Policies to promote wildlife conservation in a spatially heterogeneous landscape

Miller, Andrew
miller.5776@osu.edu

Miteva, Daniela
miteva.2@osu.edu

Gopalakrishnan, Sathya
gopalakrishnan.27@osu.edu

Abstract

Effective payments for conservation are an important tool to provide transfers from those who derive utility from wildlife involved in human-wildlife conflict and those who bear the economic costs, in order to reduce poaching and promote coexistence. We consider the cost effectiveness of payment schemes across two management goals: poaching reduction and farmer welfare compensation. We build upon previous models to consider how these payments should be applied over space when farmers face heterogeneous depredation risk and thus heterogeneous incentives to poach wildlife. We compare commonly used uniform *ex-post* compensation to spatially targeted compensation, finding that poaching can be reduced further by targeted payments given a limited government agency budget. Regarding the management goal of transfers to livestock owners to promote tolerance, we find that "payments for presence" may be preferred in some settings to increase farmer welfare without distorting stocking decisions. Our work suggests that wildlife managers should consider the use of each of these types of payments, dependent on key parameters in each particular setting, and that careful analysis of a particular setting is important before the implementation of a program.

JEL classification: Q15, Q20, Q57

1. Introduction

The topic of human-wildlife conflict is one of the most controversial discussions in the field of conservation (Nyhus et al., 2005). Large carnivores are often at the center of such human-wildlife conflicts–for example, lions in sub-Saharan Africa, jaguars in Brazil, tigers in Nepal, among other locations and species (Treves and Bruskotter, 2014). For these species, people report large existence values for large carnivores globally, whereas the net benefits from these species may be negative locally due to issues such as lost livestock (Nelson, 2009). An example of such spatial mismatch between the beneficiaries and the people bearing the cost of conservation became obvious in the decision to reintroduce wolves in Colorado in 2020: county-level maps of the vote show that urban voters overwhelmingly voted in favor of the wolves, while rural voters tended to vote against them (Summers, 2020). Unstable political support for a species may cause unstable management practices and undermine the local viability of the species.

Poaching is one response to the unresolved spatial mismatch. For instance, in the United States, wolf mortality by poaching has been estimated to be as high as 60% in some areas (Treves et al., 2017). Since large carnivores have large ranges, even a small number of poaching incidents can have large impacts on populations (Adams et al., 2008).

Financial instruments that have been used to promote co-existence can take on multiple forms. The first is compensation for confirmed depredations (*ex-post* compensation), where the farmer can file claims on suspected depredation events. These programs vary in the stringency of the confirmation process and the percentage of market value that farmers are reimbursed, with some programs even paying above the market rate, though transaction costs must also be taken into account when considering the real compensation amount. These programs are widespread and have been used for such species as lions, tigers and elephants (Maclennan et al., 2009; Bulte and Rondeau, 2005), and all U.S. states within the wolf range have programs to compensate livestock loss. The second is subsidies for activities which reduce depredation risk, which can include the installation of fences, increased human and dog presence among the livestock, and the use of fladry. These programs are typically administered as grant programs, where farmers can apply to receive funds for specific purposes. These subsidies are not the focus of this paper.

Finally, payments for ecosystem services (PES) have been proposed as a way to mitigate the human-wildlife conflict and create incentives for local households to tolerate large carnivores. Wunder (2007) defines these payments as "a voluntary, conditional agreement between at least one 'seller' and one 'buyer' over a well-defined environmental service—or a land use presumed to produce that service". By this definition, *ex-post* compensation for loss is not a PES. PES can be given to households for the presence of wildlife (*ex-ante* payments), or for individuals inhabiting the wildlife range. In order for PES schemes to succeed, the willingness to pay (WTP) of the users of an environmental service (ES) must exceed the landholders' cost of providing the service and ES users must be able to organize payments (Wunder et al., 2018). Additionally, Wunder et al. (2018) recommend that payment schemes be spatially targeted, be differentiated on provider's costs of provision, and operate under enforced conditionality. Previous work has found that with perfect information, in aggregate, *ex-ante* payments may outperform the *ex-post* payments as they do not incentivize super-optimal livestock stocking rates (Skonhoft, 2017; Skonhoft and Solstad, 2020), disincentivize depredation mitigation measures below the socially optimal level (Bulte and Rondeau, 2007; Zabel et al., 2011; Ravenelle and Nyhus, 2017), or result in endogenous habitat conversion to pasture land (Bulte and Rondeau, 2007). Compensation schemes that distort the incentives of livestock owners are inefficient from a social planning perspective, though lower administrative complexity may explain their continued use. While PES programs have proliferated in the past decades[1], many programs fail to account for the heterogeneous costs of ES provision and the resulting heterogeneous incentives result. Payment programs for the presence of large carnivores remain relatively rare (Zabel and Roe, 2009), perhaps due to the widespread and indirect nature of the benefits Salzman et al. (2018). In the context of wolves in the U.S., Arizona had a "pay-for-presence" program which ran from 2013-2020. Landowners could apply for payments based in part with known wolf-pack range overlap, and partly based on confirmed wolf-den location, with payments in the range of $38,000-60,000 (U.S. Fish and Wildlife, 2022). California recently introduced a plan to make payments based on landowner overlap with wolf range and the number of livestock on the land, but payments have not yet been made at the time of writing (California Department of Fish and Wildlife, 2023). *Ex-post* payments to promote large carnivore conservation remain

[1] For reviews, descriptions and evaluations of PES programs, see Puri et al. (2016), Miteva et al. (2014), Salzman et al. (2018) and Wunder et al. (2018)

the predominant method of payment (Zabel et al., 2009). However, it remains unclear what the distributional impacts of these two payment types are.

A separate strain of the literature considers spatial risk models, in order to construct spatial risk maps for depredations due to large carnivores (Treves et al. 2004; Ausband et al. 2010; Behdarvand et al. 2014; Clark et al. 2020). However, these do not address farmer decision making and payments, rather focusing on the spatial distribution of depredation risk only . Chen et al. (2013) use a risk map to define distinct insurance zones with premiums that varied with depredation risk, which is conceptually close to determining how *ex-post* payments would vary over space, but do not consider poaching or other endogenous production decisions in their model, and define spatial insurance zones at the village level whereas our analysis is conducted at the parcel level and includes endogenous poaching. Yoshida and Kono (2022) consider human-wildlife conflict at the urban boundary in a one-dimensional model where policymakers' choice variable is the urban boundary, but is conceptually very different in the motivations of the agents under consideration, and does not address payments to promote coexistence of livestock and wildlife.

Gray wolves (*Canis lupus*) is a large carnivore of the *Canidae* family, weighing from 18-80 kilograms (40 to 175 pounds). Wolves prey mostly upon wild ungulates such as moose, elk, white-tailed deer, mule deer, caribou, muskox and bison, and their diet often brings them into conflict with humans raising livestock (Naughton-Treves et al., 2003). Though the wolf's range once included most of North America north of 15-20 degrees latitude, human pressure, habitat loss caused extirpation through much of North America, with exception of northern Minnesota. In 1973, the gray wolf was listed as an endangered species, but has been delisted and relisted several times in the past decades, including a period of time from 2012-2014 in which the Minnesota Department of Natural resources oversaw public hunting seasons. Currently, the wolves are under federal endangered species protection, and wolves cannot be killed by members of the public except in defense of human life (Minnesota Wolf Management Plan, 2022). In addition to their direct benefits for wildlife viewing, wolves have significant existence value for many Minnesotans (Schroeder et al., 2020; Chambers and Whitehead, 2003).

In this paper, we extend the static farmer decision model with perfect information in Skonhoft (2017) to allow for a comparison of the impact of *ex-ante* and *ex-post* payments across space. We consider heterogeneity coming from two sources: farm area (impacting the total cattle stocking amount) and the risk of wolf depredation, arising from modeled wolf population and real landscape characteristics. Farmers choose a livestock stocking rate and level of poaching effort, in order to maximize profit. By varying the level of the *ex-ante* and *ex-post* payments, we compare farmers' behaviors and the resulting wolf population with consideration given to three management goals: reduced poaching and farmer compensation, and cost-effectiveness (given limited department of agriculture and wildlife agency budgets). Using data from a county in Minnesota, we find that, when careful monitoring and compliance are not assured, *ex-post* payments are more cost-effective in achieving these management goals.

Our work contributes to the literature on the impact evaluation of payments for ecosystem services schemes, payments to promote tolerance and effective policy design by considering the heterogeneity in outcomes and space. To the best of our knowledge, this paper is the first to integrate spatial risk mapping and analysis of the relative cost-effectiveness of *ex-ante* and *ex-post* payments to promote conservation. We show how spatial risk mapping can be combined with a farmer profit maximization model to reveal hotspots where poaching and livestock depredation are likely to occur with and without payments for ecosystem services. Our model can be used to for spatial targeting: identify areas where the payments are not going to be effective as well as suggest appropriate payment levels. For these reasons, our model has important implications for the design and implementation of payments for ecosystem service schemes.

2. Model

2.1 Spatial distribution of the carnivore population

Consider livestock producers and a wild population of large carnivores sharing a two-dimensional landscape $S \in \mathbb{R}^2$, with farmers indexed by $i = \{1, 2, ..., N\}$. Each farmer manages a parcel of land (field). Each parcel is of size A_i, and management decisions are made at the parcel level. Each field i is located at S_i (with associated latitude and longitude coordinates), and has an associated vector of landscape characteristics (l_i) at the farm location. These landscape characteristics determine the carnivore presence and likelihood of depredation by the carnivores at that farm. The carnivore population is has a central point in the landscape, for example a denning site, which is denoted $S^{\star}$. The carnivore population is distributed across the landscape according to a distribution function $W(S_i, l_i)$, where the carnivore population at a given point S_i depends on that point's position relative to $S^{\star}$, as well as the characteristics of the landscape at that point.

We treat the carnivore population at the beginning of the period as exogenous. This can be thought of as a minimum viable carnivore population as determined by biologists or mandated by policy. We then consider the problem in the context of cost-minimization on the part of the wildlife agency. We assume that deer and other wolf prey are abundant, and so we assume away increases in the carnivore population due to cattle depredation. We also ignore any substitutions between the carnivores natural prey populations and livestock.

2.2 Farmer profit function

We now introduce a risk-neutral profit-maximizing livestock producer at each farm S_i in the landscape. Since the livestock producers differ only in their location in the landscape and associated landscape variables, we at times suppress the index i to make equations more readable. We assume that the farmer chooses one stocking rate and intensity of poaching effort (introduced later in this section) across the whole parcel. Though this is a one period model, we assume that this farmer harvests the livestock so as to keep the herd size at an equilibrium stocking rate, X, so that the farmer gains revenue only from the growth of the livestock, which occurs linearly, is given by the parameter a, and is net any non-carnivore related losses. The farmer must pay an associated cost given by the cost function $C_X(X) = (c/2)X^2$, which is convex, twice differentiable, and increasing in X. This cost function is the same as that used in Skonhoft (2017) and is informed by the livestock production literature (e.g. Lawrence and Strohbehn, 1999), but assumes no fixed costs of production.

Absent depredation, the farmer chooses a stocking density X, in order to maximize profit. The farmer's profit function is given by

$$\pi_i^I = A_i\Big(paX_i - C_X(X_i)\Big) \tag{1}$$

Here, p is the exogenous market price per head of cattle, a is a growth parameter net non-carnivore related losses, and $C_X(X)$ the stocking cost function. The fields are not heterogeneous in the elements introduced so far, so the optimal stocking rate in the absence of predation is not affected by the field sizes. From (1) we have $\partial\pi^I/\partial X = A_i\,(pa - cX_i) = 0 \Rightarrow X_i^{I\star} = pa/c$. Plugging $X_i^{I\star}$ into the profit function, we get that $\pi^{I\star} = A_i\Big(\frac{p^2a^2}{2c}\Big)$. This is important because it gives the farmer profit with no depredation and can be used to compare profit with depredation to the case where the carnivore population does not exist.

Depredation function

Now we add depredation of the livestock by the carnivore population to the farmer's profit function. The farmers are heterogeneous only in their distance to the carnivore population center, landscape attributes l_i and the size of their farms, A_i. Risk of depredation depends on livestock presence, wolf presence, and landscape attributes (Clark et al., 2020). Thus, we introduce the depredation risk, ψ_i which determines the risk of depredation as a function of landscape attributes alone. Together, we have the expected depredation per acre given by $X_iW_i\psi_i$. This tells us that proportion of livestock lost at a given location is determined by the stocking density of livestock at that location, the carnivore population at that location, and the depredation risk at that location given the landscape characteristics.

$$\pi_i^{II} = A_i\Bigg[pX_i\Big(a - W_i\psi_i\Big) - C_X(X_i)\Bigg] \tag{2}$$

and taking the first order condition, we have that $\frac{\partial\pi^{II}}{\partial X} = A_i\,[p\,(a - W_i\psi_i) - cX_i] = 0$. Solving for X, we have $X_i^{II\star} = p(a - W\psi)/c$, which is less than $X_i^{I\star}$ by $pW\psi/c$. The optimal stocking density is now a function of the site of the farm and resulting risk of depredation. *Ceteris paribus*, more depredation risk results in lower stocking densities. We note that if the livestock growth parameter minus the carnivore population times the depredation risk goes to zero

$(a - W\psi)$, the optimal stocking rate is zero. The total amount of livestock for a given farmer will then be $A_i X_i^{II\star}$, meaning that larger farmers will have more head of cattle *ceteris paribus.* $\pi_i^{II}(X_i^{II\star}) = A\left[p^2(a - W_i\psi_i)^2/2c\right]$. The "lost" profit as a result of the carnivore population by the difference in optimized profit functions, $\pi^I\left(X^{I\star}\right) - \pi^{II}\left(X^{II\star}\right) = A_i\left[\frac{p^2 W_i^2 \psi_i^2}{2c}\right]$. This difference is important in evaluating "lost" profit due to the presence of carnivores.

