

## LETTER

# Conservation, risk aversion, and livestock insurance: The case of the snow leopard

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## Abstract

Livestock insurance consists of livestock owners pooling resources together in order to hedge against the risk of attacks by predators on their individual herds. We use an economic model to study optimal livestock insurance and to discuss its viability in improving outcomes for livestock owners. The benefit from insurance depends on the livestock owners' level of risk aversion. We calibrate the model using data from *Project Snow Leopard* and investigate the potential of livestock insurance for achieving conservation goals. The model predicts that leopard killings would decline under the proposed livestock insurance contract. The level of the decline depends on the degree of risk aversion. Our analysis calls for surveys that measure risk aversion of local livestock owners to be conducted in any situation where insurance is considered as a policy towards achieving conservation goals. Finally, we discuss how the proposed livestock insurance scheme could be implemented in practice.

## KEYWORDS

conservation, livestock insurance, optimal risk-sharing, risk aversion

## 1 | INTRODUCTION

As the human population continues to grow, the required large home ranges and the threat posed to livestock jeopardize the fragile coexistence of large carnivores and humans (Linnell et al., 2001). The snow leopard (*Panthera uncia*) provides but one example of endangered species with possibly as few as 4000 remaining in the wild. It is widely but thinly distributed throughout mountainous Central Asia. Numerous studies have described preemptive and retaliatory killings of the snow leopard, often associated with attacks on local livestock, as one of the biggest threats to the survival of the species in the wild (Fox et al., 1991; Husain, 2003; Jackson, 1979; Schaller et al., 1987, 1988). Such actions are believed to account for more than half of all

snow leopard deaths. Together with other threats, such as loss of habitat and climate change, the killings have driven the snow leopard to near extinction.

In this paper, we use economic modeling of livestock insurance in order to (1) derive an insurance contract that optimally mitigates livestock risks across participants and (2) identify a critical factor in determining the success of livestock insurance in achieving conservation goals: livestock owners' risk aversion. We calibrate the model for the case of the snow leopard and demonstrate how it could be beneficial both in mitigating risk to livestock owners and in accomplishing conservation goals. Finally, we discuss the desirable features of the contract, some of its limitations, and how it could be implemented in practice.

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Several studies have documented that attacks on livestock by snow leopards is a main concern for local livestock owners. Often, laws that permit the killing of animals that threaten humans and property are used indiscriminately to provide immunity for these killings (Mishra, 1997; Oli et al., 1994; Schaller et al., 1988; Treves & Naughton-Treves, 2005). At the same time, there are some indications that, if threats to their livestock could be put aside, villagers in the areas populated by the snow leopard are otherwise not averse to conservation goals. Hanson et al. (2019) used questionnaires administered to 705 households at two sites in the Nepal Himalayas to measure attitudes towards snow leopards and their conservation. Overall, 10.4% of respondents were very positive towards snow leopards, while 50.1% were positive and 19.0% were neutral. However, livestock owners often have very low incomes, and possible wildlife conservation benefits must be weighed against the potential economic losses from leopard attacks on their herds. This situation is not unique to snow leopards. Similar challenges are present in other cases where large predators exist in the proximity of livestock.

Livestock insurance consists of the local villagers pooling resources together in order to hedge against the risk of attack on their individual herds. While existing arrangements vary, a common feature is that those livestock owners who experience an attack receive compensation. This comes from payments by other livestock owners, often subsidized from additional resources, such as contributions from conservation funds and ecotourism. In many cases, such compensation schemes have failed. China, for example, introduced a compensation scheme to mitigate the human–elephant conflict in Xishuangbanna Dai in Yunnan province, where elephants can cause damage to rubber plantations. The system performed poorly, leading to funding shortfalls and what were perceived as insufficient payouts. Several authors have emphasized the interplay between conservation goals and human incentives (Caro, 2020; Kareiva & Marvier, 2015). It is important to understand what economic factors might predict whether livestock insurance is likely to succeed.

In a celebrated paper, Diamond and Dybvig (1983) built an economic model of insurance for situations where income is subject to risk. They identified a necessary condition for such insurance contracts to be beneficial for the participants. Namely, the participants in the insurance scheme must be sufficiently *risk averse*. We will formally define risk aversion and explore its implications in the next section. Informally, risk aversion refers to the preference for a predictable payoff over one which might be higher in expected terms, but is more uncertain. For example, a risk-averse investor might choose to put their money into a safe bank account earning a low but certain interest rate, over investing in the stock market. The latter implies high

expected returns, but also involves a probability of experiencing losses. Insurance contracts can be used to mitigate various kinds of income risk. We will argue that livestock insurance can be viewed in a similar light.

