploitation may increase other costs or generate other risks. These other risks are generated via a common pool and are not internalized. In this context of institutional failure and missing property rights, individuals may be particularly dependent on the common pool pasture to insure against catastrophic risk. Therefore, exploitation and the costs or damages of the commons may exceed costs calculations from standard models that ignore interactions with other markets.

The self-protection and insurance literature largely focus on two market effects: how reducing the losses associated with a disaster leads to less self-protection, and how reducing the price of insurance when individuals engage in self-protection reduces incentives for self-protection (Ehrlich and Becker, 1972). Ehrlich and Becker (1972) demonstrate that a larger "loading factor" or the markup above a "fair price" for insurance discourages insurance. We demonstrate that ecological interactions create an "ecological loading factor." The ecological loading factor that decision makers respond to is dependent on the set of resource shadow prices that those decision makers respond to. Indeed, relationships like predator-prey feedbacks can increase ecological loading factors. Furthermore, the process of self-insuring can go beyond failing to mitigate an adverse event and can increase the probability of the event. This makes insuring using ecological production costly and shifts cooperative managers to focus on "self-protection."

We contribute to the literature by placing the "ecological insurance concept" in the context of the theory of the second-best (Lipsey and Lancaster, 1956). The most common use of "ecological insurance" may be cases where financial insurance markets are missing. However, when ecological insurance involves open access to commons and processes in the commons generate the risk (e.g., through ecological externalities), then self-protection is in fact "group protection." Therefore, the coordination problem involves unpriced risk and underpriced resources. Specifically, common property regimes reduce realized shadow prices and reduce the realized "ecological loading factor." This leads to excess investment in using ecological production to generate a private self-insurance asset, but this increases the probability of bad events in addition to leading to undersupply of common pool resources. An important insight is that ecosystems provide opportunities for self-insurance and for group or self-protection. Assumptions of cooperative solutions focus on protection rather than insurance, which leads us to question the "ecological insurance metaphor."

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). Indeed, common pool resources remain common throughout the world and are often most important to the poorest in society and resource degradation is tied to poverty traps (Dasgupta and Mäler, 1995; Stavins, 2011).

1.2. Case study: Senegalese agro-pastoralists and locust outbreaks

Few environmental crises can be accurately described as biblical plagues, but locust outbreaks can be (Exod. 10:15 RSVCE). Locust outbreaks are an important ecosystem externality associated with intense livestock grazing. 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 to 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, a privately owned capital stock, are 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 insures against risk can lead to a case where rural households over-invest in the "insuring asset" and miss out on higher returns that come from raising crops. We refer to this phenomenon as an ecological insurance trap.

2. The insurance trap

We develop a model of a decisionmaker faced with the choice between investing effort in a high-valued, but risky, activity or in developing a stock of private capital that can provide an alternative revenue source. This stock of private capital influences the probability of adverse events through a second stock, which depending upon human institutions can be either treated as private property or commons. Weak institutions incentivize reliance on private capital and increase the probability of adverse events. This leads to a trap that is resilient to increased scientific understanding.

Individuals can produce environmentally dependent goods using the production function $F(u(t);\theta(x(t))) = F(u(t), x(t))$ by applying effort, u, at time t where production is subject to a potential disaster that occurs with probability $\varphi(x(t)) = 1 - \theta(x(t))$.[1] The risk of disaster, and by extension, the expected return on this activity, depends on stock x, which reduces the probability of catastrophe, $\theta'(x) > 0$. The stock x grows according to

$$\frac{dx(t)}{dt} = \dot{x}(x(t), Z(t)) \tag{1}$$

The variable $z_i(t)$ is a private capital stock. The sum of private capital stocks $Z(t) = \sum_i z_i(t)$ influences the growth rate of stock $x(t)$ through ecological interactions. We assume that stock Z consumes stock x, $\frac{\partial \dot{x}}{\partial Z} < 0$, for example through a predator-prey relationship. Changes in individual stocks of private capital, z_i, depend on the amount of effort owners invest in managing them, $w_i(t)$, the stock $x(t)$, and withdrawals from the stock to provide private income, $h_i(t)$.

$$\frac{dz_i(t)}{dt} = \dot{z_i}(w_i(t), h_i(t), x(t), z_i(t)) \tag{2}$$

Institutional arrangements influence whether stock x is private property that enables foresighted management of x. Individuals receive a flow of revenue $R(h_i(t), z_i(t))$, which depends upon the withdrawal rate, h_i, and stock effects from stock z_i. If society cooperates (i.e., uses a property rights regime), then society acts as if $\frac{\partial Z}{\partial z_i} = 1$ and makes decision about w and h (as if) collectively.[2] Conversely, without cooperation, the stock x is a common pool resource (CPR) that leads to myopic management of x. When x is a CPR individuals manage z_i by choosing effort w_i and withdrawal rate h_i in a decentralized manner, not internalizing the full impact of their management decisions on stock x because when x is a CPR decisions are made as if $\frac{\partial Z}{\partial z_i} \approx 0$ (Cheung, 1970; Dasgupta and Heal, 1979).

[1] We omit time in our notation to minimize clutter unless doing so causes confusion.

[2] We assume that cooperation enables cooperators to act as if the stock is private property, which would be achieved with well-defined property rights or long-term tenure security, and internalizes ecosystem externalities and risk (Baland and Platteau, 1996; Ostrom, 1990), so that decisions are made as if $z_i = Z$, $w_i = w$, and $h_i = h$.

Connecting decisions and the probability and consequences of catastrophe makes risk endogenous (Shogren and Crocker, 1999). There are three pathways to manage risk. First, individuals can focus on investments in z_i and hold more z_i to decreases the consequences of disaster should one occur (self-insurance or adaptation) (Ehrlich and Becker, 1972). This pathway is available irrespective of whether society cooperates or treats x as a CPR. Second, individuals can change the value at risk by shifting effort away from the risky activity and towards managing their investments z_i, while simultaneously taking a higher withdrawal h_i to replace income that could have been produced through activity F (income replacement). Faced with a CPR, individuals may endogenize risk through self-insurance and by changing the value put at risk and adapting to $\theta(x(t))$. Finally, in the cooperative case society can reduce the probability of disaster by managing the state of x (group-protection or mitigation). This (self) group-protection approach requires a degree of coordination so that $0 < \frac{\partial Z}{\partial z_i} \leq 1$.

Assuming individuals face the labor allocation constraint $u_i + w_i = 1$, individual [3] decision makers act as if they maximize

$$\max_{u_i(t)\in[0,1],h_i(t)\in\mathbb{R}^{++}} \int_0^\infty (F(u_i(t),x(t)) + R(h_i(t),z_i(t)))\, e^{-\rho t} dt \tag{3}$$

subject to (1) and (2), where ρ is the discount rate.[4] The probability of a disaster $\varphi(x) = (1-\theta(x))$ is bounded between zero and one.