Poaching effort

We now introduce the second control variable of the farmer, poaching effort. We define "poaching" to be any killing of the carnivore population. This is a slight abstraction from the reality of our setting described in section **??**, since farmers can legally kill wolves when the life of a person, pet or livestock is in immediate danger, but are otherwise not allowed to kill wolves (**?**). The farmer can reduce the carnivore population on each parcel S_i through poaching effort Z_i, which can be thought of in terms of hours per acre. Specifically, the carnivore population remaining on a farm after poaching effort is $A_i W_i(1 - \eta Z_i)$, where η is a parameter that determines the effectiveness of hunting effort. The total poaching effort of farmer i is given by $A_i Z_i$. Since the carnivore population cannot become negative, $Z \in [0, 1/\eta]$. The poaching effort has the associated cost function $C_Z(Z)$, which we give the explicit form form $C_Z(Z) = (b/2)Z^2$. With the inclusion of poaching variable, we replace W_i in the depredation function with $W_i(1 - \eta Z_i)$, and the profit function becomes

$$\pi_i^{III} = A_i\Big\{pX_i\Big[a - W_i(1 - \eta Z_i)\psi_i\Big] - C_X(X_i) - C_Z(Z_i)\Big\} \tag{3}$$

Now, the first order conditions consist of the partial derivative of (3) with respect to both control variables. The first order conditions for an interior solution are

$$\frac{\partial \pi^{III}}{\partial X_i} = A_i\Bigg[p\left[a - W_i(1 - \eta Z_i)\psi_i\right] - cX_i\Bigg] = 0 \tag{4}$$

$$\frac{\partial \pi^{III}}{\partial Z_i} = A_i\Bigg[pX_i\eta W_i\psi_i - bZ_i\Bigg] = 0 \tag{5}$$

which can together be solved for

$$X_i^{III\star} = \frac{pb(a - W_i\psi_i)}{cb - (pW_i\eta\psi)^2} \tag{6}$$

$$Z_i^{III\star} = \frac{p^2\eta W_i\psi_i(a - W_i\psi_i)}{cb - (pW_i\eta\psi_i)^2} \tag{7}$$

These are plugged into the profit equation to obtain the optimized profit. The farmer chooses the corner solution of $Z = 0$ when $\pi(X^{II}, 0) > \pi(X^{III}, Z^{III})$ for a given set of parameters, which is equivalent to π^{II} given in equation (2).

Wildlife service payments

To promote coexistence between humans and the carnivore population, and to decrease poaching, the WS can offer two types of payments, *ex-ante* payments based on the carnivore population at a certain location, and *ex-post* payments based on the depredation sustained by each farmer. Skonhoft (2017) model a Stackelberg game (Schelling, 1981) in order to compare the equilibrium outcome with the WS as leader, and the farmers as following. In our case, we are only interested in the farmers response to endogenously determined payments. The game proceeds as follows: 1. The WS defines the payment levels (p_W, p_X) to be realized at the conclusion of the time period. 2. The farmers observe the payments and choose the optimal stocking rate (X) and poaching effort (Z) given their landscape characteristics and the payment levels. 3. Poaching occurs, and the carnivore population is reduced. 4. Depredation occurs, and the livestock available for sale is reduced. 5. Payments occur and profits are realized.

Due to our assumption of perfect information, our problem can be solved by backward induction since we can obtain farmer response functions for any WS policy. In order to focus on the response of farmers to various policy scenarios, we vary the payment levels and compare farmer's behaviors. The *ex-ante* payment function at payment level p_W for farmer i is given by $p_W A_i W_i$, and the *ex-post* payment function at payment level p_X for farmer i is given by $p_X A_i X_i W_i (1 - \eta Z_i)\, \psi_i)$. In words, the farmer receives p_X for every animal killed by the carnivores, where the number of livestock killed depends on the post-poaching distribution of wildlife. We assume that p_X is net any transaction costs of the farmer. We also assume that

$p_X \leq p$, since poaching effort is trivially zero if $p_X > p$, and we are unaware of a conservation program which sets its *ex-post* payments greater than the market price once transaction costs and non-lethal effects of wildlife presence are accounted for.

2.3 Farmer optimization problem with *ex-post* payments

With the addition of the *ex-post* payments, we have the farmer profit function:

$$\begin{aligned}\pi_i^{\textit{ex-post}} =& A_i \Bigg\{ pX_i \Bigg[a - W_i(1-\eta Z_i)\psi_i \Bigg] - C_X(X_i) - C_Z(Z_i) \\ & + p_X X_i W_i \left(1-\eta Z_i\right) \psi_i \Bigg\}\end{aligned} \tag{8}$$

In words, given the distance from the center of the carnivore population, landscape characteristics and WS policy, the farmer chooses stocking rate X_i and poaching effort Z_i to maximize profit across all managed parcels. This problem can be solved for the farmer response functions, $X_i^\star(p_X)$ and $Z_i^\star(p_X)$, which can be analyzed to determine how farmers will respond to the policy scenarios of interest.

First, we show the first order necessary conditions with suppressed function arguments. We assume a stocking rate of greater than zero since we do not model farmer "shutdown", and do not see zero stocking rates in our simulation. A corner solution of zero poaching effort can occur however. The first order conditions give us:

$$\frac{\partial \pi}{\partial X} = pa - cX_i - (p - p_X)\big[W_i(1-\eta Z_i)\psi_i\big] = 0 \tag{9}$$

$$\frac{\partial \pi}{\partial Z} = (p - p_X)X_i W_i \eta \psi_i - bZ_i \leq 0 \tag{10}$$

with condition 10 being an equality when $Z > 0$. Positive poaching effort is supported so long as $(p - p_X)X_i W_i \eta \psi_i > 0$. We can see from 9 that, in keeping previous literature, the *ex-post* payment level increases the stocking rate.

The term $(pa - cX_i)$ in equation (9) is the FOC of the stocking rate problem with no depredation or government payments. The second part adds the revenue lost due to depredation, adjusted for the reduced carnivore population due to poaching, and the WS *ex-post* payment. Equation (10) shows that the farmer increases the poaching effort until the additional profit from the reduction in depredation is equal to the marginal cost of poaching effort.

In the special case where the WS sets the *ex-post* payment to be exactly equal to the market price for livestock, p, it is easy to see that the optimal stocking rate collapses to $X = \frac{pa}{c}$, which is equal to the farmers optimal stocking rate with no carnivores. The optimal poaching effort is then $Z = 0$. Since $Z^\star = 0$ for $p_X > p$, we will limit our analysis to values of p_X on the range of $[0, p]$. Rearranging (10) to solve for $Z^\star$ and taking the partial derivative with respect to p_X, we have $\partial Z^\star / \partial p_X = (W_{ij}\psi_{ij}\eta / b) \left[(p - p_X)\left(\partial X^\star / \partial p_X\right) - X^\star\right]$, we see that $Z^\star$ is decreasing in p_X, so long as $(p - p_X)\left(\partial X^\star / \partial p_X\right) - X^\star < 0$, which is true for all combinations of parameters under consideration. The term $(p - p_X)\left[W_{ij}(1 - \eta Z)\psi_{ij}\right]$, which is the cost of depredation to the farmer after accounting for poaching and *ex-post* payments, is non-negative by assumption, since $p_X \in [0 < p]$ and $Z \in [0, 1/\eta]$.

To find the interior solution, we can set the first order conditions of farmer's profit function to zero and solve for X and Z to obtain each farmer's response for given parameters, including *ex-ante* and *ex-post* functions. These solutions to the farmer optimization problem can be written $X_i^\star(p_W, p_X)$ and $Z_i^\star(p_W, p_X)$ for any policy by the WS:

$$X_i^{ex\text{-}post} = \frac{bpa - b(p - p_X)W_i\psi_i}{cb - (p - p_X)^2(W_i\eta\psi_i)^2} \tag{11}$$

$$Z_i^{ex\text{-}post} = \frac{ap(p - p_X)W_i\eta\psi_i - (p - p_X)^2(W_i\eta\psi_i)^2}{cb - (p - p_X)^2(W_i\eta\psi_i)^2}; \quad Z_i^{ex\text{-}post} > 0 \tag{12}$$

From (11), it is clear that $X_i^{IV\star}$ is increasing in p_X, since it is a part of a positive term in the numerator and is reducing a negative term in the denominator.

2.4 Farmer optimization problem with *ex-ante* payments

We now introduce the *ex-ante* or "performance payment" made by the wildlife agency to the farmer at the beginning of the season. Importantly, we do not model any sort of conditionality in this payment, so that the farmer receives the payment solely on the carnivore population at the beginning of the season, and is not penalized for poaching. This modelling decision is clearly inappropriate in cases where the wildlife agency has the means to monitor wildlife populations on a small enough scale that the payments can be made conditionally on the continued presence of the carnivore. However, in our reading of the few *ex-ante* payment programs that have been attempted in the U.S., payments have been made on the basis of overlap between the farmer's land and the carnivore range, not based on a more refined measure of carnivore population. For this reason, we have chosen not to model conditionality here. The farmer's profit function with *ex-ante* payments is given by

$$\pi_i^{ex\text{-}ante} = A_i \left\{ pX_i \left[a - W_i(1-\eta Z_i)\psi_i \right] - C_X(X_i) - C_Z(Z_i) + p_W W_i \right\} \tag{13}$$

We can see that the *ex-ante* payment does not enter the first order necessary conditions for an interior solution, so that the marginal stocking rate and poaching effort are not affected by the *ex-ante* payment p_W. This is in keeping with results from previous literature stating that one of the advantages of *ex-ante* payments is that they do not distort the farmer's stocking decision, e.g. Skonhoft (2017). However, *ex-ante* payments can have an effect on poaching behavior by pushing more farmers into the corner solution. Thus, *ex-ante* payments can be used to reduce poaching without distorting stocking decisions by pushing a greater number of farmers into the corner solution. Conditional on poaching effort being greater than zero, the *ex-ante* payments have no effect on the marginal poaching effort for each farmer. Skonhoft (2017) imposes the constraint that the farmer be fully compensated for the presence of the wildlife, so that the maximized profit under no depredation is equal to that with *ex-ante* payments. Recalling that the maximized profit with no depredation is denoted $\pi^{I^\star}$, we find this condition at

$$\begin{aligned} \pi^{I^\star} - \pi_i^{ex\text{-}ante} = & A_i \Big(paX_i - C_X(X_i) \Big) \\ & - A_i \left\{ pX_i \left[a - W_i(1-\eta Z_i)\psi_i \right] - C_X(X_i) - C_Z(Z_i) + p_W W_i \right\} \end{aligned} \tag{14}$$

This can be solved for the quadratic equation $\tilde{Z} = \frac{\eta p X_i \psi_i W_i \pm \sqrt{(\eta p X_i W_i)^2 - 2b(pX_i\psi_i W_i - p_W W_i}}{b}$. Since

Z_i cannot be negative, we have

$$Z_i^{ex\text{-}ante} = \begin{cases} 0 & \text{if} \quad \eta p X_i \psi_i W_i \leq \sqrt{(\eta p X_i W_i \psi_i)^2 - 2b(pX_i\psi_i W_i - p_W W_i)} \\ & \text{or} \quad pX_i W_i \psi_i = 0 \\ Z_i^{III\star} & \text{if} \quad \eta p X_i \psi_i W_i > \sqrt{(\eta p X_i W_i \psi_i)^2 - 2b(pX_i\psi_i W_i - p_W W_i)} \end{cases} \tag{15}$$

Here, $Z_i^{III\star} = \frac{p^2 \eta W_i \psi_i (a - W_i \psi_i)}{cb - (pW_i \eta \psi_i)^2}$, which is the optimal poaching effort found under no payments. Thus, for the parameters of any given farmer, there is a p_W at which the farmer will not poach. This is illustrated in figure 1. The stocking rate is also equal to the stocking rate with no payments or poaching, so that $X_i^{ex\text{-}ante} = p(a - W\psi)/c$. It is interesting to note that the *ex-ante* payment level that solves this threshold equation for an individual farmer is $p_W = pX_i\psi_i$, so that the payment per carnivore per acre at which the farmer drops to zero poaching is $pX_i\psi_i W_i$. This is the same payment per acre needed to fully compensate farmers for losses via *ex-post* payments ($p_X = p$), and implies that an individual farmer can be induced to refrain from poaching entirely with the same cost via either type of payment.

Using these solutions, we can apply this model to a specific spatial context to see where "hotspots" human-wildlife conflict and poaching are likely to occur. Note that the farmers' response are heterogeneous based on the expected depredation that they face, both in terms of wolf population and in terms of whether the landscape lends itself to depredation. We can also use these solutions compare the cost of poaching reduction and farmer profit restoration under the two types of payments.

3. Policy Background and Study area

Minnesota, a state in the northern Midwest of the United States, is estimated to have a population of 2,244 to 3,252 gray wolves (*Canis lupus*), with an average mid-winter pack size of 3.63 wolves per pack, and an average pack territory size of 117 km^2 (Erb and Humpal, 2020). Minnesota's wolf population has been steadily growing from north to south since the 1970's, and now covers more than half of the state. At the same time, Minnesota has a large human population relative to most of the gray wolf's range, resulting in an exceptionally high levels of livestock conflict in this state. Attitudes towards wolves vary widely in Minnesota, but there are clear differences across stakeholder groups. For instance, 62.2% of livestock producers have a negative attitude toward wolves versus 19.6% of the general public (Schroeder et al., 2020). Following a February 10, 2022 court order, gray wolves are federally protected outside of Alaska and the Northern Rocky Mountain region, so that hunting, trapping and retaliatory killing is not allowed except to protect human life or with special authorization in Minnesota. Prior to the federal listing of wolves, Minnesota held wolf hunting seasons in 2012-2014, with an average of 308 wolves being killed in each season (Erb et al., 2014), which shows a latent demand for recreation hunting of wolves within the region.