Given the importance of risk aversion for decision-making under risk, a large body of knowledge in economics is devoted to exploring its implications and to developing effective methods to measure risk aversion in the field (Arrow, 1965; Eckel & Grossman, 2008; Holt & Laury, 2002). Yet, risk aversion has received little or no attention in the context of livestock insurance. Suryawan-shi et al. (2014) conducted surveys to quantify attitudes of the local community inhabiting the high-elevation Spiti Valley of the Indian Trans-Himalaya. The focus of the study was on how these preferences scale from individuals to villages. They gathered information on what they considered to be the key explanatory variables in determining the villagers' attitudes towards snow leopards and wolves. These variables included gender, education, age, number of income sources, agricultural production, livestock holdings, the number of livestock killed, and village size. Attitudes toward risk, however, were not elicited.

The paper proceeds as follows. Section 2 describes the modeling. In Section 3, we employ data from Hussain (2000) to calibrate the optimal livestock insurance contract. The paper concludes by discussing some of the strengths and limitations of the proposed contract as well as how it could serve as a blueprint for actual livestock insurance contracts around the world. The derivation of the optimal contract can be found in the Appendix.

## 2 | METHODS

We study optimal livestock insurance using a model based on the need to mitigate risk. In the proposed scheme, livestock owners would first decide whether to enter the collective risk-sharing arrangement, after which the corresponding payoffs would be realized according to the contract. Thus, the contract must ensure that the terms imply that livestock owners have an incentive to enter. For simplicity of exposition, we will assume that each owner is endowed with the same number,  $w$ , of livestock. For mathematical convenience, we will treat livestock as being divisible in what follows.

“Unlucky” owners, denoted by  $U$ , will experience an attack by a predator, killing  $d$  of their livestock. “Lucky” ones, denoted by  $L$ , will not experience any attack. In any given year, a known fraction,  $a$  of livestock owners will be unlucky, where  $a$  denotes the normalized predator population size. Higher values of  $a$  indicate a higher presence of snow leopards, hence a higher probability of experiencing an attack. For example, the extreme case of  $a = 0$  would

indicate that the predator population size is so small that an attack is extremely unlikely, while  $a = 1$  would indicate a population that is so large that an attack is virtually certain. We assume that, while each individual livestock owner is subject to the same risk of attack, the total number of attacks is predictable. This feature, known as “no aggregate risk,” is consistent with the observed data in the pilot case we consider. We later use historical data from actual attacks to calibrate this probability. The assumption that each individual owner is subject to the same risk of attack is a simplifying one. Farmers might take a variety of mitigation measures to reduce that probability and protect their livestock, for example, by building higher or more durable fences. The probability of attack in what follows should be viewed as the one resulting after all such preemptive measures have been exhausted. This allows us to concentrate on the size of the snow leopard population as the main determinant of the probability of attack. Of course, in reality livestock owners are heterogeneous and some might be able to reduce the probability of attack by so much that they would not benefit from livestock insurance. Our analysis applies to those owners who remain vulnerable enough to benefit from and enter the insurance scheme.

Each owner cares about their resulting livestock size,  $c$ . This is associated with a utility function  $u(c)$  that is increasing in  $c$ , indicating that owning more livestock results in a higher utility. We might think of  $u(c)$  as describing the satisfaction that the owner derives from all the benefits associated with owning a herd of size  $c$ .

Even under insurance coverage for livestock losses, snow leopards may still be perceived as a nuisance that livestock owners wish to reduce, or even eliminate. But there are reasons, for example, ecotourism, why livestock owners might also value the presence of the snow leopard. All that matters for our analysis is that, threats to livestock aside, local communities enjoy some perceived (tangible or intangible) payoff from preserving the large predator. We will assume that they value the existence of predators according to an increasing and concave function  $f(a)$ . The concavity assumption captures the economically meaningful feature of decreasing marginal returns. Of course, absent any such payoff ( $f(a) = 0$ ), the best action would be to eliminate the entire leopard population (set  $a = 0$ ). In that case, the insurance contract would not improve the conservation of the snow leopard. However, even in that case, as long as the remaining snow leopards cause losses due to attacks, the insurance contract would still be beneficial in mitigating risk, by ensuring that the losses are shared among the livestock owners.

What are the possible outcomes for the livestock owners? Absent an insurance contract, the size of their individual livestock will depend on whether it experiences an attack. If an owner is lucky, their stock will remain intact:

