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Moral Hazard, Externalities, and Compensation for Crop Damages from Wildlife*

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A principal–multiple agent model is used to examine wildlife damage abatement and compensation programs in a setting in which farmers suffer damages and hunters use the wildlife for recreational purposes. In addition to externalities inherent in abatement, abatement/compensation policy confronts the issue of moral hazard. By representing the principal as a wildlife management authority who acts on behalf of hunters, we investigate contracts in which transfers of more or less severe hunting regulations, a public good that aids in dispersing wildlife, and monetary payments from hunting license fees can be used to overcome moral hazard.

I. INTRODUCTION

While modern husbandry has displaced much wildlife habitat, it has also improved habitat for some wildlife species. For examples including wolves and sheep, bears and trees, elk and hay, pelicans and pond-raised crawfish, and waterfowl and grain, society must balance the substantial crop damages caused by increased concentrations of wildlife with the recreational benefits of wildlife refuges. In 1988, the USDA Animal Damage Control Program (ADCP) spent over $26 million on damage control and another $11 million on administration, and 14 U.S. states and 4 Canadian provinces provided some sort of compensation for wildlife damages to agricultural crops [21].[1]

Policy makers recognize that adoption of the standard externality-compensation approach can be inefficient in the wildlife damage context because that approach

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[1] Whether damages are considered to be the responsibility of the landowner, the general public, or the consumptive users of wildlife populations is a property rights issue. Thus the decision to compensate implies a specific distribution of property rights. Damage and/or compensation programs imply that the public has some liability for damages to private lands; funding programs through hunter's fees implies hunters have liability for a share of the damages. All state wildlife agencies responding to a 1989 survey reported a preference to have licensed hunters utilize problem animals, but recognized landowners' right to restrict hunting on their land.

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fails to account for the endogeneity of farmers' choices of abatement effort to the compensation scheme. For example, a survey of state wildlife damage programs indicates that most program administrators feel that although compensation payments for crop losses due to wildlife ‘‘may soothe agricultural interests, they also eliminate incentives to maintain agricultural practices that reduce losses and reduce incentives for landowners to open their property for hunting, thus perpetuating damage caused by wildlife’’ [32].[2] The moral hazard problem arises because of uncertainty inherent in wildlife management and damage abatement techniques. Because directly monitoring on-farm abatement effort is often prohibitively expensive, uncertainty in abatement techniques generates asymmetric information between the payers and recipients of compensation. The information asymmetry precludes enforcement of contracts that directly specify levels of abatement.

In addition to moral hazard, abatement of crop losses that is based on diffusion of concentrations of wildlife may depend on the actions of large numbers of farmers whose individual decisions will typically have external effects. For example, at very low levels of abatement effort, a single farmer's abatement effort is likely to simply increase wildlife depredation on neighboring farms, with no net gain for society. On the other hand, if the successful diffusion of wildlife depends on all farmers in a community applying abatement effort, then no single farmer captures all of the benefits from her abatement effort, which implies a sub-optimal level of abatement effort will be chosen.

The present paper applies an agency approach to the issues of moral hazard and externalities inherent in crop damage abatement/compensation programs. Crop damage caused by Canada geese in the Horicon Marsh area of Wisconsin provides a specific context for the discussion, but the agency approach presented below can be adapted to the examples mentioned previously. To motivate the approach taken below, consider a market for crop damage insurance for farmers. Along with moral hazard (which a private insurance company can presumably overcome as well as a government agency), the problem confronting private insurers is that unusually high crop damages from unusually large populations of geese are likely to be correlated across space and time, which precludes pooling the risks of farmers. Insurance can be efficiently provided by pooling a group that benefits from large populations of geese with farmers. Therefore, we suppose that a state wildlife management authority acts as a principal on behalf of hunters to design an insurance contract with farmers that addresses the moral hazard issue while insuring farmers against crop losses. The governments' ability to compel behavior, manifested in license fees charged to hunters and hunting regulations, is thus critical to obtaining crop insurance. Previewing results, in the first-best insurance contract that obtains when farmers' abatement choices are observable, hunters transfer some of the benefits they receive from an unusually large population of geese to farmers by accepting regulations that they find more onerous but are more effective at dispersing geese, and use revenues from license fees as partial compensation for crop losses. Thus the first-best contract achieves optimal risk sharing between hunters and farmers as groups, as well as among farmers. Under

[2] Additionally, note that in a 1993 draft environmental impact study, the USDA compared its current ADC policy of providing abatement assistance only with (among others) a policy of ‘‘compensation only’’ and ruled out the compensation alternative due to the loss of private abatement incentives, the anticipated high level of damages, and the expense of attempting to verify and assess losses.

asymmetric information on the provision of abatement effort, contracts use statistical indicators of the farmers' group effort and individual efforts to vary compensation payments in order to provide abatement incentives.