Using a representative county from Minnesota, Beltrami county, we illustrate the advantages of our model. Beltrami county is part of a 40-mile wide band running roughly east and west across Minnesota where depredation is especially common due to being a part of the wolves' core range, but being far enough south that cattle grazing density is high. However, overall levels of confirmed damage by wolves are low relative to the amount of livestock. For instance, during the fiscal years 2018-2022, the Minnesota Department of Agriculture made *ex-post* payments of $621,000 across the state, with $71,905 being made in Beltrami county (Kjeseth, 2022). While there have been no *ex-ante* payments used in Minnesota, the Minnesota Department of Agriculture recently announced $45,000 in grant funding to prevent depredation of livestock by wolves in 2024. Rawksi (2023). This money can be used for depredation mitigation measures such as the purchase of guard animals, fencing and shelters, and theoretically would not cause the distortion in stocking rate that our model implies. Beltrami county is Minnesota's fourth largest county, with an area of 3,056 square miles (7,920 km^2).

4. Data

We apply our model to parcel-level data Beltrami County, which is situated in northern (Beltrami County GIS, 2022). In Beltrami county, there are 4,718 parcels classified as agricultural. We drop parcels which are not classified as being for agricultural use. The agricultural parcels are quite large, with an average parcel size of close to 52 acres. We also used deer density by wildlife management area (Michel and Giudice, 2022) and road density from (Beltrami County GIS, 2022) to calculate the vector of landscape characteristics for each parcel. We use crop cover data from the United States Department of Agriculture (USDA) CropLand Data Layer (Han et al., 2012), which we use to determine how many acres on each parcel would be suitable for livestock, and exclude parcels which are completely used for grain crops such as corn and soybeans. Finally, we use landcover data from the National Land Cover Database (NLCD) published by the U.S. Geological Survey (NLDC, 2019) to determine the landscape characteristics of each parcel, which determines the probability of depredation occurring on that parcel given the stocking rate and wolf population. We simulate the impact the *ex-ante* and *ex-post* payments over the landscape. The vector of coefficients determining the risk of depredation given the landscape was taken from equation (4) in Treves et al. (2004), in which the authors estimate a depredation risk function using farm-level data in Minnesota and Wisconsin:

$$\begin{aligned}\psi(l_{ij}) =& 0.10\, conifer + 0.13\, open\ water + 0.13\, deer\ density - 0.16\, pasture/hayfield \\ & - 0.58\, crops - 0.13\, emergent\ wetland - 0.41\, road\ density\end{aligned} \tag{16}$$

In the specifications with a wolf population, we set the center of wolf activity to be near the center of a wolf pack as reported by Erb and Humpal (2020). η, the parameter which determines the effectiveness of poaching effort was calculated so that two hours of poaching effort would result in the eradication of wolves on a particular acre. The wolf population varies, but is set to 247 wolves in the base scenario.

We set the livestock growth parameter to be 0.36 over the length of the grazing season, and an average end of season weight to be 850 lbs. (Henke, 2017). The cost of preventing poaching is sensitive to p, the market price of cattle through the effect of p on both the stocking rate and poaching effort, but in most specifications it is set to \$1,976 based on a feeder cattle price of \$2.36 per pound (USDA AMS, 2023). We set c, the stocking cost per animal to \$788.44 based on Lawrence and Strohbehn (1999) and adjusted to 2023 dollars.

While the payments made by the Minnesota Department of Agriculture are supposed to be set at the market price, significant transaction costs and uncertainty about claim verification make so that the effective *ex-post* compensation is less than the true cost of cattle depredation to the farmer. In addition, there is some evidence cattle stressed by the threat of depredation do not grow as quickly even when killing does not occur, possibly due to inefficient grazing patterns or stress to mother cows (Ramler et al., 2014). Thus, we consider the market price of beef to be the upper bound of the net *ex-post* payment made to farmers.

5. Simulation

5.1 *Ex-post* payments for poaching reduction

We compare the solution to the farmers optimization problems in the models laid out above. First, we solve for the homogeneous optimal stocking rate in the absence of depredation or payments. We compare this to the effect of wolf depredation on farmer profits with no poaching effort. Next, we add the optimal levels of poaching effort, and then compare to the full model with the two types of payments aimed at reducing poaching, at payment levels of 75% of the net price of livestock, and full compensation of $p_X = p$. We then show the wolf population remaining over the range of possible *ex-post* payments. These results allow us to observe how the different elements of the model enter into the simulation.

5.2 *Ex-ante* vs. *Ex-post* payments

Given our model parameters, we compare the cost of poaching reduction, by incrementally increasing each type of payment separately and mapping the wolf population remaining after the poaching response. The *ex-ante* payments were increased from \$0-900 per carnivore, with the upper limit being determined by the amount needed to completely eliminate poaching given the model parameters. The *ex-post* payment was varied from \$0-1972 per lost animal, where \$1972 is the market price per animal. This allows us to compare the cost per wolf saved in using each type of payment.

5.3 Targeted vs. uniform *ex-post* payments

It is possible that targeted payments could increase the cost effectiveness of payments to reduce poaching. One possible payment scheme would be for the wildlife service to observe the farm with highest expected level of poaching effort and fully compensate that farmer so that $p_X = p$ for that farmer. This could be done iteratively until the budget was expended. Maintaining the WS as the first mover, the fully compensated farmers would respond with the zero-wolf stocking rate and zero poaching effort. We consider this algorithm for payment targeting, and compare to the uniform *ex-post* payments. As noted in section 2.4, with targeted *ex-ante* compensation at the level needed to induce each individual farmer to refrain from poaching, the problem is identical to fully *ex-post* compensation, with identical results.

6. Results

In specification one, the farmers vary only in the area under their control. With no depredation, poaching or government payments, we find that the optimal stocking rate is 0.9004 head per acre, with a mean stocking amount of 18.92 per farmer. This stocking rate is within the range of possible stocking rates reported in Minnesota, which can vary based on forage quality and the amount of supplemental feed used (**?**). The average profit per farmer is \$6,716.74, or \$319.61 per acre. These numbers are also within the range of those typically observed in the upper Midwest, though profit per acre for grass-fed beef can be highly variable depending on input costs and grazing conditions (**?**).

In specification two, we see that the stocking rate is reduced slightly due to the depredation faced, with an average stocking rate of 0.8974 and average stocking per farmer of 18.859 head respectively. Though the average amount of depredation faced is quite small at 0.023 animals per farmer, this comes out to an average cost of 45.025 per farmer at the chosen market price, and a total cost of \$65,601.02 across all farmers. We also see an total lost profit across all farmers of \$65,793.503, which also accounts for the relatively small amount of profit lost due to reduced stocking rates due to depredation. Figure 6 illustrates the areas in which the losses are highest. Not surprisingly, losses are highest in the area nearest the wolf den location, but losses vary somewhat throughout the map due to the landscape heterogeneity that causes risk of depredation to vary. In particular,

In specification three, we add poaching to the farmer's optimization problem. The average poaching effort seems small at 0.071 hours per acre per farmer. However, when multiplied by the number of acres under each farmer's control, this is an average of 1.5028 hours per farmer, with a max of 156.24 for one farmer. Unsurprisingly, larger amounts of land controlled is correlated with higher levels of wolves killed (see figure 8). This fact is not trivial when we consider the extensive transaction costs inherent in each of these payment schemes. When aggregated across the landscape and multiplied by the "poaching effectiveness" parameter (η), we get a total of 9.04 wolves poached across the landscape with no payments made by the WS. This poaching effort is centered around the location of the wolf den, but larger farms naturally have higher levels of expected wolves killed (see figure 9a). This poaching effort reduces the average depredation cost of the farmer to 42.32, the average stocking rate increases slightly to 0.8983, and the average and total lost profit is reduced slightly to \$43.776 and \$63,782.09 respectively.

Figure 7 shows the poaching effort with no payments. We can see that the majority of the poaching effort is centered around the center of the wolf population, as is expected. However, we also note a relative hotspot in the northwest of the county, which, given its distance from the center of the wolf population implies that its landscape characteristics are highly correlated with depredation. With better parameter inputs and real data on wolf locations and depredations, this type of map could be used to target extension interventions or determine high priority areas to monitor for poaching.

We now add an *ex-post* payment equal to 75% of the market price of cattle ($p_X = \$1,479$). This has the effect of decreasing the average poaching effort to 0.3768 hours per farmer, resulting in a total of 2.27 wolves killed, which is 6.77 fewer than were killed in the case with no WS payments. Figure 9 maps the comparison of the number of wolves killed without and with *ex-post* payments. Since the *ex-post* payments reduced the cost of depredation experienced by the farmer, the average stocking rate is increased slightly to 0.8997 head per acre. The average “lost” profit per farmer relative to the case with no depredation is reduced to $40.83, and the total “lost” profit is $59,484.31.

We now consider the results of the full model as the *ex-post* payment varies from zero to the market price of cattle (inclusive of transaction costs), that is, the range $p_X \in [0, p]$. We find that the amount of poaching reduced across the landscape increases linearly with the amount of the *ex-post* payment, and that full preservation of the wolves present on the landscape occurs when the *ex-post* payment is equal to the market price of cattle.

6.1 *Ex-ante* vs. *Ex-post* payments

Figure 16 shows the cost path to the WS as a higher wolf population is maintained. That is, it shows the total payment made via each payment type by the WS at each level of final wolf population maintained. Intuitively, this is due to the fact that in our model, the WS has no way to monitor farmers poaching behavior, so the *ex-ante* payment only reduces poaching by causing farmers close to the threshold to switch zero poaching. As the *ex-ante* payment level increases, fewer and fewer farms have positive poaching effort. However, *ex-ante* payments made to those farmers with positive poaching are increasing the costs to the WS without reducing poaching, and payments made to the farmers who not poaching increase costs as well, again without reducing poaching at the margin. One the other hand, *ex-post* payments reduce poaching effort for all farmers with positive poaching effort linearly. The intuition behind this result holds for contexts in which *ex-ante* payments cannot be made conditional on compliance of the farmer so that they are not affecting the marginal decision of the farmer. This also suggests that heterogeneity in the depredation faced by farmers is an important factor in explaining the predominance of *ex-post* payment schemes for large carnivore conservation in the U.S. As shown in the following section, the cost of reducing poaching effort to zero for an individual farmer via the two methods is identical. However, when payments can only be made homogeneously, *ex-post* payments are more cost-effective in reducing poaching than *ex-ante* payments.

6.2 Targeted vs. uniform payments

We report the results of the iterative targeted payment algorithm, where full compensation payments are made to the farmers in order of expected poaching effort until the budget is exhausted. By looking at figure 17 we see that targeted payments achieve the conservation goals at much lower budgets than homogeneous levels of *ex-post* payments applied across all farmers. It is beyond the scope of this paper to determine theoretically under what conditions this would be the case, but this result is promising since it suggests that wildlife services and conservation NGOs could likely stretch limited budgets much further by implementing targeted *ex-post* payments in cases where *ex-ante* payments would be impracticable to implement. In the context of the U.S., WS budgets are often constrained to the point that state programs have even run out of funds mid-season for depredation compensation and payments-for-presence, making this an important secondary result. Since the farmers' incentive to poach in our model is based solely on depredation pressure, this implies that government agencies looking to target payments should start with areas where depredation risk is high. In our context, these are areas with some combination of high total depredation risk based on equation 16, and proximity to center of the pack activity. For instance, in our landscape, crop production is an important factor reducing the depredation risk, while deer density is associated with higher risk.

7. Discussion

We have shown the effect that *ex-post* payments have in a spatially heterogeneous landscape, and shown that, while *ex-post* payments cause mild increases in stocking rates, they reduce poaching to zero as the payment amount approaches the market price of livestock. We have illustrated the spatial differences in depredation risk that can arise due to both characteristics of the landscape, and the distribution of the carnivore population on the landscape. We have also shown that in absolute terms, farmers controlling more land contribute more to total poaching than farmers with less land, implying that where payments have fixed transaction and monitoring costs, the WS should focus on larger landholders. Where the government desires to increase farmer profits without distortion of farmer incentives, *ex-ante* payments may be effective. However, given our model parameters, *ex-post* payments achieve poaching reduction much more cheaply than *ex-ante* payments. Finally, the use of targeted payments to fully eliminate the poaching of those farmers most likely to engage in poaching reduces poaching much more cheaply than payments which reimburse all losses across the landscape at an equal rate is the government agency is budget constrained.

The previous results should be considered with the following limitations in mind. First, our model is static, considering expected outcomes over a single grazing season, and not accounting for the impact that poaching would have in subsequent time periods on depredation and *ex-ante* payouts. Second, we do not model the risk preferences of farmers, or uncertainty in depredation outcomes. Many farmers are likely to be risk-averse, and their incentives to each type of payments will vary based on how risk is modelled. In terms of *ex-ante* payments, we model a PES scheme with poor monitoring and conditionality. While this is reflective of the reality of some PES schemes, we are hopeful that future programs will include improved wolf location monitoring and payment conditionality. We also do not consider the spillover effects of poaching. The killing of wolves has complex effects of the future behavior of wolves since it disrupts their social structure, and at a minimum it would affect the wolf presence on nearby farms, which we abstract from. The inclusion of spillovers would include a game theoretic element to the farmer's poaching decision which is beyond the scope of this paper. We also simplify the farmer poaching decision by assuming zero positive utility and a homogeneous propensity to break the law. Due to concerns of targeted killing of wolves, there is limited publicly available data on wolf distributions and depredation patterns. With access to this data, the parameters of the model could be estimated to improve the depredation risk element of the model, making this model a practical tool for the identification of potential hotspots for the targeting of payments to reduce poaching and enforcement by the WS.