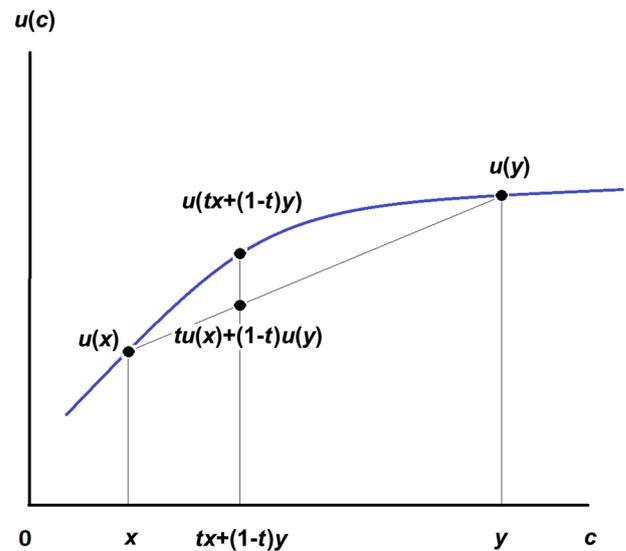


FIGURE 1 A utility function under risk aversion: utility,  $u$ , is a concave function over possible outcomes,  $c$ , implying a higher utility from the certain outcome over that from a lottery that has the same expected value

$c_L = w$ . If an owner is unlucky, their livestock will be reduced to  $c_U = w - d$ . In other words, absent insurance, a fraction  $a$  of livestock owners will experience an attack and lose  $d$  of their stock, while the remaining  $(1 - a)$  lucky ones will have their livestock intact. Taking into account the utility  $f(a)$  from conservation-related utility or (direct or indirect) income from ecotourism, the resulting *expected utility* to a livestock owner prior to the realization of the attacks is

$$a \cdot u(w - d) + (1 - a) \cdot u(w) + f(a). \quad (1)$$

The *optimal insurance contract* is the one whose terms maximize the expression in (1). This immediately identifies a trade-off. The higher the value of  $a$  (more snow leopards around), the higher the return from conservation, but also the higher the probability of experiencing losses due to an attack. We will impose the natural assumption that the losses to a livestock owner if they experience an attack dominate the conservation value they enjoy from the existence of the predator. The contract must specify the terms in a way that optimally balance these two factors. Would the livestock owners benefit by pooling resources in order to diversify risk through an insurance contract? The answer depends critically on a parameter that has so far been largely ignored in the actual implementation of livestock insurance: *risk aversion*. Diagrammatically, risk aversion is represented by the curvature of the utility function (see Figure 1). To illustrate the concept, consider a lottery that results in a payoff of, say  $x = \$1$  with probability  $t = \frac{1}{2}$ , and  $y = \$3$  with probability  $(1 - t) = \frac{1}{2}$ . The expected

payoff from the lottery is thus  $\frac{1}{2} \cdot u(\$1) + \frac{1}{2} \cdot u(\$3)$ . Risk aversion implies a higher utility from the certain outcome  $u(t \cdot x + (1 - t) \cdot y) = u(\$2)$  over that from the lottery that has the same expected value. In other words,  $u(t \cdot x + (1 - t) \cdot y) > t \cdot u(x) + (1 - t) \cdot u(y)$ , or, equivalently, the utility function  $u$  is concave (see Figure 1).

In summary, risk aversion creates a motive for insurance. Given the size of their herd, the expected losses from an attack, and the historical probability of attacks, what is the best feasible compensation scheme? Furthermore, what does the optimal insurance contract imply for the resulting size of the predator population?

The contract specifies the postcompensation allocation of livestock among both the unlucky ( $c_U$ ) and the lucky owners ( $c_L$ ). These are derived as the solution to a constrained optimization problem outlined in the Appendix. The main properties of the solution can be summarized as follows. Provided that livestock owners are risk averse, the optimal livestock insurance contract is such that  $c_U = c_L = c^*$ . That is, optimal risk-sharing implies that all livestock owners share the costs from attacks equally. In addition, the resulting size of the wildlife population will be higher under such a contract, provided that

$$u'(c^*) < \frac{u(w) - u(w - d)}{w - (w - d)}. \quad (2)$$

The insurance contract gives rise to an allocation of livestock that is different from the one in the absence of livestock insurance. The latter would imply  $w - d = c_U$  and  $c_L = w$  for unlucky and for lucky owners, respectively. However, risk averse livestock owners would be willing to make a transfer payment when they do not experience an attack, in exchange for receiving a payment in the case when they do. This conclusion is easy to interpret. Since we assumed that the villagers are ex ante symmetric, the optimal insurance scheme implies that the lucky owners should transfer part of their livestock to the unlucky ones, so that losses are equally spread across the group. If livestock were perfectly divisible, this would be implemented by transferring the required fraction of livestock. In practice, this can be accomplished by introducing fractional ownership, or by implementing corresponding monetary transfers to affected villagers from unaffected ones using the market value of the livestock at the time of the attack. Thus, the symmetric allocation where both lucky and unlucky owners end up with  $c^*$  units of livestock provides the best way for the livestock owners to share risk. It is important to note that this conclusion requires the presence of risk aversion. Otherwise, this arrangement would not be viable, as livestock owners would prefer to face the risk without entering the insurance contract. Thus, measuring risk aversion prior to establishing

an actual insurance scheme is essential in ensuring that it will have a chance to succeed.