The optimal levels of effort $u_i(t)$ and withdrawals from the stock that provides private insurance, $h_i(t)$, maximize the current value Hamiltonian,

$$H = F(u_i(t),x(t)) + R(h_i(t),z_i(t)) + \lambda_i(t)\dot{x}(x(t),Z(t)) + \mu_i(t)\dot{z}_i(u_i(t),h_i(t),x(t),z_i(t)) \tag{4}$$

The co-state or adjoint variables $\lambda(t)$ and $\mu(t)$ represent the institutionally constrained optimal shadow prices for capital assets of x and z_i respectively. The first-order conditions for problem (3) are

$$H_{u_i} = F_{u_i}(u_i,x) + \mu_i\dot{z}_{iu_i}(u_i,h_i,x,z_i) = 0 \tag{5a}$$

Because of condition (5a), and the constraint on u_i and w_i, when u_i andw_i are constrained to the unit circle this implies

$$F_{u_i}(u_i,x) - \mu_i\dot{z}_{iw_i}(w_i,h_i,x,z_i) = 0 \tag{5b}$$

$$H_{h_i} = R_{h_i}(h_i,z_i) + \mu_i\dot{z}_{ih_i}(u_i,h_i,x,z_i) = 0 \tag{6}$$

And portfolio-balance conditions (Horan et al., 2018a), also known as no-arbitrage conditions (Karp, 2017).

$$\dot{\mu}_i = \rho\mu_i - \frac{\partial H}{\partial z_i} = \left(\rho - \dot{z}_{iz_i}(u_i,h_i,x,z_i)\right)\mu_i - R_{z_i}(h_i,z_i) - \lambda_i\dot{x}_z(x,Z)\frac{\partial Z}{\partial z_i} \tag{7}$$

$$\dot{\lambda}_i = \rho\lambda_i - \frac{\partial H}{\partial x} = (\rho - \dot{x}_x(x,Z))\lambda_i - F_x(u_i,x) - \mu_i\dot{z}_{ix}(u_i,h_i,x,z_i) \tag{8}$$

The institutional arrangements qualitatively affect the value and evolution of the shadow prices, λ and μ (Horan et al., 2011). There is a critical difference between the decentralized decision process and the social planner's decision process, which is shown in the third RHS term in Eq (7). When individuals fully internalize the marginal impact of theirz_i on stock$Z$, $\frac{\partial Z}{\partial z_i} = 1$, the third RHS term is $\lambda\dot{x}_Z(x,Z)$. However, in the decentralized case $\frac{\partial Z}{\partial z_i} = 0$ and the third RHS term vanishes. The relationship between the change in the μ_i for the social planner and decentralized institutions is

$$\dot{\mu}_{social\,planner} = \dot{\mu}_{decentralized\,commons} - \lambda_i\dot{x}_Z(x,Z)Z_{z_i} \tag{9}$$

Intermediate cases of are also possible, where the influence of the stock x on the shadow value of private capital depends upon how individuals internalize the relationship $\frac{\partial Z}{\partial z_i}$.

The treatment of risk also impacts the evolution and value of the shadow price of x. If risk is treated as exogenous, which includes the fully and costlessly insured case, then the second RHS term in Eq (8), $F_x(u_i,x)$, vanishes. This occurs because if the risk of catastrophe is not impacted by the stock x, then there is no feedback between Z and the stock x. Eq (8) shows that, all else equal, the equilibrium marginal value of x 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

[3] By extension, because $\frac{d\dot{z}_i(u,h_i,x,z_i)}{dw} > 0 then \frac{d\dot{z}_i(u,h_i,x,z_i)}{du} < 0$.

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

$$\dot{\lambda}_{endogenous} = \dot{\lambda}_{exogenous} - F_x(u_i, x) \tag{10}$$

Intermediate cases are possible but depend upon how the marginal impact $F_x(u_i, x)$ is internalized.

Proposition 1. *If interior combinations of optimal control rules exist, then they must maintain the relationship that the marginal rate of capital substitution between x and z equals the ratio of shadow prices.*

Using the Hamilton-Jacob-Bellman identity and the definitions of the shadow values, take derivatives of the value function with respect to x and z, $V_x = \lambda$ and $V_z = \mu$, and divide one by the other and using the chain rule yields

$$\frac{\partial x}{\partial z_i} = \frac{\mu_i \left(\frac{\partial Z}{\partial z_i}\right)}{\lambda} \tag{11}$$

where the LHS is the marginal rate of capital substitution between stocks and the RHS is the ratio of shadow prices. Using the definition of the shadow value μ of z it is clear that the numerator of the RHS depends upon how the marginal $\frac{\partial Z}{\partial z_i}$ is internalized by decisionmakers, $\mu_i \left(\frac{\partial Z}{\partial z_i}\right)$.

A corollary of Proposition 1 is that for any interior solution the marginal rate of substitution between the stock that can provide group or self-protection, x, and private capital z_i, depends on the shadow values of both capital stocks, which have a nonlinear relationship because of ecological interactions between the stocks and because of the institutional regime.

When x is a CPR, the shadow value μ_i of private capital, z_i, is larger *ceteris paribus*, because the negative impact of private capital on the stock x is omitted. This causes individuals to substitute towards private capital. In a world with strong property rights, z_i, becomes more expensive. Even if individuals are unaware of the potential linkages between z_i and the probability of disaster due to limited scientific knowledge, the shadow price of z_i still depends upon z_{z_i} through feedbacks due to the dependence of z_i on stock x and the potential for rents from a higher growth rate of stock x.

Proposition 2. *The implicit ecological "loading factor" or deviation from "fair" insurance price is equal to the marginal rate at which the decision maker trades-off between production in the environmentally dependent good produced through process **F** in the good and bad states of the world.*

Rewrite the expected revenue $F(u_i, x) + R(h_i, z_i)$ as a convex combination of the payout with and without the adverse events, by explicitly including the probability of disaster $\varphi(x) = 1 - \theta(x)$ and production function in the good state $f(u_i)$, and the bad state $g(u_i)$.

$$F(u_i, x) + R(h_i, z_i) = (1 - \varphi(x))(f(u_i) + R(h_i, z_i)) + \varphi(x)(g(u_i) + R(h_i, z_i)) \tag{12}$$

where $f(u_i) > g(u_i)$, then taking a derivative with respect to u_i and substituting the result into (5) the first-order condition for the optimal allocation of effort becomes

$$(1 - \varphi(x))f_{u_i}(u_i) + \varphi(x)g_{u_i}(u_i) + \mu_i \dot{z}_{u_i}(u_i, h_i, x, z_i) = 0 \tag{13}$$