This work holds promise for government agencies tasked with managing carnivore-livestock conflict. By incorporating spatially explicit landscape characteristics into the model, agencies can see how the costs of payments vary over space. With the inclusion of detailed wolf distribution and livestock depredation data, an agency could determine where to target depredation mitigation grant money and anti-poaching enforcement. Finally, we show that the conservation goals of an agency with a limited budget may be met more cheaply by targeting the farmers with the greatest expected poaching effort for complete compensation, reducing those farmers' poaching effort to zero.

8. Conclusion

In this paper we extend a model to include livestock producers facing heterogeneous depredation from a wild carnivore population and conservation payments in space, producing maps which combine landscape characteristics with farmer responses to show where poaching is likely to occur. We solve for the farmer's optimal stocking rate and poaching effort as functions of the WS policy, showing that the farmer's poaching effort is unchanging in *ex-post* payments, and the farmer's stocking rate is increasing in *ex-post* payments. We then simulate this model over a landscape with heterogeneous farm size, landscape characteristics and distance from the carnivore location, and find how the farmer response varies with various levels of payments, showing that targeted *ex-post* payments may improve the efficacy of the current compensation system.

Extensions of this work could include empirical tests of the farmer response functions using currently unpublished geo-located livestock depredation and poaching data to validate the model, particularly whether stocking rates and poaching effort levels vary through space in the way predicted by the model. The inclusion of risk preferences and uncertainty over depredation and poaching outcomes would allow us to answer important questions about how farmer incentives and wildlife agency costs change depending on the assumptions about how risk affects realized payments. More accurate estimation of wolf population and depredation risk parameters would improve the usefulness of the spatial poaching and costs maps to local policymakers. Extension of the model to include the dynamics inherent in wildlife populations and livestock management would allow us to examine whether this is a stable equilibrium and more realistic interactions between livestock densities, carnivore populations, and wild ungulate populations. Finally, a more nuanced model of farmer propensity to poach could greatly improve the model's usefulness to wildlife agencies for understanding where to target enforcement of conditionality in payments.

9. Tables and Figures

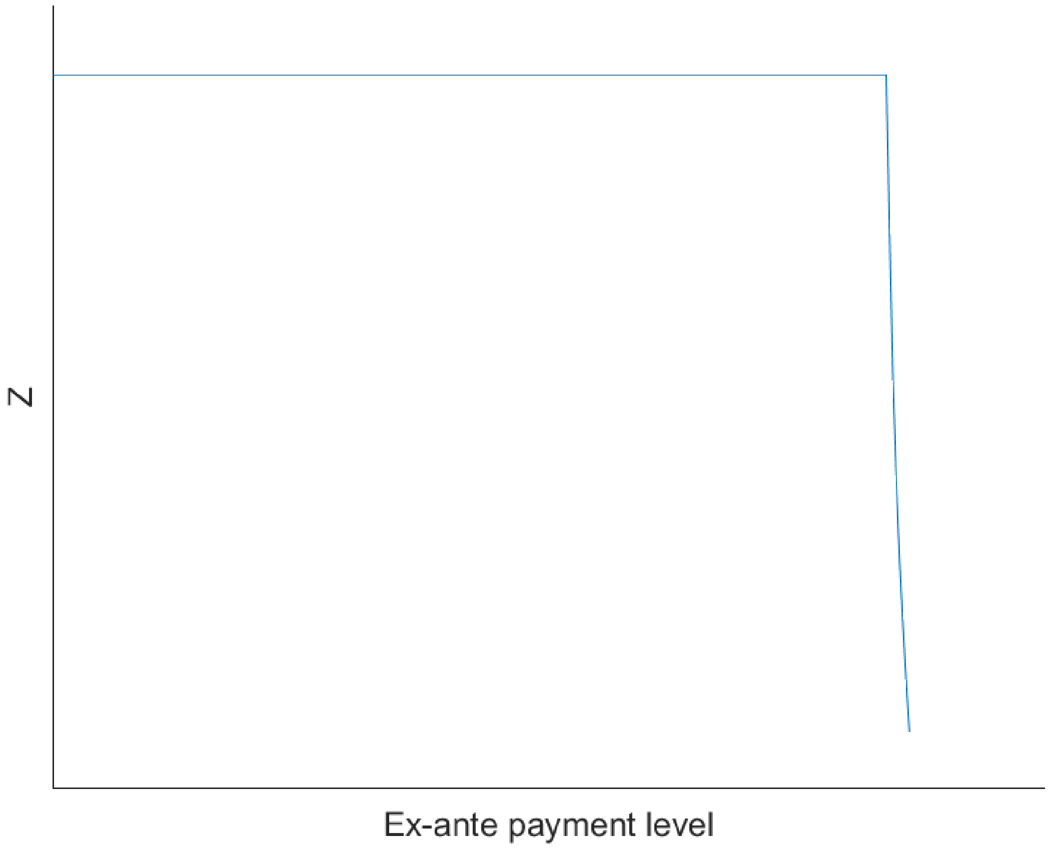
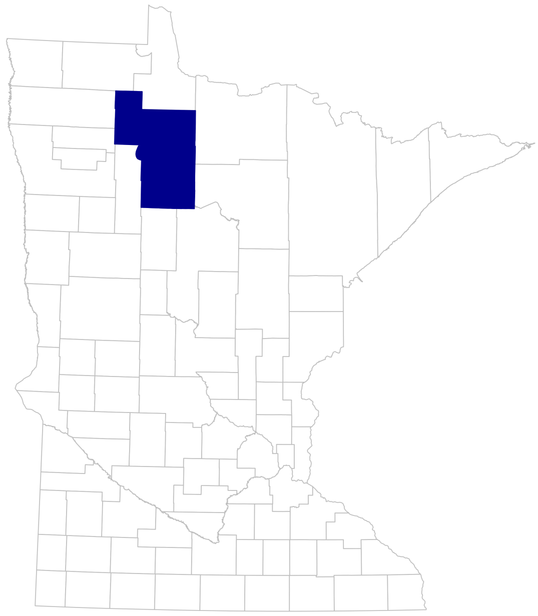
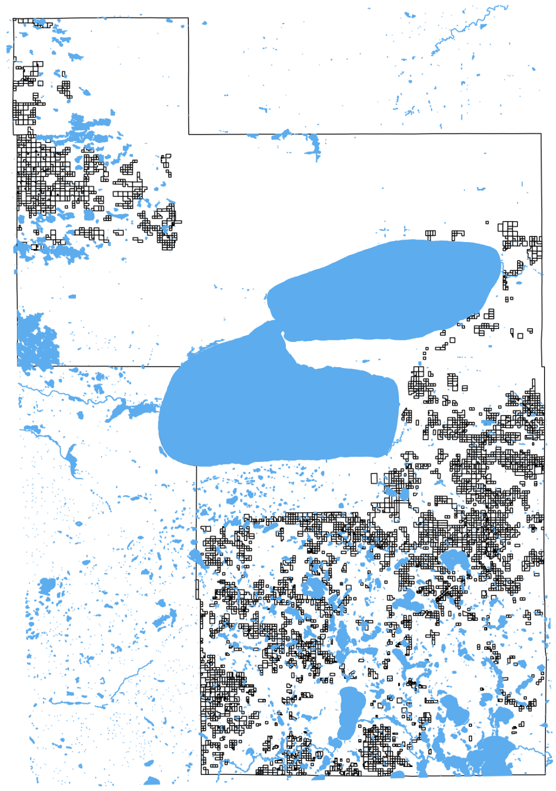


Figure 1: Illustration of the threshold equation for zero poaching.

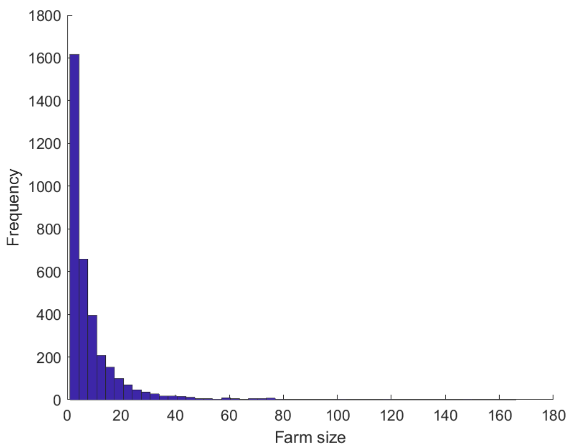


(a) Location of Beltrami County within Minnesota

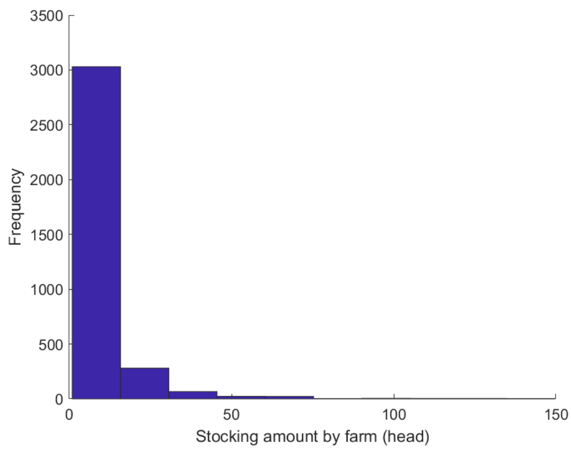


(b) Agricultural parcels in sample

Figure 2: Study area: Beltrami County, Minnesota, U.S.



(a) Distribution of farm size



(b) Distribution of stocking amount

Figure 3: The total stocking amount is driven by farm size.

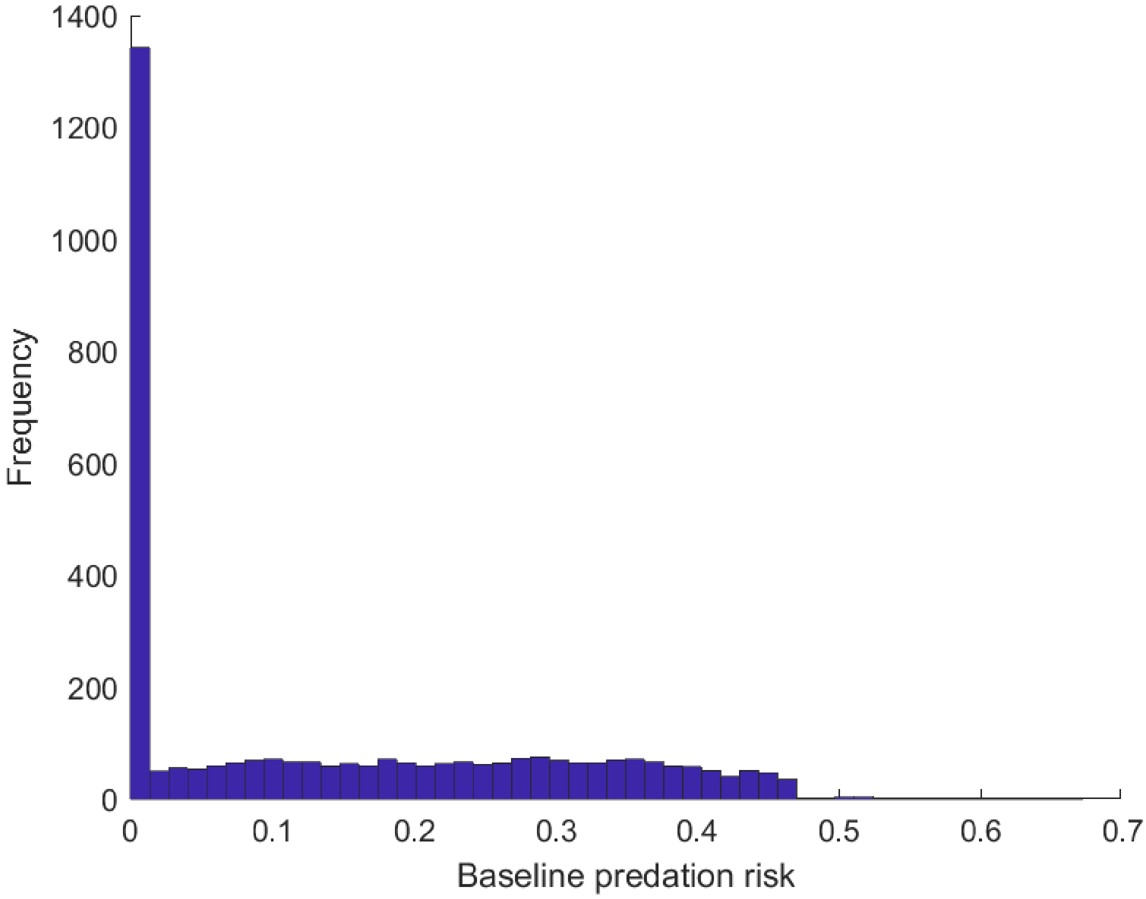


Figure 4: Distribution of depredation risk

Table 1: Results for cases I-V

	I	II	III	IV	V
Depredation included	No	Yes	Yes	Yes	Yes
Poaching included	No	No	Yes	Yes	Yes
Ex-post payment	\$0	\$0	\$0	\$1,479	\$1,972
Avg. stocking rate	0.9004	0.8973	0.8976	0.8997	0.9004
Avg. poaching effort per farm	-	-	0.6356	0.1598	0
Avg. profit per farm	2845.6807	2826.5579	2827.2385	2840.9308	2845.6807
Avg. depredation per farm	-	19.0579	17.7065	18.8133	19.1876
Total wolves killed	-	-	9.0233	2.2684	0
Total cost to government	0	0	0	48524.3174	65985.9859