To summarize, participating in a livestock insurance contract makes the livestock owners better off through sharing the losses from potential attacks. However, this does not automatically imply that livestock owners will find it in their best interest to forgo actions that reduce the size of the endangered predator species. After all, the loss of livestock might still be too painful, even if it is shared through the insurance scheme. While insurance spreads the losses, these can still be quite painful, especially in very poor communities. We discuss the effects of insurance on large predator conservation in the next section, when we calibrate the model to data from *Project Snow Leopard* (PSL).

### 3 | RESULTS

To illustrate the model, we use data from Hussain (2000). He reports on *PSL*, a pilot insurance scheme in the village of Skoyo in Baltistan located west of Skardu. On the whole, local livestock owners in this part of Pakistan are extremely poor, with an average per capita income of about US\$300 per year. In rural areas, over 95% of income is estimated to come from livestock and agriculture. In addition to representing a significant source of income, livestock is important as an asset on which livestock owners can rely in times of unexpected temporary or permanent hardship. This feature also points to the importance of risk aversion in the livestock owners' decisions.

The study confirms that the individual risk from a leopard attack is randomly and almost evenly distributed among the livestock owners. Skoyo consists of 24 households with an average of about 25 goats each. A few other animals were present, but goats were the vast majority and the only ones covered by the insurance scheme. Furthermore, the snow leopard is the only wild predator in the area. Snow leopard attacks on domestic livestock were regularly recorded over a period of 5 years prior to the launching of the initiative. Data on livestock losses due to predation revealed that 55 animals were killed during this period, an average of 11 animals per year. This loss rate is consistent with that of other areas and appeared to be remarkably stable over time, justifying our assumption of no aggregate risk. The implementation of the insurance scheme by the PSL had livestock owners set aside a collective pool of money beforehand. More precisely, each participant contributed 1% of a goat's value. This was based on the (seemingly arbitrary) decision that the villagers' premium payments should cover 50% of the costs of the average annual loss. The other 50% was to be covered by a different fund, coming from ecotourism. The insurance premiums were

**TABLE 1** Risk-aversion classification over different values of the CRRA (Holt & Laury, 2002)

CRRA coefficient	Risk classification
$-0.15 < b < 0.15$	Risk neutral
$0.15 < b < 0.41$	Slightly risk averse
$0.41 < b < 0.68$	Risk averse
$0.68 < b < 0.97$	Very risk averse
$0.97 < b < 1.37$	Highly risk averse
$1.37 < b$	“Stay in bed”

paid annually and kept in an account at a local bank. The average value per goat was calculated to be 1500 Pakistani rupees (about \$30 at the time). While our proposed insurance scheme is self-financed and does not involve premiums or outside funding, we will use the numbers of animals and the frequency of attacks reported by PSL in our calibration.

Mapping this structure to our model, there are 24 households with  $w = 25$  animals each, for a total of 600 goats. From these, 11 goats (1.8335%) were killed in a year, leaving 589 animals in the village. We first assume each attack kills at most one animal per household, in which case 11 households were affected yearly, reducing their stock to:  $w - d = 24$ . The resulting state-dependent utility function is

$$\begin{cases} u(24); \text{ with probability } a = \frac{11}{24}; \\ u(25); \text{ with probability } 1 - a = \frac{13}{24}. \end{cases} \quad (3)$$

The optimal insurance contract prescribes  $c_L = c_U = c^*$ , which implies that  $c^* = \frac{589}{24} = 24.54166$ . The quantity  $-\frac{c \cdot u''(c)}{u'(c)}$  is known as the *coefficient of relative risk aversion (CRRA)*, and it is perhaps the central parameter in economic models of risk. Since livestock owners' utility is increasing in the size of their livestock, we have that  $u'(c) > 0$ . Similarly, since the loss of an extra animal is more painful if a villager owns only a few animals, than if they own a large herd we have that  $u''(c) < 0$ . Thus, the CRRA is a positive number. Following economic studies of measuring risk aversion, we will use the utility function:  $u(c) = \frac{c^{1-b}}{1-b}$ , where  $c$  stands for a villager's livestock size. For this function it is easy to compute that the CRRA equals  $b$ . Higher values of  $b$  are associated with higher risk aversion. In a classic paper, Holt and Laury (2002) perform measurements of risk aversion in economic experiments involving lottery choices. They classify the relevant ranges of risk aversion using the above utility function as presented in Table 1.

For the livestock owners to benefit from the insurance contract in the model calibrated to PSL data, we must have

$$u(c^*) > a \cdot u(w - d) + (1 - a) \cdot u(w), \text{ or,} \\ u(24.54166) > \frac{13}{24}u(25) + \frac{11}{24}u(24). \quad (4)$$

If livestock owners are not sufficiently risk averse ( $b \leq 0$ ), the insurance arrangement would simply not be desirable given their needs. When  $u(c) = \frac{c^{1-b}}{1-b}$ , Figure 2 plots the difference between the expected utility from the livestock insurance contract and that in the absence of the contract under different levels of risk aversion,  $b$ . The curve stays positive, indicating that participating in the optimal insurance contract would benefit livestock owners in all cases where  $b > 0$ , with the highest benefits in the “slightly risk averse” region (around  $b = 0.3$ ).