Rearranging terms yields

$$\frac{\varphi(x)}{(1 - \varphi(x))}\left(1 + \frac{\mu_i \dot{z}_{iu_i}(u_i, h_i, x, z_i)}{\varphi(x) g_{u_i}(u_i)}\right) = -\frac{f_{u_i}(u_i)}{g_{u_i}(u_i)} = -\frac{\partial f(u_i)}{\partial g(u_i)} \tag{14a}$$

Using Proposition 1, Eq (14) is rewritten

$$\frac{\varphi(x)}{(1 - \varphi(x))}\left(1 + \frac{\lambda x_{z_i} \dot{z}_{iu_i}(u_i, h_i, x, z_i)}{\varphi(x) g_{u_i}(u_i)}\right) = -\frac{f_{u_i}(u_i)}{g_{u_i}(u_i)} = -\frac{\partial f(u_i)}{\partial g(u_i)} \tag{14b}$$

The right-hand side is the marginal rate of substitution between production of the environmental sensitive good in good state and in the bad state, the "price of insurance" (Ehrlich and Becker, 1972). Ehrlich and Becker (1972) state that the "fair price of insurance" is $\varphi/(1-\varphi)$. At a "fair" price, a higher probability of a bad event, θ, implies a larger required $f_u(u_i)$ relative to $g_u(u_i)$, leading individuals to shift their effort to maintaining z_i. The fair price depends only on the state of x, and is invariant to institutions. The deviation from the "fair price," the second term in parenthesis on left-hand side of (14b), is the "loading factor" described by Ehrlich and Becker (1972). This term depends upon institutions.

The loading factor exists because the market fails to internalize all costs. When externalities come through the ecosystem the term "fair price" is misleading. It is true that an ecosystem externality exists because of ecological interactions that occur outside the market. This ecosystem externality can lead to a loading factor. It is not clear that it is "unfair" for planners to account for these otherwise unpriced ecological interactions. In the case of ecosystem externalities the loading factor is related to the recognized user cost of the resource rather market failure.

A corollary of Proposition 2 is that self-insurance, produced through greater investment of effort in z_i, appears less expensive in the decentralized case relative to the private property or coordinated case. The "ecological load factor" depends upon the opportunity cost of the foregone stock z_i, and the impact of Z on the stock x (14b). The denominator of this term is the expected marginal value of effort in the bad state and positive. The numerator is negative, as μ is positive when z_i is a good, and $\dot{z}_{iu_i}$ is negative by assumption (in (14b) $\lambda > 0$ and $x_{z_i} > 0$ by 11). The magnitude of the price of insurance may be negative because the insurance is provided though a pre-existing capital stock. However, it is the relative size of the price of insurance under different institutional arrangements that matters for our analysis. In the decentralized case individuals omit the impact of z_i on Z, $\frac{\partial Z}{\partial z_i} = 0$, increasing the shadow price of z_i, μ_i, and reducing the price of self-insurance. It is the lower price of self-insurance that leads to the insurance trap in the decentralized case, as an increase in z_i also increases Z, leading to a reduction in the stock x, and an increase in the probability of a bad event. An increase in effort allocated to growing the stock z_i does not imply a larger standing stock z_i, as individuals are able to make withdrawals. From (6), we also expect a lower rate of withdrawal in the decentralized case, as the shadow value $\mu_i \left(\frac{\partial Z}{\partial z_i}\right)$ is greater in the decentralized than in the centralized case. Decision makers view self-insurance as inexpensive because they neglect to account for the ecosystem externality.

A second corollary of Proposition 2 is that scientific understanding of ecological relationships can increase the relative value of group protection only with private property rights. When decision makers internalize the relation $\varphi(x)$, there are two changes in (14b). First, the loading factor shrinks and the price of self-insurance falls because the shadow price λ_i of the stock x is greater when risk is endogenous, increasing the numerator of the second term in parentheses in (14b). The second effect is that all else equal decision makers manage for a different level of x, and a greater value x increases the "fair price" of insurance $\frac{\varphi(x)}{(1-\varphi(x))}$. Following Ehrlich and Becker (1972) when the price of insurance internalizes efforts to self-protect, there is a potential for self (group)-protection and insurance to be compliments, but this depends upon the ability of individuals to limit Z, $\frac{\partial Z}{\partial z_i} \neq 0$.

The insurance trap is the result of human institutions acting through the loading factor to lower the price of self-insurance. From Proposition 2, we can decompose the price of self-insurance into its "fair price," which is determined by nature and the "ecological loading factor," which is determined by human institutions. Without institutional reform, individuals are trapped. The magnitude of the loading factor leads self-insurance to be relatively cheap and induces individuals to over invest in capital to harvest the commons and the commons themselves.

3. Numerical example

We develop a numerical example to crystalize intuition. 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 open access in the Gordon (1954) sense. There is the potential for locust outbreaks that reduce revenue from cash crops, but locust outbreaks do not directly impact livestock. The probability of locust outbreaks increases with pasture degradation in the form of reduced plant protein − a condition favoring locusts (Cease et al., 2012). High livestock stocking density degrades pasture creating a link between livestock stocking levels and locust outbreaks. The parameter values and functional forms are detailed in the Appendix.

We analyze the bioeconomic model for nine cases and summarize our numerical results in Table 1 with welfare and probability calculations. In the first case individuals are restricted to farming. Individuals who lack the option to invest in cattle face an exogenous probability of catastrophe and maximize their expected profit by dedicating all their effort to farming. This yields an expected income equal to the price of the produced crops, p_c, weighted by the probability the crop survives, $\theta(x)$.

We then consider four scenarios under two property rights regimes; where the pasture, x, is private property, and when x is a CPR. The four different scenarios include when individuals can only invest effort in managing livestock, when individuals are costlessly insured against locust outbreaks, when the probability of locust outbreaks is exogenous, and when the probability of locust outbreaks is endogenous. 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 (see Appendix) allows us to compute the optimal path at any point in state space, including over the stable limit cycle because it approximates the value function and associated shadow prices for every combination of state variables.