In the large number of applications of principal–agent models agency, we are aware of only two previous applications to environmental/resource economics issues. Tietenburg and Segerson [27] consider the optimal combination of sanctions against a firm and/or its employees for law violations. Segerson [26] considers incentive schemes for controlling non-point pollution, which may be difficult to precisely ascribe to any one source due to random environmental factors or the presence of multiple potential sources. Her analysis is similar to the present paper in that if multiple agents can pollute, then free riding may be a problem.

The paper is organized as follows. Section II sets the stage for the theoretical model by describing recreational benefits, crop damage problems, and current management policy for Canada geese. Section III provides a principal–multiple-agent model which ties compensation to farmers for crop losses to observable indicators of their abatement effort. Section IV concludes by briefly applying the insights of the analysis of Section III to the compensation/abatement program associated with the Horicon Marsh and discusses generalizing the approach to other similar problems.

II. RECREATIONAL BENEFITS, CROP DAMAGES, AND ABATEMENT EFFORTS AT HORICON MARSH

Wisconsin is located within the Mississippi Flyway (MF), which encompasses the ranges of four Canada goose populations migrating from western James Bay, Canada to northern Mississippi. Halfway through their migration these geese find the 30,000 acre Horicon Marsh. The 20,000 acre Horicon National Wildlife Refuge within the marsh and high quality forage on the surrounding agricultural lands concentrate about three-quarters of MF geese. In 1990, the Mississippi Valley population (MVP), which comprises about 90% of the geese in the MF, was estimated at over 1 million geese. This corresponds to over 900 thousand geese migrating through Wisconsin, with a high proportion resting for extended periods of time at Horicon Marsh.

Annual changes in the ‘‘peak count,’’ the number of birds in one place on the single day when the concentration is highest, are shown in Fig. 1 for the Horicon area and for east-central Wisconsin. The growth in North American Canada goose populations apparent in Fig. 1 is attributed to wildlife management, sanctuary provided by publicly funded wildlife refuges along migratory waterfowl routes, and an increase in forage provided by private agricultural activity [4, 11, 22, 25, 30, 31]. Horicon Marsh is located in the heart of a dairy and feed grain producing region where geese annually consume and trample hundreds of thousands of dollars of agricultural produce. Without the forage provided by private agricultural activity, the geese would be less likely to concentrate at Horicon Marsh and less likely to, as has been documented, stay in the region for lengthening periods of time during the fall migration. There are no other food sources other than private farm lands around Horicon Marsh that could support the number of geese that stay there.

Although no attempt has been made to place a value on the recreational benefits of Canada geese in the MF, evidence indicates these benefits may be

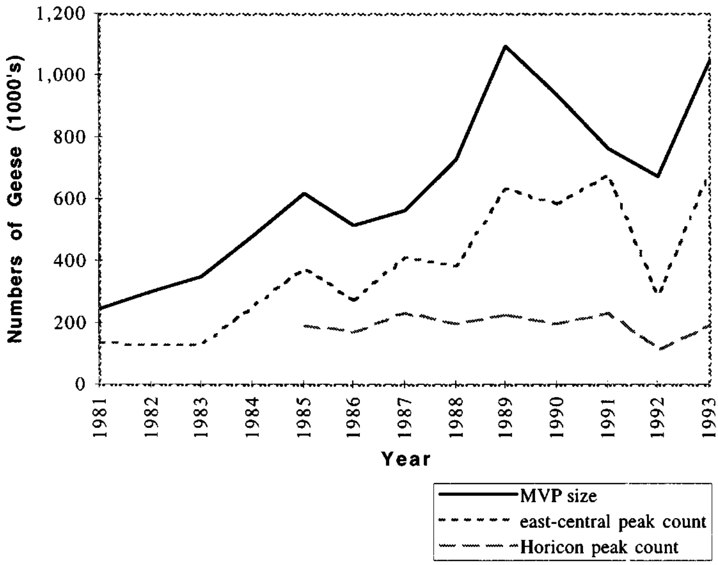

FIG. 1. Canada goose numbers.

significant [2, 17, 18, 28, 31]. Bishop and Heberlein [2] estimated that hunters were willing to pay $21 in 1978 for a permit to shoot one goose in the Horicon Zone (HZ) (24,600 acres surrounding the marsh) during the first two weeks of October in that year. Each year, more hunters apply for than receive the limited number of goose hunting permits allowed by Wisconsin's goose harvest quota. Figure 2 shows the number of geese allotted to the Horicon area and all Wisconsin hunters and indicates Wisconsin's Canada goose hunting quotas have more than doubled