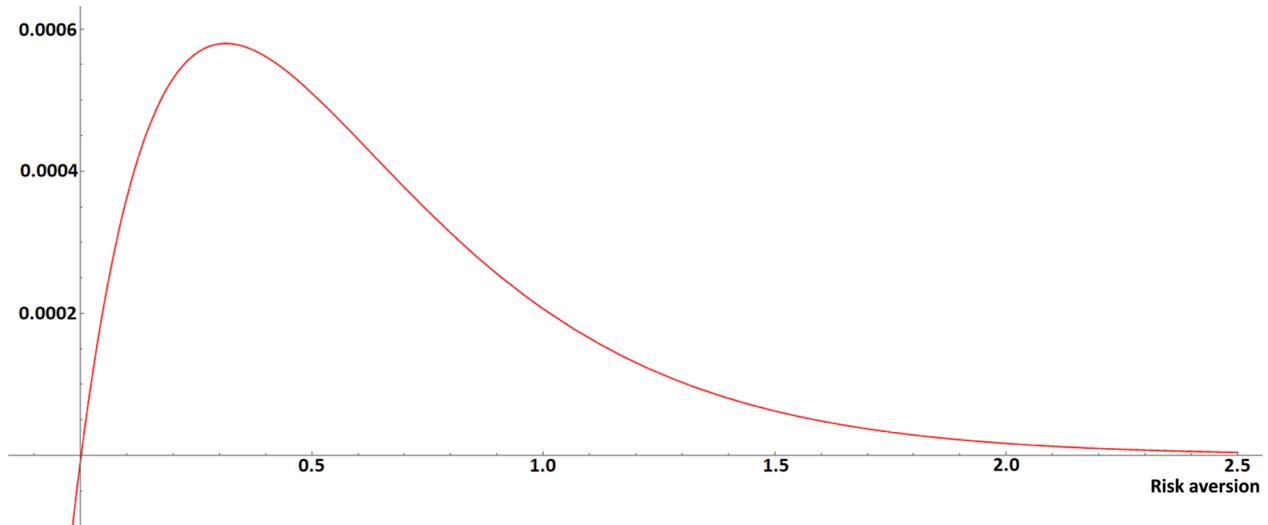
Thus, livestock owners would need to be at least “slightly risk averse” for the insurance scheme to be viable. However, even if this condition is satisfied, and the insurance contract is adopted and beneficial in mitigating risk for the livestock owners, this does not automatically guarantee that it will lead to fewer leopard killings. As shown in the Appendix, a higher difference between  $\frac{u(w) - u(w-d)}{w - (w-d)}$  and  $u'(c^*)$  corresponds to a higher marginal value from conservation. Since  $f$  is a concave function, this implies a higher size of the snow leopard population under the optimal livestock insurance contract. For the livestock owners to find it beneficial to let the size of the snow leopard population increase under the optimal insurance contract, we must have that

$$\frac{u(w) - u(w - d)}{w - (w - d)} - u'(c^*) > 0. \quad (5)$$

When  $u(c) = \frac{c^{1-b}}{1-b}$ , we have that  $u'(c) = c^{-b}$  and  $u'(c^*) = 24.54166^{-b}$ . Thus, insurance would also result in fewer leopard killings in all cases where the optimal insurance contract is effective in mitigating risk ( $b > 0$ ). Figure 3 plots this difference (in units of marginal utility) as a function of the risk-aversion parameter,  $b$ . The effectiveness of the insurance contract in reducing leopard killings is maximal when livestock owners are slightly risk averse and declines as risk aversion increases.

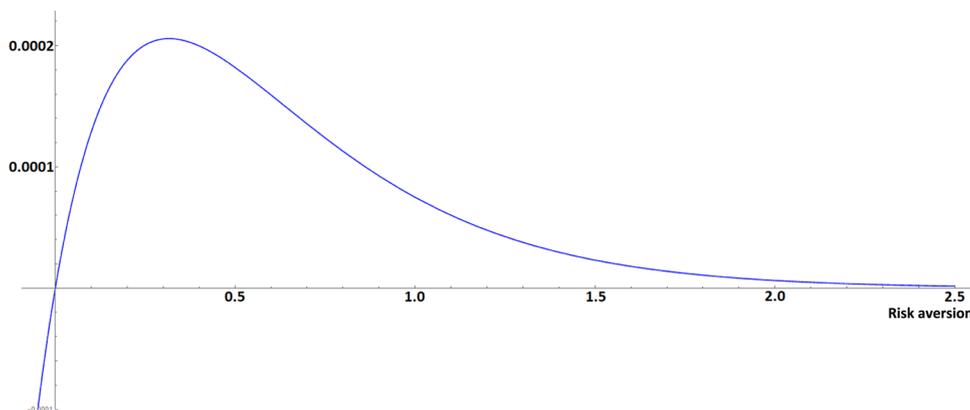
In summary, the behavior of livestock owners is likely to change when the optimal insurance contract is in place, leading to fewer killings, and a higher size of the snow leopard population. The greatest benefit for the snow leopard population is predicted to be at the same values of risk aversion where livestock owners would also benefit the most from the optimal insurance contract.