3.1. Ranching only

When pastoralists are restricted to ranching, they have a revenue function that is independent of the probability of a locust outbreak. Livestock and harvests are modelled as substitutes in production because of stock effects that 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 or

Table 1
Numerical results of different risk and property rights regimes. The first column denotes the property rights regime and the risk regime. Cycle length and variables are measured in daily units assuming a 120 day annual growing season. For the CPR case min, avg, and max refer to the levels at the minimum, maximum and average levels of grass biomass. Welfare is calculated as either the infinite sum at equilibrium or using the average values of variables over the stable limit cycle. "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 per growing day	Cycle Length (growing days)	"naïve" Welfare (USD)	Welfare (USD)
Farming Only			2500.0	0.0	0.56%	100%	0.000%	N/A	$4563	$4537
Private	Ranching Only		1749.1	1284.2	28.02%	0.0%	1.398%		$3465	$3465
	Fully Insured		1879.6	1102.4	23.35%	54.6%	0.486%		$5134	$4288
	Exogenous Risk		1407.79	1677.52	39.83%	46.94%	0.497%		$4983	$3678
	Endogenous Risk		2212.05	560.51	11.20%	57.04%	0.500%		$5023	$4606
Common	Ranching Only	min	44.7	2066.5	69.95%	0.0%	0.237%	456	$1003	$1003
		avg	293.6	2057.3	68.08%		0.229%			
		max	1007.0	1986.4	52.44%		0.266%			
	Fully Insured	min	69.1	2069.0	69.88%	92.9%	0.052%	488	$4317	$1746
		avg	513.1	2033.7	64.59%	64.3%	0.053%			
		max	1383.5	1697.4	40.64%	25.5%	0.056%			
	Exogenous Risk	min	31.7	2054.3	69.98%	96.2%	0.006%	489	$3417	$1114
		avg	267.0	2087.2	68.39%	48.8%	0.004%			
		max	776.0	2092.9	58.72%	0.0%	0.004%			
	Endogenous Risk	min	10.7	2045.1	70.00%	1.0%	0.002%	552	$3993	$1288
		avg	256.1	2050.7	68.52%	63.3%	0.004%			
		max	1040.8	1970.7	51.45%	0.0%	0.003%			

because of animal products like milk. 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 the Appendix. The feedback control diagram shown in Fig. 1 displays the solutions to these problems. The right panel shows the optimal strategy from each point in state space for the private grassland, and the left 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. 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.

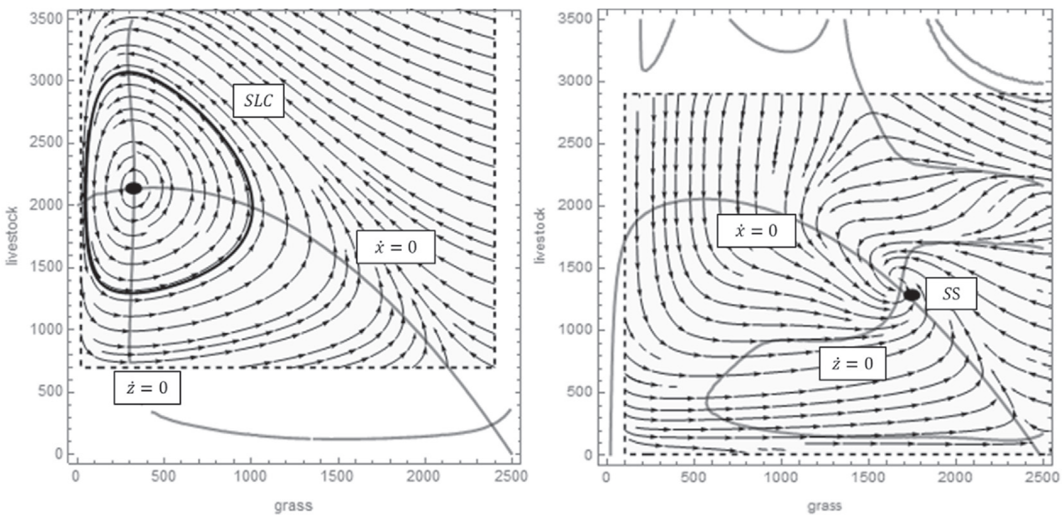

Fig. 1. The optimal mixture of grass and livestock when pastoralists are only able to spend time ranching. The right panel is when pastoralists have private property rights over pasture, and a steady state level of livestock and grass is maintained (SS), which is both solved for analytically and approximated numerically by our solution method. On the left, the pasture is common pool property and a stable limit cycle occurs (SLC). The approximation areas for our solution method are bounded by a dashed line, with optimal trajectories plotted within.

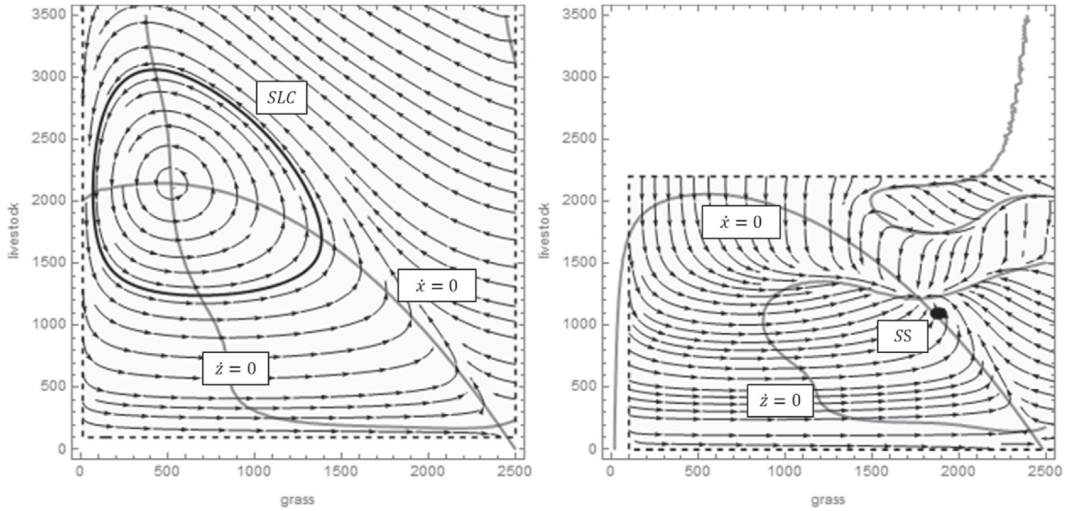

Fig. 2. The optimal mixture of grass and livestock when pastoralists are fully insured for locust risk. The right panel is when pastoralists have private property rights over pasture, and we solve analytically for a steady state level of livestock and grass (SS) as well as numerically approximating this point at the intersection of the $\dot{y} = 0$ and $\dot{x} = 0$ nullclimes. On the left, the pasture is common pool property and a stable limit cycle occurs (SLC). The approximation areas for our solution method are bounded by a dashed line, with optimal trajectories plotted within.

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 can recover more than when animals are 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.

3.2. *Farming and ranching with insurance*

Next, consider a pastoralist who 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. 2) show the optimal choice at every point under this scenario with private property (right panel) and common property pasture (left 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 I). 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 the pastoralist 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 locust plagues.

3.3. *Farming and ranching with exogenous risk but no insurance*

In our next two cases the pastoralist is not insured against locust plagues. We first assume the state of science is such that individuals treat locust outbreaks as exogenous and beyond human control (Fig. 3). 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 (self-insurance). Their efforts to increase livestock growth lead to larger harvests (income replacement), 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.