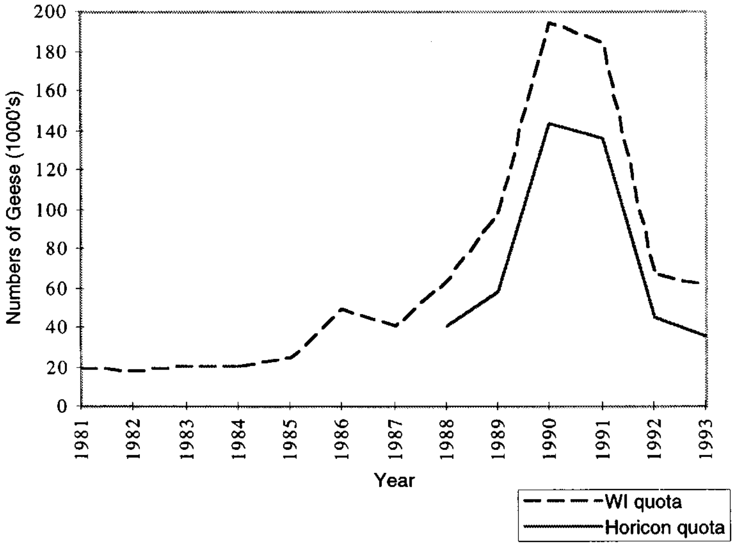

FIG. 2. Canada goose harvest quotas.

between 1979 and 1993. Wisconsin goose hunters annually harvest about a quarter of the total allowable harvest of the MVP Canada geese, and harvested 35,800, 51,280, 88,200, 100,400, 32,156, and 37,800 geese in the years from 1988 to 1993 from the Horicon area alone [1].[3]

Canada geese roost on Horicon Marsh overnight, by day making short flights to forage for feed. The geese eat crops including seeding alfalfa, winter wheat, and standing corn, trampling almost as much as they consume [3, 4, 15]. In 1985, when half as many geese used the Marsh as do today, Heinrich and Craven identified over 5,000 Horicon area farms as being potentially affected by goose damage. Farmers have reported aggregate crop losses of between $990,000 and $1,500,000, with damages varying in severity among farms from thousands of dollars per year to almost insignificant levels [3, 5, 15, 17, 28]. For comparison, fees paid by hunters to access private lands in the HZ during 1993 totaled $190,000 [1]. Private and public damage abatement costs estimated for 1988 totaled $430,000. Over 77% of reported losses up to that time occurred within a 10 mile radius of Horicon Marsh, with most of the rest within 25 miles [15].

The policy of wildlife authorities responsible for Canada geese management—the U.S. Fish and Wildlife Service (USFWS) and the Mississippi Flyway Council (MFC), an international migratory bird council—is to manage the overall goose population in order to increase wildlife-related benefits throughout the flyway [31]. Neither the USFWS nor the MFC are legally obligated to accept a role in mitigating the costs of geese to Horicon area farmers [30]. Allowable goose harvest quotas are fixed by the USFWS to distribute hunting opportunities throughout the migratory range and to allow escapement and reproduction rates which will continue to increase the goose population. However, Wisconsin's high goose harvest quota helps to relieve the farmer's share of the costs of feeding geese in two ways. First, some farmers charge hunters access fees. But the market for fee hunting is minimal due to the quantity and quality of available public hunting land.[4] Second, concentrated hunting activity disperses the geese from the Horicon

[3] The variability in harvests reflects harsh weather during the 1992 season that killed a large proportion of that year's goslings. Harvest rates were adjusted to keep the MVP at a goal of 1 million. It is interesting to note the rapid recovery of the MVP in the following year.

[4] Horicon area farmers received significant income by leasing out goose hunting rights to their farms until the mid-1960's, when the market for season-long leases was destroyed by a change in hunting regulations. The new regulations required that (1) all geese shot in Wisconsin be tagged, (2) only hunters who receive permits drawn in an annual lottery receive these tags, and (3) each permittee receive a limited number of tags per season (typically 1 to 3). These rules were imposed to more effectively monitor the goose harvest and to more equitably spread goose hunting benefits over more hunters in Wisconsin and the flyway. Prior to their implementation, Wisconsin's annual goose quotas were reached in as few as 2 to 5 days, and the hunt on lands surrounding the Horicon National Wildlife Refuge came to be described as a slaughter. While the new regulations effectively spread the hunt over more hunters, the market for private leases virtually vanished once hunters were faced with the uncertainty of getting a permit in a given year, a yearly tag limit, and an ample supply of public hunting grounds on and near Horicon Marsh. Horicon area farmers are still able to rent out blinds on a daily basis. However, low rental rates, time and burdens associated with rentals, and lack of weekday demand leave Horicon area farmers with limited benefits from geese. Thus, institutional changes in hunting regulations intended to increase benefits to hunters also increased the net costs of geese to area farms. In 1993, 63% of HZ hunters paid an average access fee of $7 per day for three days to use private lands, and a total of $190,000 in access fees was collected by private landowners in the HZ [1].

area and the private fields, thus providing a form of damage abatement.[5,6] However, hunting activity alone does not keep private losses to tolerable levels, and additional solutions to the crop damage problems are left to landowners, Wisconsin's state legislature and Department of Natural Resources (DNR) and the USDA's ADC program.