Net benefit from optional insurance



**FIGURE 2** Benefit from optimal insurance: the difference between the expected utility from the livestock insurance contract and that in the absence of the contract (in units of utility) under different levels of risk aversion,  $b$ .

Insurance conservation benefit



**FIGURE 3** Optimal insurance and conservation: the effectiveness of the insurance contract in reducing leopard killings (measured in units of marginal utility) as a function of the risk-aversion parameter,  $b$ . This is maximal when livestock owners are slightly risk averse and declines after that as risk aversion increases.

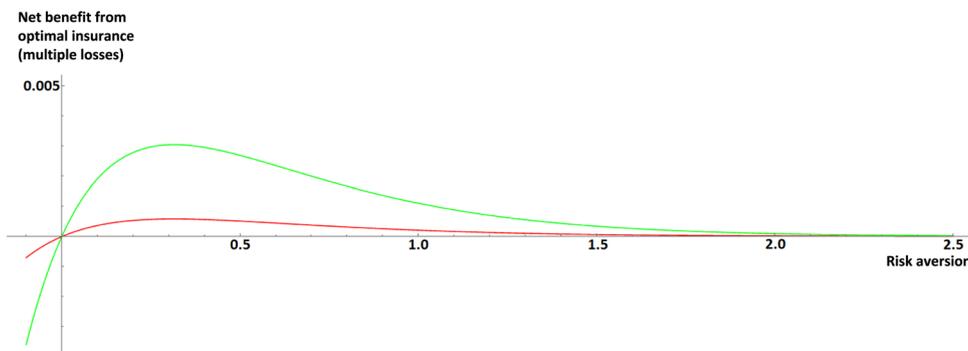
Hungry snow leopards can sometimes jump into a barn and remain trapped. Once inside, they may kill several animals, thus inflicting heavy losses on the owner. To capture this effect, we consider an example where each attack results in killing on average 3 of the 25 animals of the same livestock owner. Since we assume that the adverse shock is three times as severe, to approximately match the total death rate seen in the data (2% of the goats killed in a year), the shock would have to be experienced by a smaller number of livestock owners. More precisely, we consider the case where four households experience an attack, losing three animals each, thus,  $w - d = 22$ . The state-dependent

utility function becomes

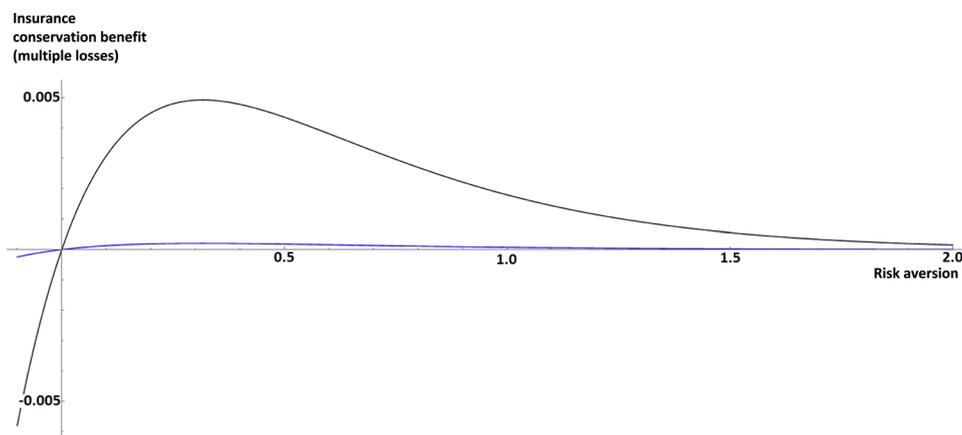
$$\begin{cases} u(22); & \text{with prob. } a = \frac{4}{24}; \\ u(25); & \text{with prob. } 1 - a = \frac{20}{24}. \end{cases} \quad (6)$$

In this case, there are  $600 - 12 = 588$  remaining animals in the community and, as the losses are experienced equally under livestock insurance, we have that  $c^* = \frac{588}{24} = 24.5$ .