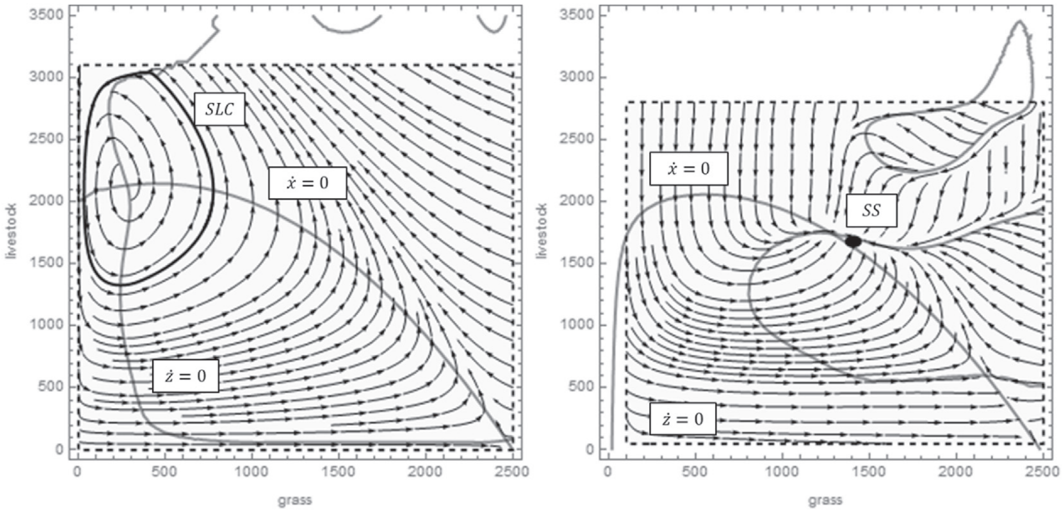

Fig. 3. The optimal mixture of grass and livestock when locust risk is exogenous and pastoralists are not perfectly insured. The right panel is when pastoralists have private property rights over pasture, and a steady state level of livestock and grass is maintained (SS), and this point is solved for analytically and approximated by our solution method. On the left, the pasture is common pool property and a stable limit cycle occurs (SLC). The approximation areas for our solution method are bounded by a dashed line, with optimal trajectories plotted within.

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 trade off potential income in a world where a locust plague does not occur, or their "naïve" welfare, for a higher expected welfare. Pastoralists self-insure by harvesting a lower proportion of their cattle and rely on larger standing stock of livestock to insure against catastrophe. Pastoralists also replace risky income by reducing the asset they have at risk (crops) and increasing their investment in the "safe" asset, livestock. This is because the loading factor when pasture is a CPR is always lower, making insurance artificially cheap (Fig. 4). When pastoralists have property rights, they internalize the marginal impact of their livestock on the growth rate of grass biomass, and the associated growth benefits in their livestock herd. Internalizing this relationship leads to a higher price of insurance relative to the CPR case, even though the impact of grass biomass on the risk of catastrophe is not internalized by the pastoralist.

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. In a riskless world performing both activities is the most profitable outcome, so 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 lower than their "naïve" welfare when fully insured. In this case, pastoralists are no more productive when they know about the payments ahead of time.

3.4. *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 hold a substantially smaller herd, leading to a healthier pasture and lower locust plague risk. When pasture is common property, pastoralists maintains larger average stock of livestock than when risk was exogenous with a slightly higher risk of locust outbreaks. Pastoralists also spend slightly less 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. Under endogenous risk the ecological load factor is larger than in any other scenario. We plot the difference in the ecological loading factor between the private property and CPR cases in Fig. 6. Outside of a small region in the lower right hand side where there are very few livestock in the system and very low risk of a locust outbreak, insurance is always more expensive under endogenous risk. In the lower right hand side of Fig. 6, insurance is cheaper under endogenous risk because the risk of catastrophe is very low. When individuals understand the impact of grass biomass on the probability of a locust outbreak, and internalize their impact on the state of the pasture, self-insuring by degrading the pasture is expensive. When pasture is a common property the pastoralist knows that larger herds 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

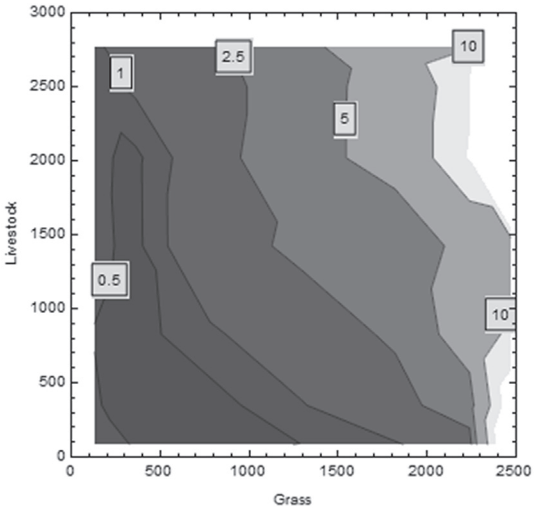

Fig. 4. The difference between the ecological loading factor under private property rights and under CPR grass when risk is exogenous. The loading factor is always higher with private property rights, increasing the price of insurance and reducing the incentive to self-insure.

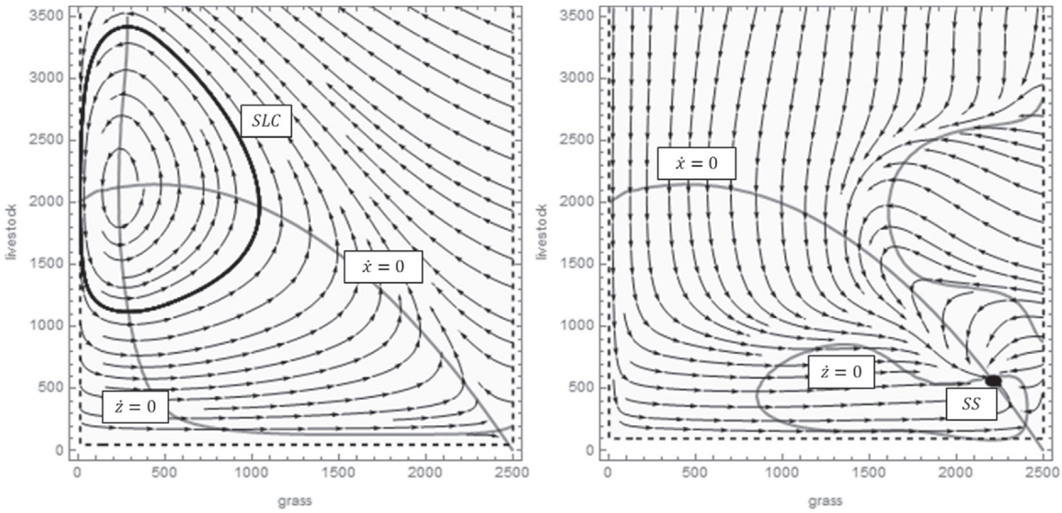

Fig. 5. The optimal mixture of grass and livestock when locust risk is endogenous and pastoralists are not perfectly insured. The right panel is when pastoralists have private property rights over pasture, and a steady state level of livestock and grass is maintained (SS). This steady state is solved for analytically and approximated numerically by our solution method. On the left, the pasture is common pool property and a stable limit cycle occurs (SLC). The approximation areas for our solution method are bounded by a dashed line, with optimal trajectories plotted within.

livestock of a rival.[5] The ecological externality is not internalized in the price of insurance in the endogenous risk CPR scenario. Instead insurance remains cheap because individuals understand the risk of catastrophe is high, but discount their ability to mitigate risk and the pastoralist invests in self-insurance (livestock).