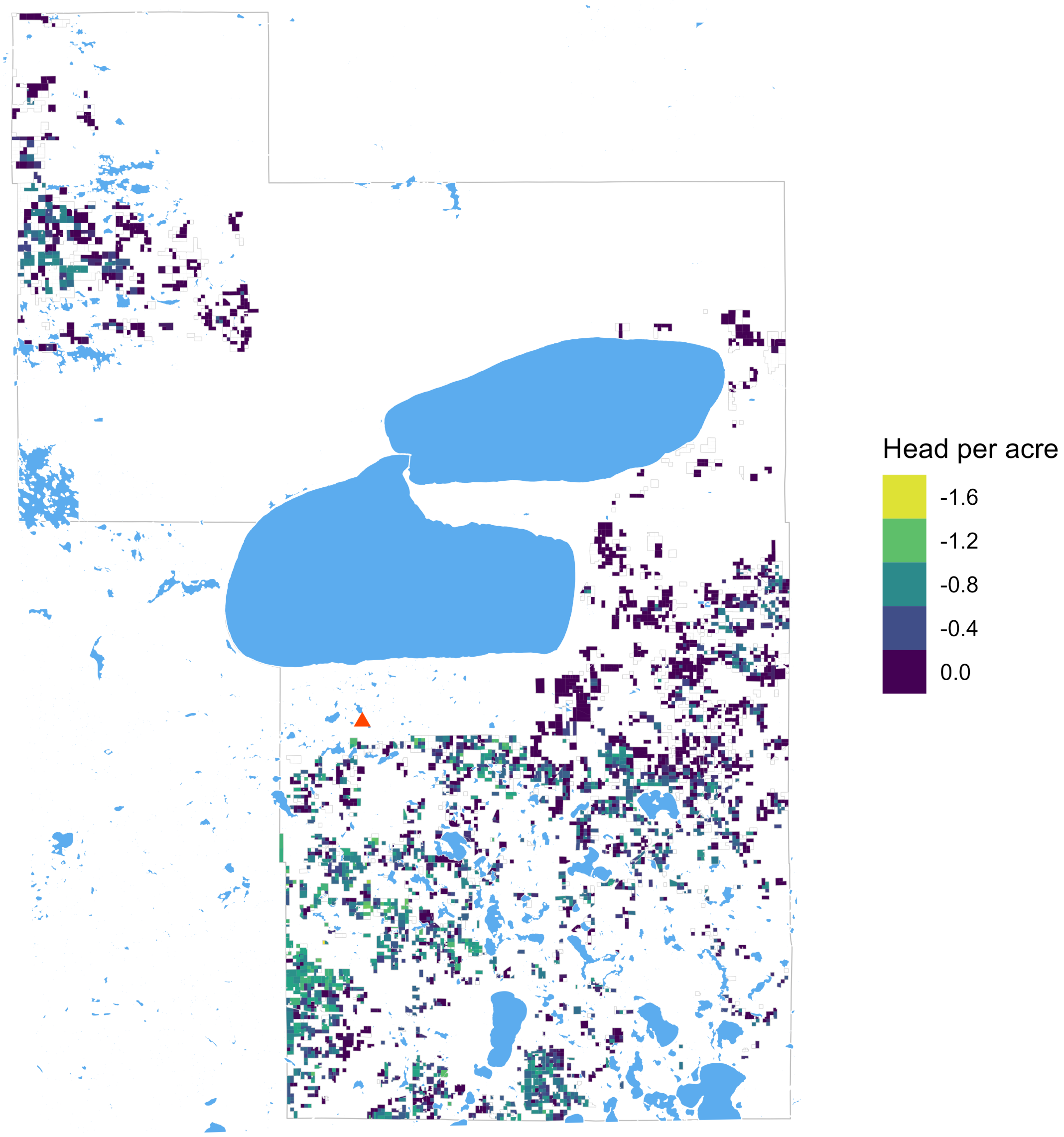


Figure 5: Percent change in stocking rate (head/acre) due to wolves.

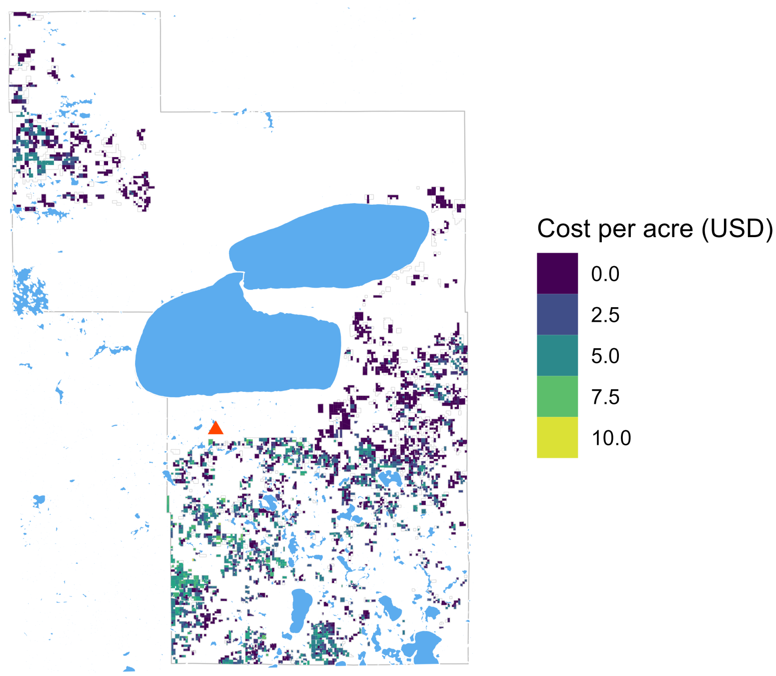


Figure 6: Cost of livestock killed per acre with no poaching or payments.

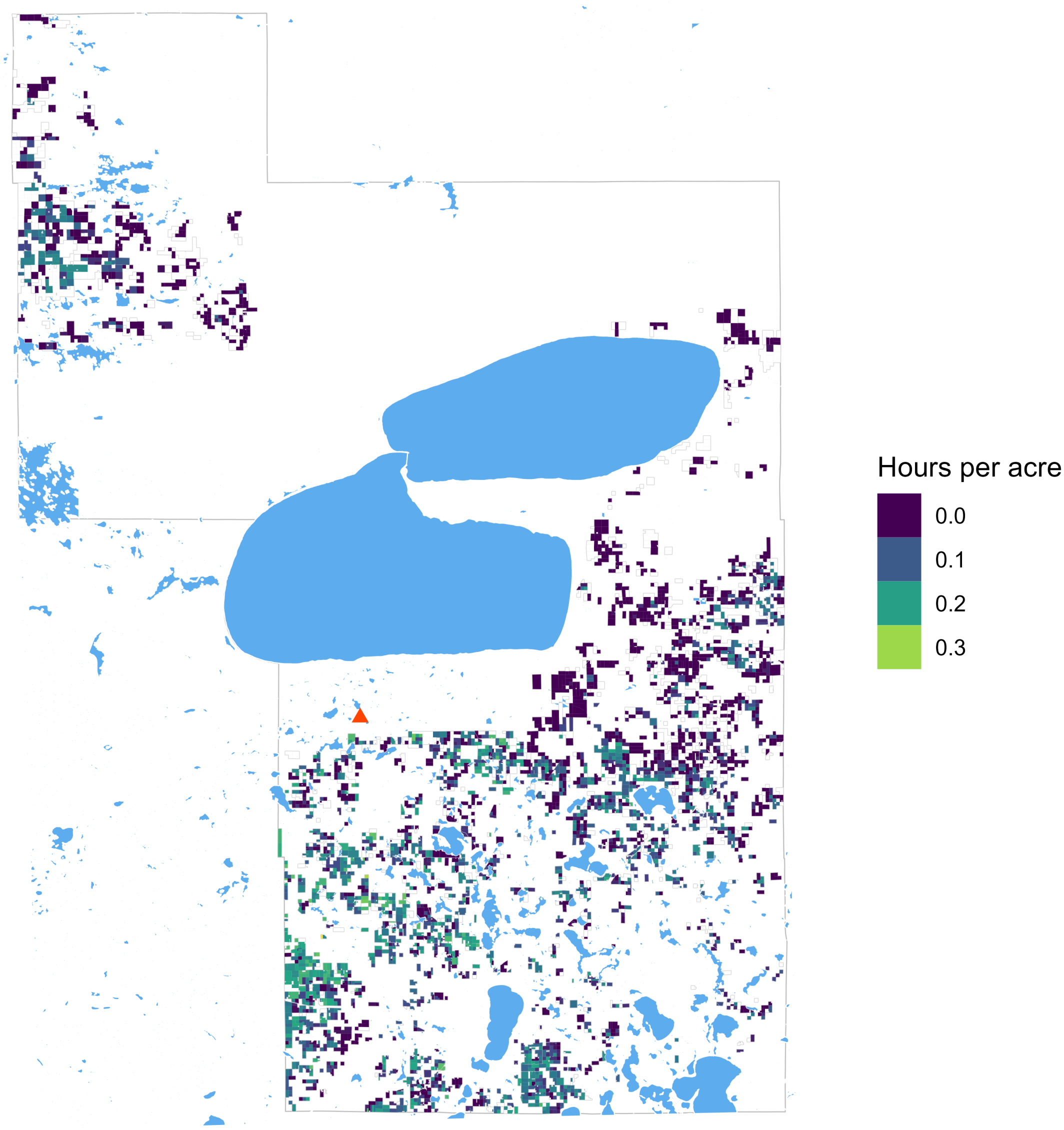


Figure 7: Poaching effort with no payments.

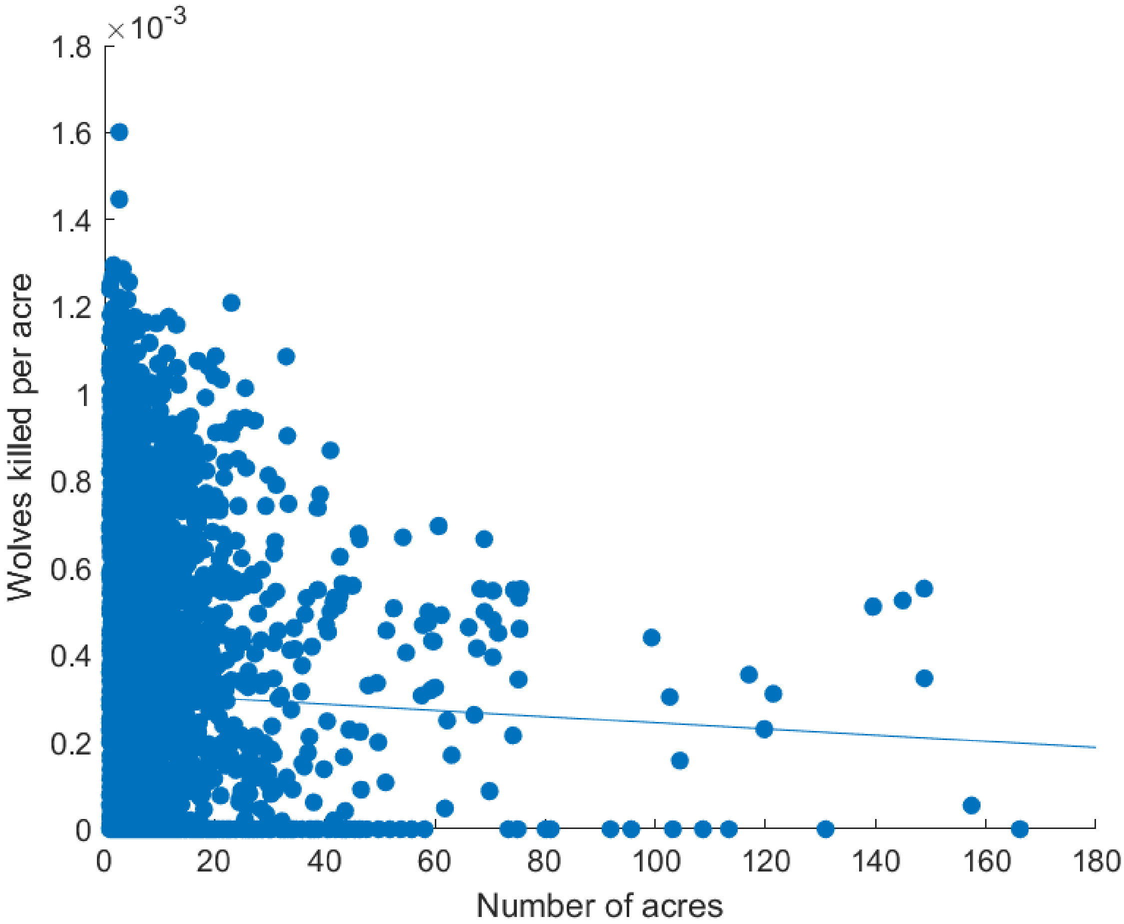
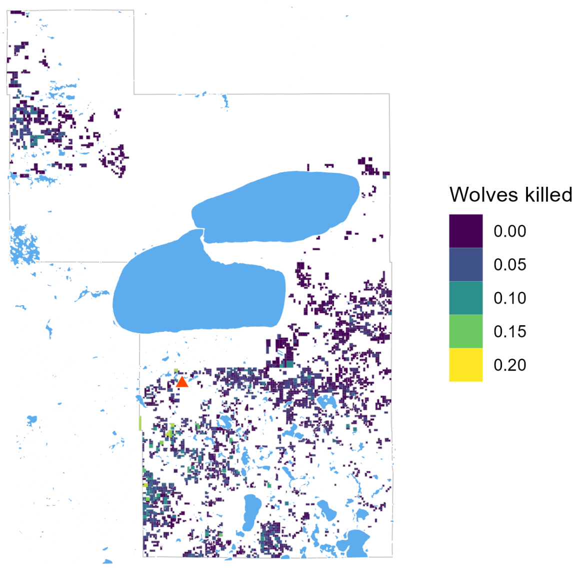
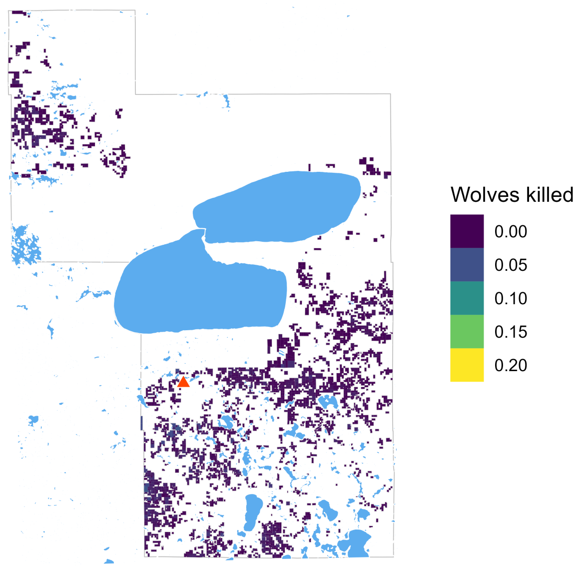


Figure 8: Total wolves killed by area under a farmer's control.