Again, the livestock insurance contract would be beneficial in decreasing snow leopard killings (green curve in



**FIGURE 4** Benefit from optimal insurance (multiple losses per owner): the difference between the expected utility from the livestock insurance contract and that in the absence of the contract (in units of utility) under different levels of risk aversion,  $b$ . The red curve is the same as in Figure 1. The green curve corresponds to the case where there can be multiple losses per attack.



**FIGURE 5** Optimal insurance and conservation (multiple losses per owner): the blue curve is the same as in Figure 1. The black curve corresponds to the case where there can be multiple losses per attack. Livestock insurance makes a bigger difference in terms of conserving snow leopards when attacks on livestock are more severe.

Figure 4). As the shock of having two of their animals killed is more severe, we find that livestock owners would benefit more from the insurance contract in this case. For comparison, the red curve in Figure 4 represents the benefits from insurance in the earlier case (maximum of one goat killed). The benefits from conservation (black curve in Figure 5) are also larger. For comparison, the blue curve in Figure 5 represents the conservation benefits from insurance in the earlier case. Thus, the existence of livestock insurance makes a bigger difference in this case in both mitigating risk for livestock owners and in terms of conserving snow leopard lives.

Unfortunately, partly due to the difficulties in monitoring the snow leopard population in the wild, reliable data on the success of PSL in increasing the predator’s population size is not readily available. Our calibrated model can be used to give an illustration of how the predator’s numbers might change under the optimal insurance contract proposed in this paper. For that, let us set  $u(c) = \frac{c^{1-b}}{1-b}$ , with  $b = 0.5$ , and  $f(a) = k \frac{a^{1-h}}{1-h}$ , where  $h = 0.25$ , and  $k =$

$\frac{1}{6}$ . Consistent with the PSL calibration, we assume  $w = 25$  and  $w - d = 24$ . In the absence an insurance scheme, the first-order condition for livestock owners optimization is given by Equation (11) in the Appendix. This can be solved to give  $a = 0.463$ , which is approximately equal to the value of  $\frac{11}{24}$  observed in the data. If the optimal livestock insurance were to be adopted, the first-order condition for optimization would be given by Equation (13) in the Appendix. This can be solved to give  $a = 0.465$ . Thus, the optimal livestock insurance would result in a predicted increase of 0.36% in the size of the snow leopard population. While this may not seem immense, it represents gains solely from reduced killings due to the hedging resulting from the insurance contract.

## 4 | DISCUSSION

Our modeling suggests that optimal livestock insurance can improve the well-being of livestock owners and may also reduce related preemptive killings of large

carnivores, such as the snow leopard. The insurance contract is derived by optimizing the trade-off between risk sharing and conservation. Thus, the contract is consistent with livestock owners' incentive to participate in the scheme and no other arrangement could improve their ex ante expected utility. These findings are of global relevance in situations where insurance or compensation schemes are considered as mechanisms towards implementing conservation goals in cases where livestock or agriculture suffer damages from wildlife. Examples of such schemes include the reintroduction of wolves in parts of North America, the conservation of elephants and large predators in Africa and Asia, as well as several others.

The economic modeling led to two main conclusions. First, measuring attitudes towards risk can be a major predictor of whether livestock insurance will be successful in practice. Economists have developed tools which can be used to effectively elicit this information. Second, the derived optimal insurance contract can serve as a blueprint for actual livestock insurance. We discuss this further next.

The proposed contract has several advantages. Unlike existing schemes, it does not rely on premiums that participants would need to pay in advance. Thus, it does not generate questions about how such contributions are invested in the interim. In addition, the contract does not require donations by outside sources such as NGOs, whose long-term supply may be uncertain. The scheme could be implemented by a cooperative of livestock owners in a village or region. It prescribes that, when losses occur, the unaffected farmers share the losses equally with those affected, by transferring an equal share of the value of the stock lost to the affected ones. The value of the animals lost is calculated using the market value of livestock at the time of the attack, which implies that overtime fluctuations of livestock prices do not distort the resulting compensation. As livestock owners do not know who among them will end up experiencing an attack, the insurance contract makes everyone ex ante better off, as it evens out potential losses across all livestock owners. Since the compensation for losing the animal is only partial, this also implies that farmers would not benefit from cheating, say by killing an animal and claiming that it was killed in an attack. Although we did not explicitly model the incentive to adopt additional costly measures, such as building more secure and protected structures in order to better protect the herds, we believe that the proposed contract does not disincentivize such practices.

Our analysis is subject to several limitations. For ease of demonstration, we assumed that all livestock owners are ex ante identical. This is in broad agreement with the data from PSL that we used to calibrate the model. At the cost of notational complexity, an analogous contract can

be derived assuming asymmetric (different herd size) owners. We have also assumed that all animals are homogeneous. In reality, animals can also vary in size, age, etc., so the statements in the paper can be interpreted as applying to "averages." The proposed loss-sharing scheme means that the contract can readily accommodate different livestock practices, ecological conditions, such as abundance of prey, and different types of livestock being present in different regions.