With no private property rights the risk-aware pastoralist prefers 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

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

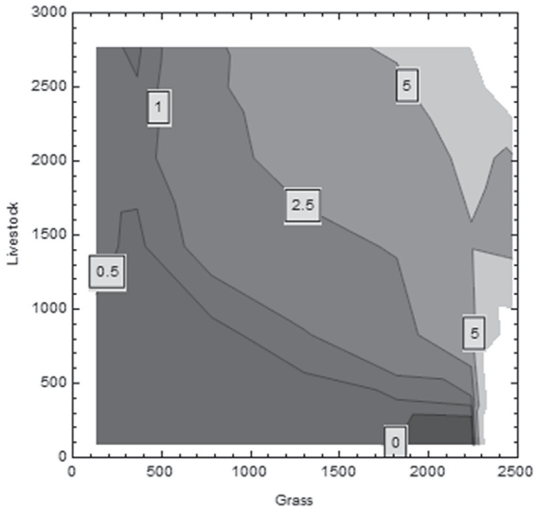

Fig. 6. The difference between the ecological loading factor under private property rights and under CPR grass when risk is endogenous. The loading factor is always higher with private property rights, increasing the price of insurance and reducing the incentive to self-insure. The load factor is slightly lower under endogenous risk in the bottom right corner, when the quantity of livestock in the system is very small and the risk of catastrophe is very low.

externality is a necessary, but not sufficient, condition for managing risk generated through ecological interaction. Greater understanding can influence preemptive management. Institutional failures cause agents to knowingly invest in activities that increase the probability of catastrophe. This is because altering the welfare impacts of bad events is often a private activity, involving private capital investments, whereas changing the probability of bad environmental events requires cooperation and broader system control. Thus human institutions and risk preferences can dominate improved ecological understanding of risk (Finnoff et al., 2007).

The impact of risk on the amount of grass and livestock pastoralists choose to hold involves two different effects, self (group)-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. Instead, the second-best strategy is to "bet the farm" on self-insurance and increase overall systematic risk. This is because in open-access commons the ecological loading factors are effectively lower, because the realized shadow price of grasslands is reduced by the common property arrangement. 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 could lose traditional access to valuable resources that helps insure against risk.[6] Alternative agreements have also evolved in other locales to maintain the traditional role of cattle as investment and insuring asset in response to human institutions (Dixit et al., 2013). 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. Possibilities short of full privatization, which may be political infeasible, could involve "grazing shares" modeling on successful catch-shares programs (Grafton et al., 2006; Libecap, 1993; Stavins, 2011) or some form of "unitization" (Crothers and Nelson, 2006; Dixit et al., 2013; Kaffine and Costello,

[6] Risk may not be fully eliminated, and livestock may help insurance against other non-locust crop failures as well.

2011; Wiggins and Libecap, 1985) that may also involve livestock sharing. Nevertheless, good intensions can lead the way to a risky world.

Conflicts of interest

The authors have no conflicts of interest.

Financial disclosure statement

This research is supported by National Science Foundation grant no. DEB-1313693.

Appendix

A.1 Analytical Solutions for Optimal Paths

It is possible to solve for equilibrium values of the shadow prices, stock sizes, and control levels, but analytical solutions for the optimal paths away from equilibrium do not exist. We find the equilibrium values by setting equations (1) and (2) and (5)–(8) equal to zero solving for the combination x, z, λ, μ, u_i, h_i. The stability of these steady states can be examined using eigenvalue analysis, however it is not possible to solve for analytical solutions for optimal paths. 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 settings 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 (5) and (6) for μ and take the time derivatives, which respectively yields

$$\dot{\mu}_i = p\frac{\left[\theta_x \dot{x} f_{u_i}(u_i) + \theta(x) f_{u_i u_i}(u_i)\dot{u}_i\right] q(x_i) z_i \eta - \left[q_{x_i}(x_i) z \eta \dot{x} + q(x)\eta \dot{z}_i\right]\theta(x) p f_u(u)\,]}{(q(x_i)\eta z_i)^2} \tag{A1}$$

and

$$\dot{\mu}_i = R_{h_i h_i}\dot{h}_i + R_{h_i z_i}\dot{z}_i \tag{A2}$$

Equation (7), (A1), and (A2) must all be equal. Either (A1) or (A2) can be set equal to (7) 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 (8) 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 between h_i and u_i, so that effectively there is only one control variable assuming an interior solution. We apply numerical solution methods in order to examine the optimal paths.

A.2 Numerical 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.[7] 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 (4)

$$\rho V(x, z_i) = \max_{u_i,\, h_i}\left\{\theta(x) p f(u_i) + R(h_i, z_i) + V_x\left(rx\left(1-\frac{x}{K}\right) - q(x)z\right) + V_z(q(x)z_i\eta(1-u_i) - \delta z_i - h_i z_i)\right\} \tag{A3}$$

Then, we approximate $V(x,z) \approx \Phi(x,z) = \sum_{n=0}^{N-1}\beta_n\omega_n(x,z)$, $\Phi(x,z)$ is a two dimensional Chebyshev polynomial with N basis functions that span the state space (Miranda and Fackler, 2004).[8] 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 Eqs (5) and (6). 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

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

[8] 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).

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.

$$\varepsilon = \rho\Phi(x,z_i) - \theta(x)pf(u_i^*) - R(h_i^*,z_i) - \Phi_x(x,z_i)\left(rx\left(1-\frac{x}{\kappa}\right) - q(x)z\right) - \Phi_z(x,z_i)\left(q(x)z_i\eta(1-u_i) - \delta z_i - h_i^* z_i\right) \tag{A4}$$

The function Φ is solely a function on observed state variables and unknown Chebyshev coefficients. Therefore, the vector of coefficients, β, that minimizes $\varepsilon'\varepsilon$ 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, 2004).

A.3 Functional forms and parameter values for numerical example.