(a) No payments



(b) *Ex-post* payment: \$1,479 (75% of market price)

Figure 9: Wolves killed per farm with and without payments.

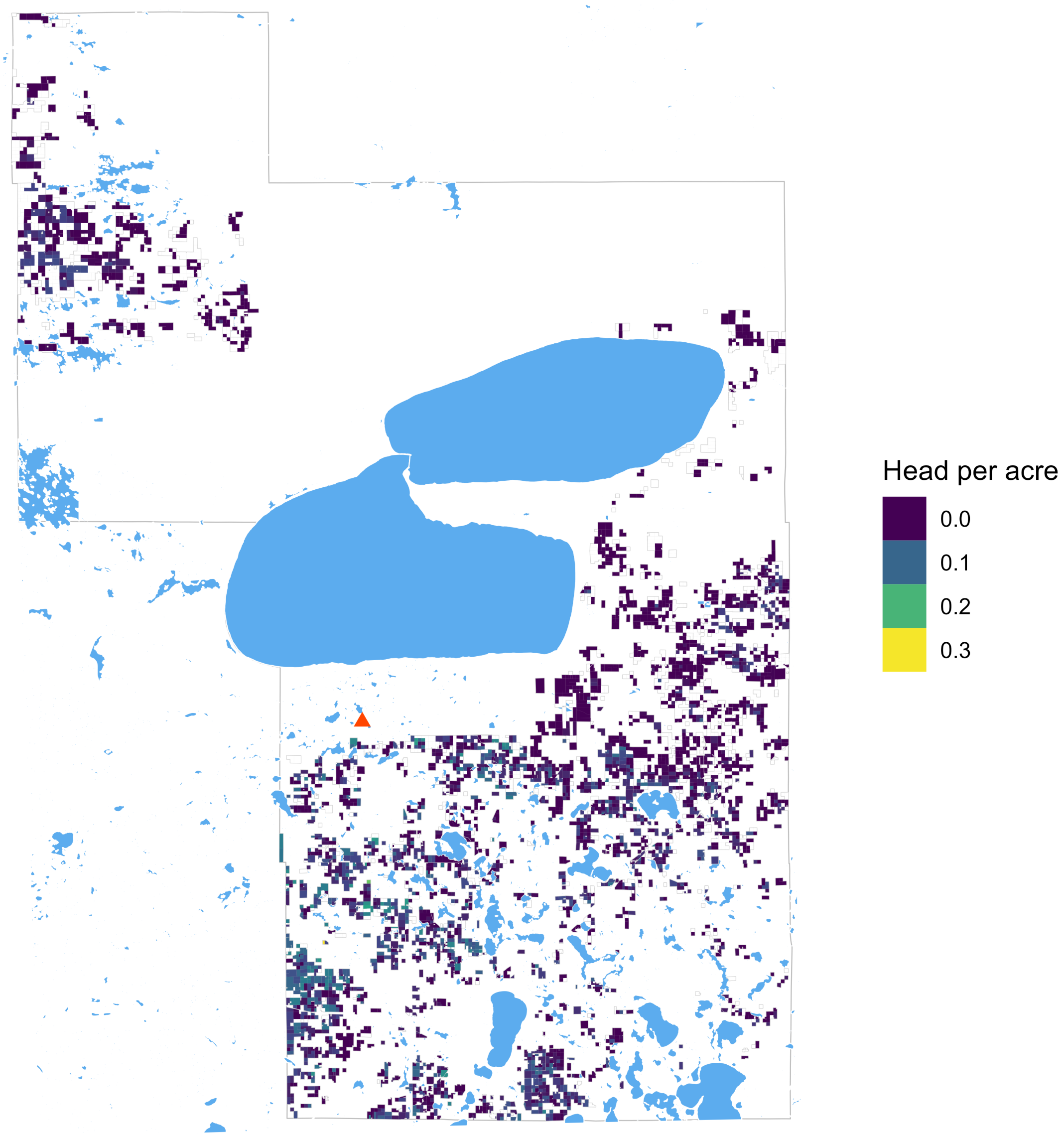


Figure 10: Percentage change in stocking rate due to inclusion of poaching (compared to the case with wolf depredation, no poaching, and no payments).

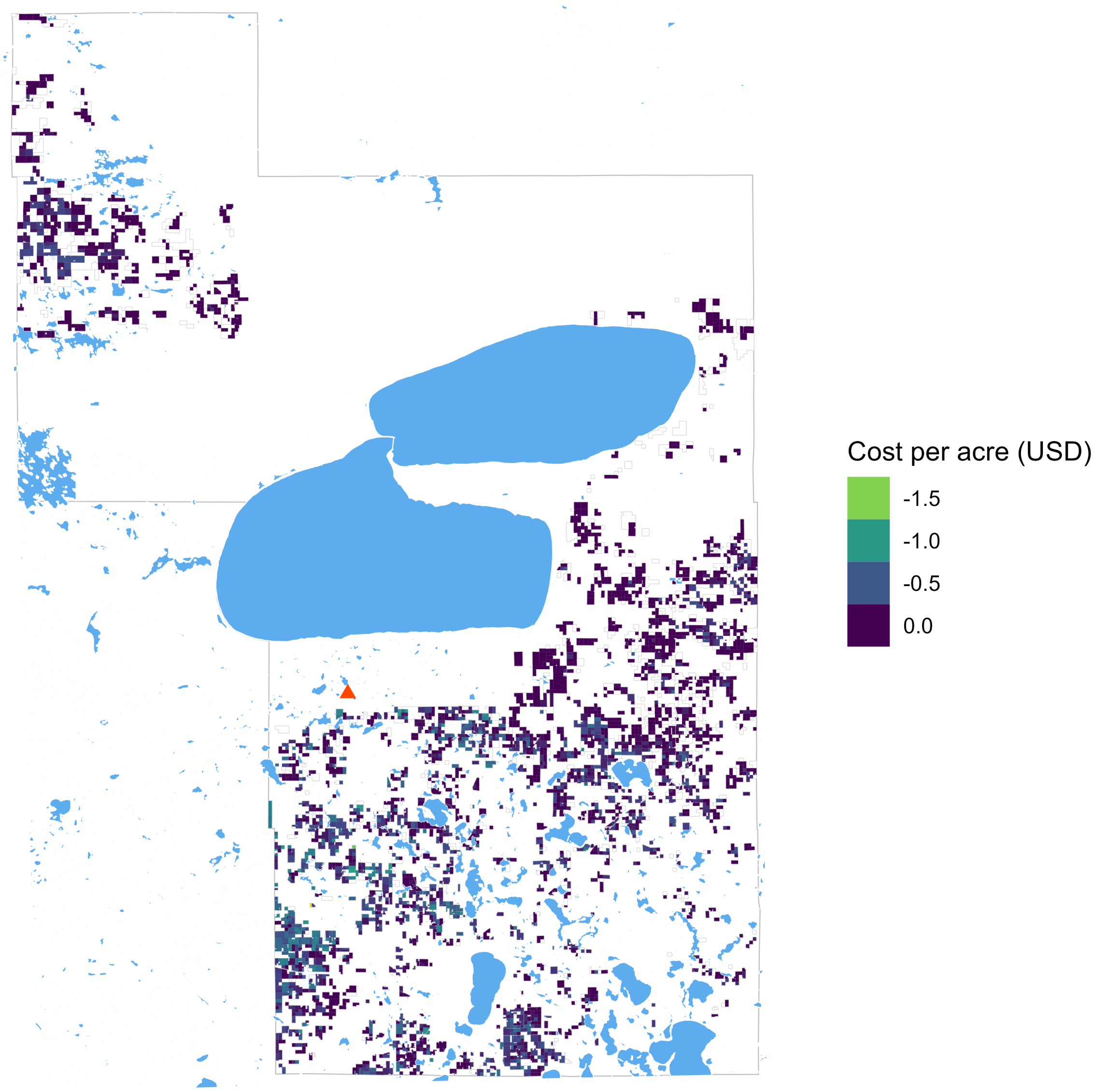


Figure 11: Change in the cost of livestock killed per acre compared to case with depredation, no poaching, and no payments.

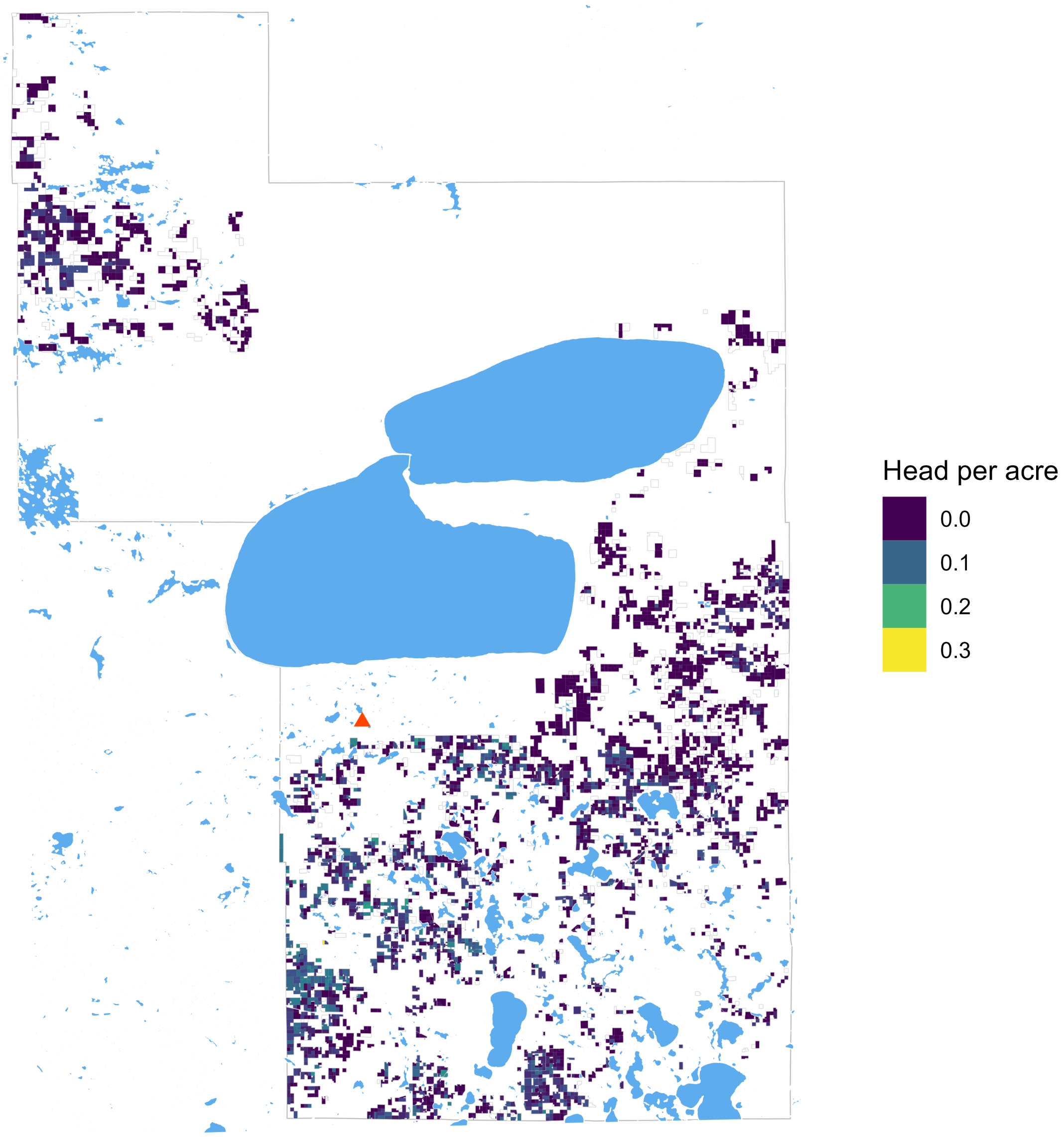


Figure 12: Percent change in stocking rate due to full compensation ($p_X = p$), compared to case with depredation and poaching but no payments.