Finally, although we argue that livestock insurance can be useful in certain contexts, it is not a panacea, and should be best thought of as part of a bigger effort toward mitigating conservation of large predators. Ideally, livestock insurance should be implemented in combination with other policies, such as reducing illegal hunting, protecting habitat, distributing subsidies from ecotourism income, and educating the affected communities about the benefits of conservation.

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## CONFLICT OF INTEREST

The author declares no conflict of interest.

## AUTHOR CONTRIBUTIONS

TLT is solely responsible for the manuscript.

## DATA ACCESSIBILITY STATEMENT

No primary data was collected for this manuscript. Analyzed papers are listed in the bibliography of this article.

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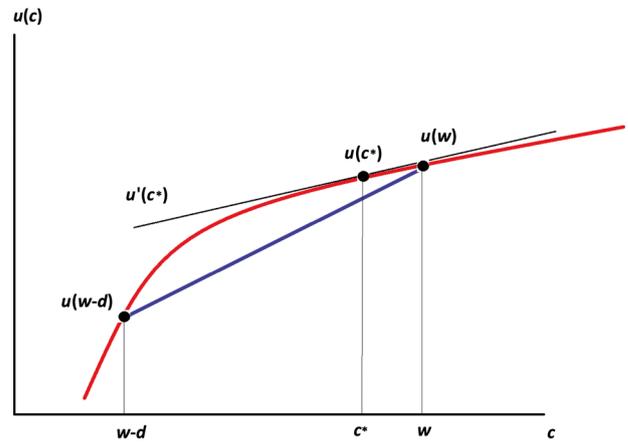
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**APPENDIX A**

Here we provide the derivation of the properties of the optimal contract in the text. The optimal livestock size for both lucky ( $c_L$ ) and unlucky ( $c_U$ ) livestock owners is the one that maximizes the expected utility of the representative owner subject to the aggregate feasibility constraint:

$$\max_{c_U, c_L, a} [a \cdot u(c_U) + (1 - a) \cdot u(c_L) + f(a)]$$

s.t.  $a \cdot c_U + (1 - a) \cdot c_L \leq a \cdot (w - d) + (1 - a) \cdot w$  (A1)



**FIGURE A1** The inequality:  $u'(c^*) < \frac{u(w) - u(w-d)}{w - (w-d)}$  is a sufficient condition for the conserved size of the snow leopard population to increase in the presence of insurance.

Letting  $\lambda$  be the Lagrange multiplier associated with the constraint in the optimization problem, the first-order conditions (FOC) for a maximum are also sufficient due to concavity. The FOC with respect to  $c_U$  and  $c_L$  at the optimum give

$$\partial c_U : a \cdot u'(c_U) = a \cdot \lambda \tag{A2}$$

$$\partial c_L : (1 - a) \cdot u'(c_L) = \lambda \cdot (1 - a). \tag{A3}$$

Combining these we obtain:  $\lambda = u'(c_U) = u'(c_L)$ , or,  $c_U = c_L = c^*$ . Turning to the  $a$  decision, if there is no livestock insurance or other risk-sharing mechanism, the expected utility of a livestock owner is given by

$$\max_{a \in [0,1]} \{a \cdot u(w - d) + (1 - a) \cdot u(w) + f(a)\}. \tag{A4}$$

The FOC with respect to  $a$  gives

$$\partial a : f'(a) = u(w) - u(w - d). \tag{A5}$$

This implies that livestock owners choose the resulting predator population in order to equate the marginal conservation benefit from predators to the marginal expected cost the predators impose on their livestock. The question arises whether the emerging predator size will be higher in the presence of the insurance contract. The FOC in the optimal contract give

$$\partial a : f'(a) = u(c_L) - u(c_U) + \lambda[w - (w - d) + c_U - c_L]. \tag{A6}$$

Since at the optimum  $c_L^* = c_U^* = c^*$ , the above expression becomes

$$\begin{aligned} f'(a) &= \lambda[w - (w - d)] \\ &= u'(c^*) \cdot [w - (w - d)]. \end{aligned} \quad (A7)$$

Notice that since risk aversion increases the utility from the optimal insurance contract,  $u(c^*)$ , the value of  $u'(c^*)$  must decrease due to concavity. The equality in the above condition then requires that  $f'(a)$  also decreases, which implies that  $a$  increases; that is, the conserved size of the

snow leopard population would increase. A sufficient condition for  $a$  to increase under the insurance scheme is that

$$\begin{aligned} u'(c^*) \cdot [w - (w - d)] &< u(w) - u(w - d) \\ \text{or, } u'(c^*) &< \frac{u(w) - u(w - d)}{w - (w - d)} \end{aligned} \quad (A8)$$

This condition is shown diagrammatically in Figure A1. It requires that the marginal utility of consumption at the optimum (when livestock owners are insured) is less than the slope of the blue line in the graph.