Parameter values and functional forms are an approximation of daily effort and harvest decisions over a 120 day growing season. Ecological parameters and functional forms are based on the associated literature (Berry et al., 2018). We assume a Holling Type II functional response for livestock feeding on grass biomass, consistent with a limited capacity of livestock to find and digest food. At higher grass biomass livestock spend less time finding food, but eventually become satiated in food.

We assume the probability of remaining in the good state is convex in x, with the loss of x having a diminishing effect at low levels of x. The production functions for crops in the good and bad state of the world assume diminishing returns in effort, with farming always being more productive in the good state. We assume Cobb-Douglas production for livestock revenue, so that a standing stock and harvests are necessary inputs for production that individually demonstrate diminishing returns. The rationale is that a higher harvest rate without a larger stock of livestock requires harvesting lower quality animals, and a larger stock of animals with a constant harvest rate initially allows pastoralists to choose higher quality animals to harvest, but this ability diminishes as the stock grows.

AI. Parameter values and functional forms

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
$q(x(t))$	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 in the good state	$0.5\left(u - \frac{1}{2}u^2\right)$
$g(u(t))$	Crop production function in the bad state	$0.25(u - 0.45u^2)$
$R(h,z)$	Cattle harvest revenue	$p_r(h^{0.75}z^{0.25})$
$\dot{x}(x(t),Z(t))$	Grass dynamic constraint	$\frac{dx(t)}{dt} = r*x(t)*\left(1-\frac{x(t)}{\kappa}\right) - q(x(t))*\sum_i z_i(t)$
$\dot{z}_i(u_i(t),h_i(t),x(t),z_i(t))$	Livestock dynamic constraint	$\frac{dz_i(t)}{dt} = q(x(t))*z_i(t)*\eta*w_i(t) - \delta*z_i(t) - h_i(t)*z_i(t)$

References

Baland, J.-M., Platteau, J.-P., 1996. Halting Degradation of Natural Resources: Is There a Role for Rural Communities? Oxford University Press, Oxford, UK.
Balikcioglu, M., Fackler, P.L., Pindyck, R.S., 2011. Solving optimal timing problems in environmental economics. Resour. Energy Econ. 33, 761–768.
Barrett, C.B., Carter, M.R., 2013. The economics of poverty traps and persistent poverty: empirical and policy implications. J. Dev. Stud. 49, 976–990.
Baumgärtner, S., 2007. The insurance value of biodiversity in the provision of ecosystem services. Nat. Resour. Model. 20, 87–127.
Baumgärtner, S., Strunz, S., 2014. The economic insurance value of ecosystem resilience. Ecol. Econ. 101, 21–32.
Berkes, F., Colding, J., Folke, C., 2008. Navigating Social-Ecological Systems: Building Resilience for Complexity and Change. Cambridge University Press.
Berry, K., Cease, A.J., Fenichel, E.P., Elser, J.J., 2018. Stoichiometric stabilization in a multi-consumer ecosystem model: grasslands, grasshoppers, and grazers. Work. Pap.
Brottem, L., Turner, M.D., Butt, B., Singh, A., 2014. Biophysical variability and pastoral rights to resources: west African transhumance revisited. Hum. Ecol. 42, 351–365.
Bryan, E., Ringler, C., Okoba, B., Roncoli, C., Silvestri, S., Herrero, M., 2013. Adapting agriculture to climate change in Kenya: household strategies and determinants. J. Environ. Manag. 114, 26–35.
Carter, M.R., Lybbert, T.J., 2012. Consumption versus asset smoothing: testing the implications of poverty trap theory in Burkina Faso. J. Dev. Econ. 99, 255–264.