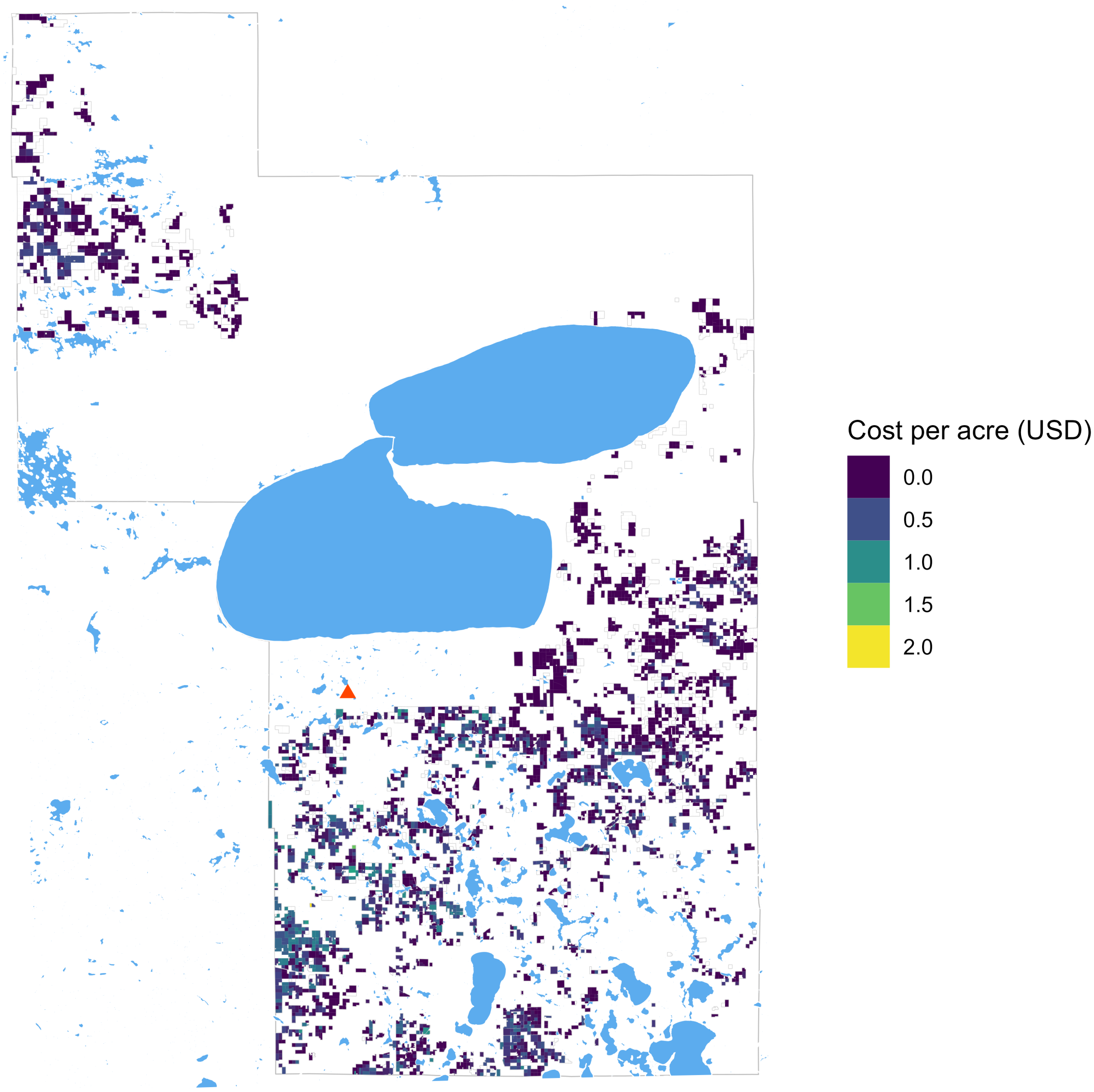


Figure 13: Change in cost of depredation per acre due to full compensation ($p_X = p$), compared to case with depredation and poaching but no payments.

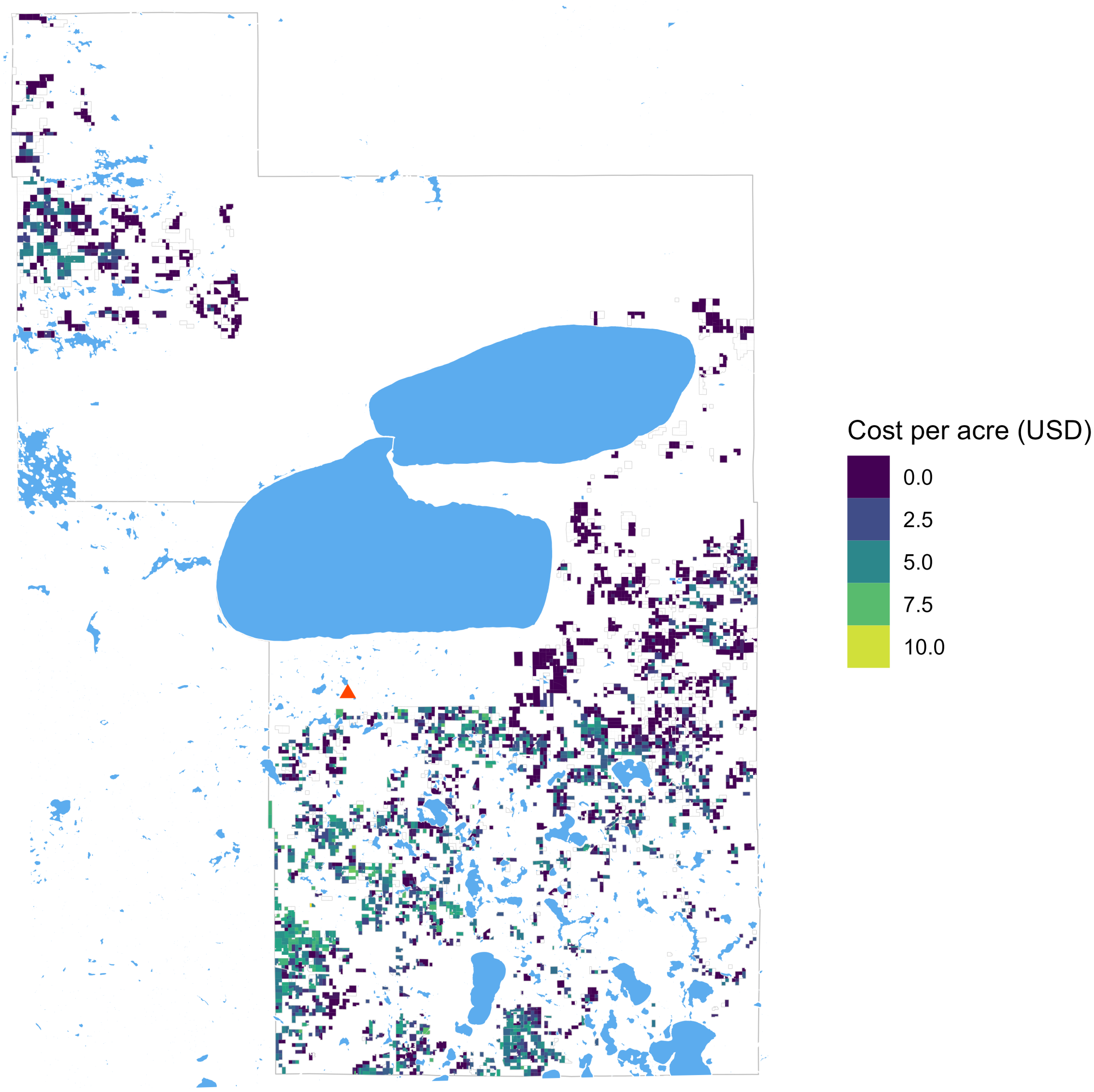


Figure 14: Cost to the WS per acre with full compensation ($p_X = p$).

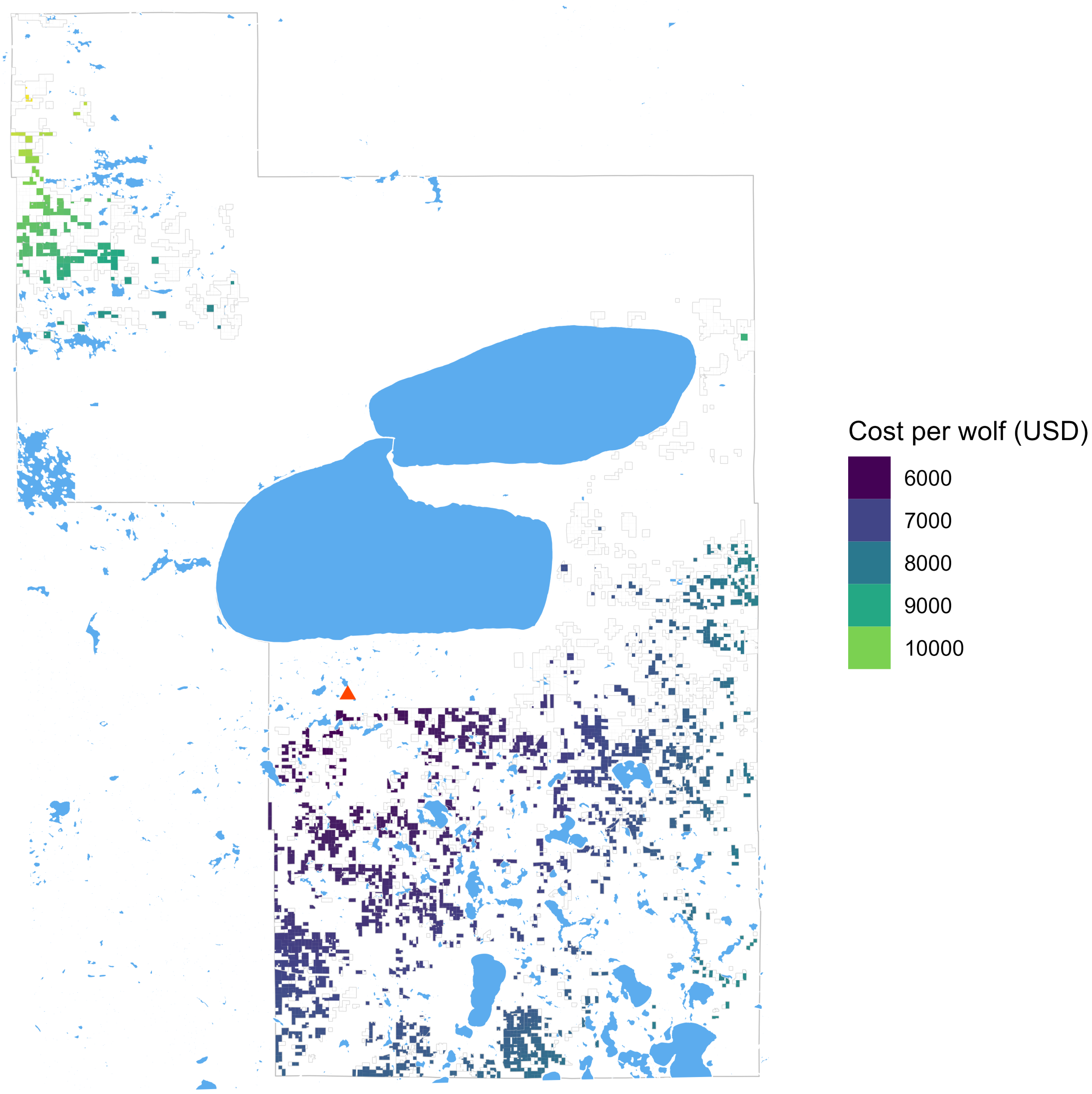


Figure 15: Cost to the WS of poaching averted (USD per wolf) with full compensation ($p_X = p$).

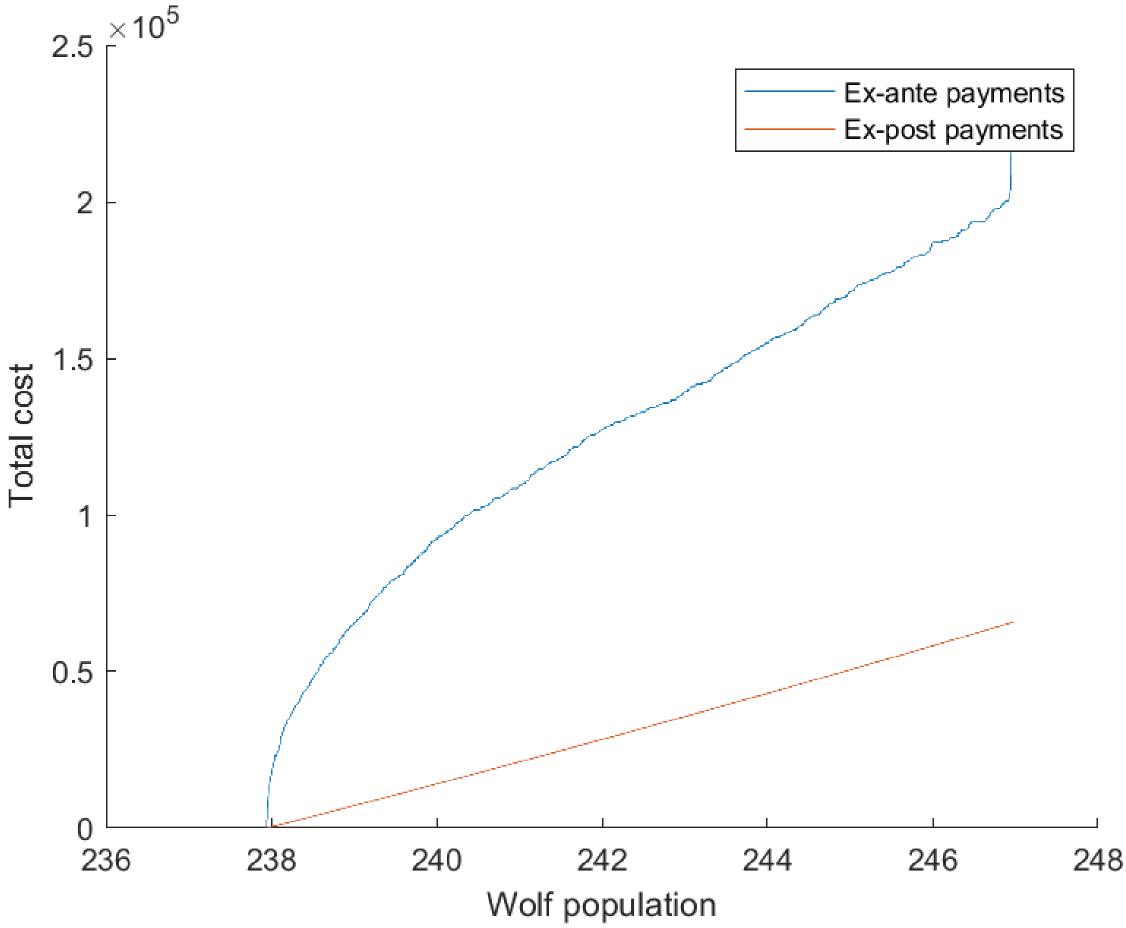


Figure 16: Given our model parameters, *ex-post* are more cost-effective in reducing poaching than *ex ante* payments

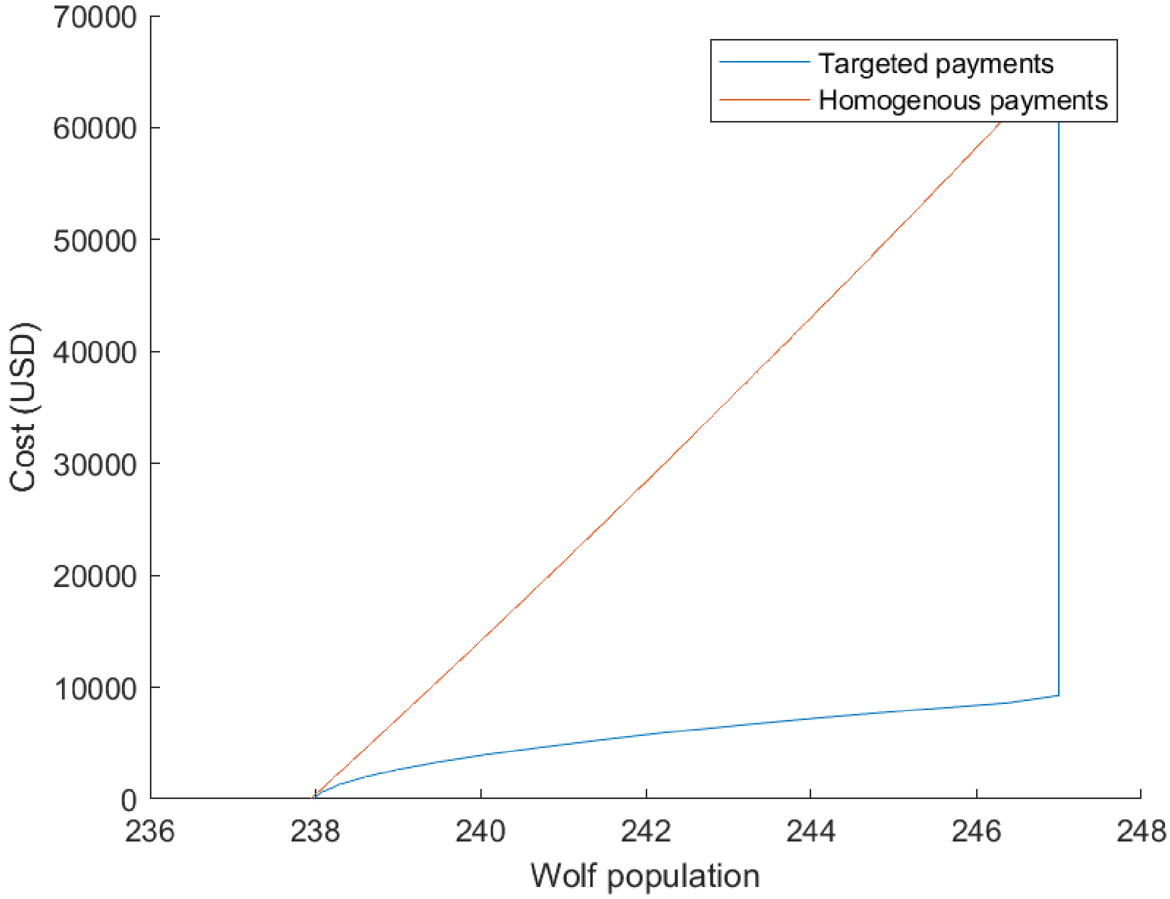


Figure 17: Cost path for targeted vs. uniform *ex-post* payments.

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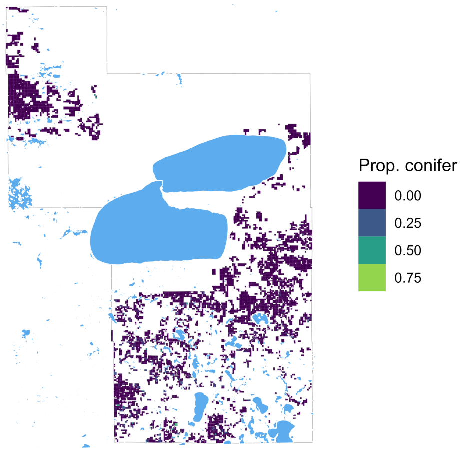
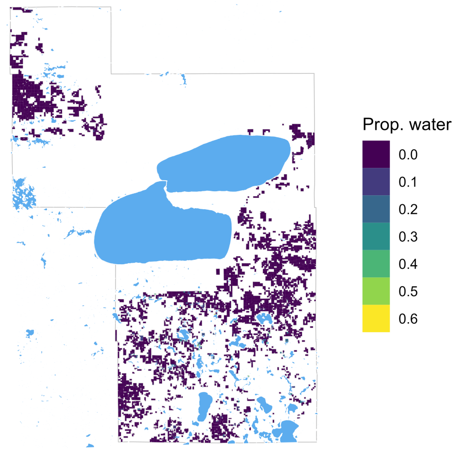
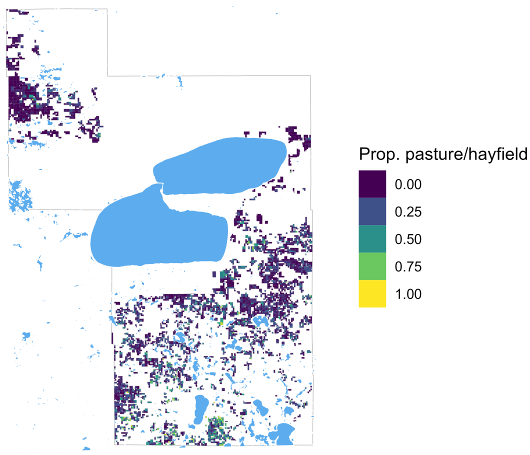
A. Additional Tables and Figures



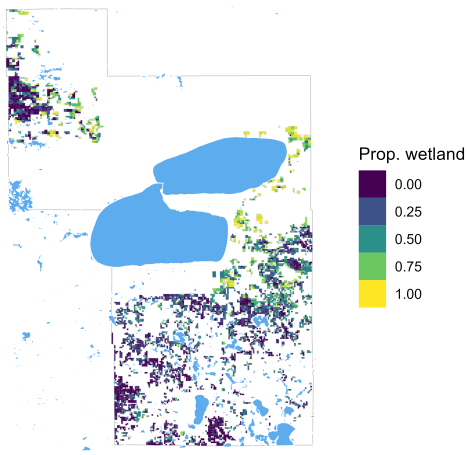
(a) Proportion of each parcel coniferous forest



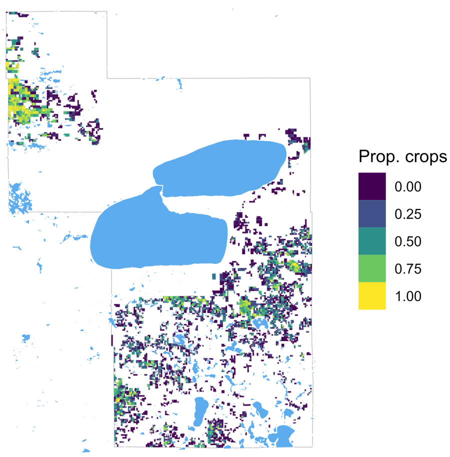
(b) Proportion of each parcel open water



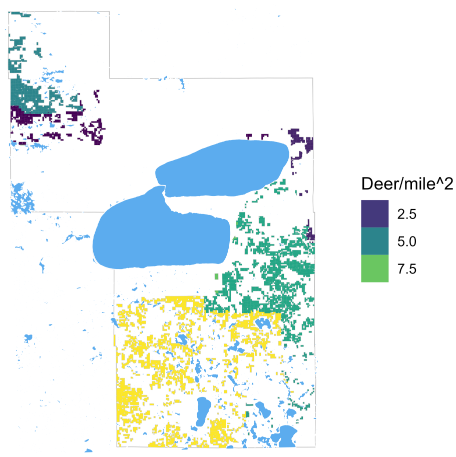
(c) Proportion of each parcel pasture/hayfield



(d) Proportion of each parcel wetland



(e) Proportion of each parcel crops



(f) Deer density areas

Figure 18: Landscape characteristics determining depredation risk

Table 2: Descriptive statistics for Beltrami county

Variable	Mean	SD
Parcel size	52.4474	38.6821
Proportion conifer	0.0144	0.0522
Proportion open water	0.0061	0.0344
Mean deer density /mi^2	7.393	2.5855
Proportion pasture/hayfield	0.1745	0.2053
Proportion wetland	0.2907	0.3059
Proportion crops	0.2455	0.2944
Road density /mi^2	0.0009	0.0018

B. Mathematical appendix

B.1 Comparative statics

The farmer profit function is given by:

$$\begin{aligned}\pi_i^{IV} =& A_i \Bigg\{ pX_i \Big[a - W_i(1-\eta Z_i)\psi_i \Big] - C_X(X_i) - C_Z(Z_i) \\ & + p_W W_i(1-\eta Z_i) + p_X X_i W_i \left(1-\eta Z_i\right)\psi_i \Bigg\}\end{aligned} \tag{17}$$

Since we are considering the general problem of a representative farmer, we supress the subscript i for the remainder of this section. With the following first order conditions:

$$\frac{\partial \pi}{\partial X} = pa - cX - (p - p_X)\big[W(1-\eta Z)\psi\big] = 0 \tag{18}$$

$$\frac{\partial \pi}{\partial Z} = (p - p_X)XW\eta\psi_i - bZ - p_W W\eta = 0 \tag{19}$$

Which can be rearranged to obtain

$$X^\star = \frac{pa - (p-p_X)W(1-\eta Z^\star)\psi}{c} \tag{20}$$

$$Z^\star = \frac{(p-p_X)X^\star W\eta\psi - p_W W\eta}{b} \tag{21}$$

Focusing first on the impact of p_W on the farmer response, we take the derivative of 20 and 21 with respect to p_W:

$$\frac{\partial X^\star}{\partial p_W} = \frac{\partial Z^\star}{\partial p_W}\frac{(p - p_X)W\eta\psi}{c} \tag{22}$$

$$\frac{\partial Z^\star}{\partial p_W} = \frac{\partial X^\star}{\partial p_W}\frac{pW\eta\psi}{b} - \frac{W\eta}{b} \tag{23}$$

We substitute 22 into 23 and rearrange in terms of $\frac{\partial Z^\star}{\partial p_W}$ to obtain

$$\frac{\partial Z^\star}{\partial p_W} = \frac{-cW\eta}{cb - p(p - p_X)(W\eta\psi)^2} \tag{24}$$

The numerator is clearly negative, and the denominator is positive for all parameter values for which $X^\star$ and $Z^\star$ are positive. Having determined that $\frac{\partial Z^\star}{\partial p_W} \leq 0$, we can easily see from 22 that $\frac{\partial X^\star}{\partial p_W} \leq 0$ if $\frac{\partial Z^\star}{\partial p_W} \leq 0$ (remembering that we assume $p_X \leq p$). Thus, we determine that both stocking rate and poaching effort are decreasing in the *ex-ante* payment, p_W.

We now turn to the effect of the *ex-post* payment level on the farmer response, following a similar process. Taking the derivatives of 20 and 21 with respect to p_X, we have

$$\frac{\partial X^\star}{\partial p_X} = \frac{W(1 - \eta Z^\star)\psi}{c} - \frac{(p - p_X)W\psi\eta}{c}\frac{\partial Z^\star}{\partial p_X} \tag{25}$$

$$\frac{\partial Z^\star}{\partial p_X} = \frac{-X^\star W\eta\psi}{b} + \frac{(p - p_X)W\psi\eta}{b}\frac{\partial X^\star}{\partial p_X} \tag{26}$$

Equation 26 can be plugged in to 25 and rearranged to obtain

$$\frac{\partial X^\star}{\partial p_X} = \frac{bW(1 - \eta Z^\star)\psi + (p - p_X)^2 W^2\psi^2\eta^2 X^\star}{cb + (p - p_X)^2 W^2\psi^2\eta^2} \tag{27}$$

which is unambiguously non-negative across the range of possible parameters and variables. Plugging 25 into 26 and rearranging, we find the following equation, from which it is clear that the sign of $\frac{\partial Z^\star}{\partial p_X}$ depends on the numerator.

$$\frac{\partial Z^\star}{\partial p_X} = \frac{(p - p_X)W^2(1 - \eta Z)\psi^2\eta - cX^\star\eta\psi}{cb + (p - p_X)^2 W^2\psi^2\eta^2} \tag{28}$$

Let us suppose that $\frac{\partial Z^\star}{\partial p_X} > 0$ so that the following holds:

$$(p - p_X)W^2(1 - \eta Z^\star)\psi^2\eta - cX^\star\eta\psi > 0 \tag{29}$$

We can substitute 20 for $X^\star$ and divide both sides of the inequality by $W\eta\psi$:

$$2(p - p_X)W(1 - \eta Z)\psi - pa > 0 \tag{30}$$