Cease, 2017. Personal Communication.
Cease, A.J., Elser, J.J., Fenichel, E.P., Hadrich, J.C., Harrison, J.F., Robinson, B.E., 2015. Living with locusts: connecting soil nitrogen, locust outbreaks, livelihoods, and livestock markets. Bioscience 65, 551–558.
Cease, A.J., Elser, J.J., Ford, C.F., Hao, S., Kang, L., Harrison, J.F., 2012. Heavy livestock grazing promotes locust outbreaks by lowering plant nitrogen content. Science 335, 467–469.
Cheke, R.A., Jago, N.D., Ritchie, J.M., Fishpool, L.D.C., Rainey, R.C., Darling, P., 1990. A migrant pest in the Sahel: the Senegalese grasshopper oedaleus senegalensis [and discussion]. Philos. Trans. R. Soc. Lond. B Biol. Sci. 328, 539–553.
Cheung, S.N.S., 1970. The structure of a contract and the theory of a non-exclusive resource. J. Law Econ. 13, 49–70.
Crocker, T.D., Tschirhart, J., 1992. Ecosystems, externalities, and economies. Environ. Resour. Econ. 2, 551–567.
Crothers, G.T., Nelson, L., 2006. High seas fisheries governance: a framework for the future? Mar. Resour. Econ. 21, 341–353.
Dasgupta, P., Mäler, K.-G., 1995. Poverty, institutions, and the environmental resource-base. Handb. Dev. Econ. 3, 2371–2463.
Dasgupta, P.S., Heal, G.M., 1979. Economic Theory and Exhaustible Resources. Cambridge University Press.
Dercon, S., Christiaensen, L., 2011. Consumption risk, technology adoption and poverty traps: evidence from Ethiopia. J. Dev. Econ. 96, 159–173.
Di Gregorio, M., Hagedorn, K., Kirk, M., Korf, B., McCarthy, N., Meinzen-Dick, R., Swallow, B., 2008. Property Rights, Collective Action, and Poverty, CAPRi Working Paper 81. International Food Policy Research Institute, Washington, DC.
Dixit, A.K., Levin, S.A., Rubenstein, D.I., 2013. Reciprocal insurance among Kenyan pastoralists. Theor. Ecol. 6, 173–187.
Ehrlich, I., Becker, G.S., 1972. Market insurance, self-insurance, and self-protection. J. Political Econ. 80, 623–648.
Fenichel, E., Adamowicz, W.L., Ashton, M.S., Hall, J.S., 2019. Incentive systems for forest-based ecosystem services with missing financial service markets. J. Assoc. Environ. Resour. Econ. 6, 319–347.
Fenichel, E.P., Abbott, J.K., 2014. Natural capital: from metaphor to measurement. J. Assoc. Environ. Resour. Econ. 1, 1–27.
Fenichel, E.P., Horan, R.D., 2016. Tinbergen and Tipping points: could some thresholds be policy-induced. J. Econ. Behav. Organ. 132, 137–152.
Fenichel, E.P., Horan, R.D., Bence, J.R., 2010. Indirect management of invasive species through bio-controls: a bioeconomic model of salmon and alewife in Lake Michigan. Resour. Energy Econ. 32, 500–518. https://doi.org/10.1016/j.reseneeco.2010.04.002.
Fenichel, E.P., Richards, T.J., Shanafelt, D.W., 2014. The control of invasive species on private property with neighbor-to-neighbor spillovers. Environ. Resour. Econ. 59, 231–255. https://doi.org/10.1007/s10640-013-9726-z.
Finnoff, D., Shogren, J.F., Leung, B., Lodge, D., 2007. Take a risk: preferring prevention over control of biological invaders. Ecol. Econ. 62, 216–222. https://doi.org/10.1016/j.ecolecon.2006.03.025.
Giese, M., Brueck, H., Gao, Y.Z., Lin, S., Steffens, M., Kogel-Knabner, I., Glindemann, T., Susenbeth, A., Taube, F., Butterbach-Bahl, K., 2013. N balance and cycling of Inner Mongolia typical steppe: a comprehensive case study of grazing effects. Ecol. Monogr. 83, 195–219.
Gordon, H.S., 1954. The economic theory of a common-property resource: the fishery. In: Classic Papers in Natural Resource Economics. Springer, pp. 178–203.
Grafton, R.Q., Arnason, R., Bjørndal, T., Campbell, D., Campbell, H.F., Clark, C.W., Connor, R., Dupont, D.P., Hannesson, R., Hilborn, R., others, 2006. Incentive-based approaches to sustainable fisheries. Can. J. Fish. Aquat. Sci. 63, 699–710.
Horan, R.D., Fenichel, E.P., Drury, K.L.S., Lodge, D.M., 2011. Managing ecological thresholds in coupled environmental–human systems. Proc. Natl. Acad. Sci. 108, 7333–7338.
Horan, R.D., Fenichel, E.P., Finnoff, D., Reeling, C., 2018a. A portfolio-balancing approach to natural capital and liabilities: managing livestock and wildlife diseases with cross-species transmission. Environ. Resour. Econ. 70, 673–689.
Horan, R.D., Finnoff, D., Berry, K., Reeling, C., Shogren, J.F., 2018b. Managing wildlife faced with pathogen risks involving multi-stable outcomes. Environ. Resour. Econ. 1–18.
Jarvis, L.S., 1974. Cattle as capital goods and ranchers as portfolio managers: an application to the Argentine cattle sector. J. Political Econ. 82, 489–520.
Kaffine, D.T., Costello, C., 2011. Unitization of spatially connected renewable resources. BE J. Econ. Anal. Policy 11.
Karanja Nganga, S., Bulte, E.H., Giller, K.E., Ndiwa, N.N., Kifugo, S.C., McIntire, J.M., Herrero, M., Rufino, M.C., 2016. Livestock wealth and social capital as insurance against climate risk: a case study of Samburu County in Kenya. Agric. Syst. 146, 44–54.
Karp, L., 2017. Natural Resources as Capital. MIT Press.
Libecap, G.D., 1993. Contracting for Property Rights. Cambridge university press, Cambridge.
Lipsey, R.G., Lancaster, K., 1956. The general theory of second best. Rev. Econ. Stud. 24, 11–32.
Loreau, M., Mouquet, N., Gonzalez, A., 2003. Biodiversity as spatial insurance in heterogeneous landscapes. Proc. Natl. Acad. Sci. 100, 12765–12770.
Maiga, I.H., Lecoq, M., Kooyman, C., 2008. Ecology and management of the Senegalese grasshopper oedaleus senegalensis (Krauss 1877)(orthoptera: acrididae) in west Africa: review and prospects. In: Annales de La Societe Entomologique de France. Taylor & Francis, pp. 271–288.
Marten, A.L., Moore, C.C., 2011. An options based bioeconomic model for biological and chemical control of invasive species. Ecol. Econ. 70, 2050–2061.
Melstrom, R.T., Horan, R.D., 2013. Managing excessive predation in a predator-endangered prey setting. Ecol. Econ. 90, 85–93.
Miranda, M.J., Fackler, P.L., 2004. Applied Computational Economics and Finance. MIT press.
Moll, H.A.J., Staal, S.J., Ibrahim, M.N.M., 2007. Smallholder dairy production and markets: a comparison of production systems in Zambia, Kenya and Sri Lanka. Agric. Syst. 94, 593–603.
Mude, A., Ouma, R., Steeg, J., Kaiuki, J., Opiyo, D., Tipilda, A., 2007. Kenya Adaptation to Climate Change in the Arid Lands: Anticipating, Adapting to and Coping with Climate Risks in Kenya-Operational Recommendations for KACCAL. International Livestock Research Institute, Nairobi, Kenya.
Naeem, S., Li, S., 1997. Biodiversity enhances ecosystem reliability. Nature 390, 507–509.
Ostrom, E., 1990. Governing the Commons: the Evolution of Institutions for Collective Action. Cambridge University Press, New York.
Pener, M., Simpson, S., 2009. Advances in Insect Physiology: Locust Phase Polyphenism: an Update. Academic Press.
Press, W.H., Teukolsky, S.A., Vetterling, W., Flannery, B.P., 2007. Numerical Recipes 3rd Edition: the Art of Scientific Computing. Cambridge university press.
Quaas, M.F., Baumgärtner, S., 2008. Natural vs. financial insurance in the management of public-good ecosystems. Ecol. Econ. 65, 397–406.
Salau, K.R., Fenichel, E.P., 2015. Bioeconomic analysis supports the endangered species act. J. Math. Biol. 71, 817–846.
Shogren, J.F., Crocker, T.D., 1999. Risk and its consequences. J. Environ. Econ. Manag. 37, 44–51.
Stavins, R.N., 2011. The problem of the commons: still unsettled after 100 years. Am. Econ. Rev. 101, 81–108.
Tarawali, S., Herrero, M., Descheemaeker, K., Grings, E., Blummel, M., 2011. Pathways for sustainable development of mixed crop livestock systems: taking a livestock and pro-poor approach. Livest. Sci. 139, 11–21.
Thornton, P., Kruska, R.L., Henninger, N., Krisjanson, P.M., Reid, R.S., Atieno, F., Odero, A.N., Ndegwa, T., 2002. Mapping Poverty and Livestock in the Developing World. International Livestock Research Institute, Nairobi, Kenya.
Turner, M.D., McPeak, J.G., Gillin, K., Kitchell, E., Kimambo, N., 2016. Reconciling flexibility and tenure security for pastoral resources: the geography of transhumance networks in eastern Senegal. Hum. Ecol. 44, 199–215.
Wiggins, S.N., Libecap, G.D., 1985. Oil field unitization: contractual failure in the presence of imperfect information. Am. Econ. Rev. 75, 368–385.
Zimmerman, F.J., Carter, M.R., 2003. Asset smoothing, consumption smoothing and the reproduction of inequality under risk and subsistence constraints. J. Dev. Econ. 71, 233–260.