The Wisconsin Wildlife Damage Program (WWDP) was implemented by the Wisconsin DNR to provide public assistance with private abatement effort and to partially compensate landowners who have exerted abatement effort but nevertheless suffered losses from foraging geese. Farmers are required to apply a pre-specified level of abatement effort during each season in order to be eligible for compensation. Difficulties arise in determining what the optimal level of on-farm abatement should be, how to monitor whether farmers actually apply the optimal level of effort, and how *ex ante*, to deal with uncertainty over the environmental conditions that occasionally converge to cause especially severe losses from goose foraging activity on private lands. A principal–agent model can closely represent the economic details relevant to these problems, but before turning to the model in Section III, consider two aspects of WWDP's approach: abatement effort, and compensation for crop losses.

1. *Crop Damage Abatement*

The WWDP relies on two forms of abatement to reduce the severity of crop losses due to foraging activities of Canada geese at Horicon: public goose dispersal effort, accomplished through regulated hunting pressure, and private on-farm abatement effort.

a. *Public abatement*: *Regulated hunting pressure*. The DNR has defined two goose hunting zones in Wisconsin.[7] The Horicon Zone includes the area surrounding Horicon Marsh. The rest of the state is defined to be the Exterior Zone (EZ), which is more than ten times as large as the HZ. It is common for less than half as many geese to be harvested in the EZ as are harvested in the HZ. The DNR attempts to allocate the state's allowable harvest quota so that the gradient of hunting pressure is in the direction of the Horicon Marsh. To avoid hunting pressure in the HZ, the geese move either to open water roosts further south along the migratory route, or one of the many smaller refuges scattered throughout the EZ. Some of the geese continue to cause damage elsewhere, but at more tolerable levels.

[5] The primary objective of hunting regulations is to maintain healthy wildlife populations and to ensure a well-managed hunt. However, because hunting pressure is a most effective form of damage abatement, Wisconsin's hunting regulations have been modified as described below to take better advantage of hunting as a form of damage abatement.

[6] In the 1980's, amid demands from hunters and wildlife management units wishing larger hunting quotas in areas of the flyway outside Wisconsin to increase the population faster, the distribution of the total annual goose harvest among flyway states and provinces became a contentious issue in flyway management. The issue grew so factious that Congress called for a General Accounting Office investigation of MVP Canada geese management disputes [31]. Discussions between flyway states lead to an offer to allocate Wisconsin an emergency quota of 80,000 additional tags in 1990 to be used only in the Horicon Zone where damage was occurring.

[7] There are actually a small number of smaller zones we will ignore for the purposes of this paper.

The total allowable goose harvest quota is allocated to individual hunters through tags won in annual drawings. The DNR regulates the number of tags issued by geographic zone and time slots within each zone [1].[8] For example, a hunter who wins a permit for the HZ may receive 3 tags, but must use each tag in a different two-week time segment or on specified weekdays.[9] Goose tags are free to hunters who have paid for waterfowl hunting licenses.

Costs of public abatement effort include direct administrative costs and opportunity costs to Wisconsin goose hunters. The proportion of the quota allocated to the HZ reflects a trade-off between the costs of public abatement effort with costs of the WWDP. In practice, as the MVP has grown, the proportion of Wisconsin's allowable harvest allocated to HZ hunters has increased [1].

Figure 1 illustrates the effect of hunting pressure. The Horicon peak count began to be recorded when the HZ was established. From then on, while the number of geese in Wisconsin increased, the numbers in the HZ remained more or less constant.

b. Private on-farm abatement effort. The most effective on-farm abatement is for private landowners to encourage hunting on susceptible fields during weekday daytime hours when there is less overall hunting pressure near Horicon.[10] Other tactics include using fluorescent flags and exploding propane cannons, patrolling fields with people, dogs, or trucks, harvesting crops a bit early, planting faster maturing varieties, and leaving crops along the perimeter of fields for geese. All on-farm abatement methods involve significant direct and opportunity costs.

No combination of on-farm methods is 100% effective. As with hunting pressure, the effectiveness of on-farm abatement effort is uncertain, depending on types of tactics, effort levels applied, numbers of geese, distance from Horicon Marsh, and random environmental factors. All else being equal, the probability of successful on-farm damage abatement increases with the level of effort expended per affected unit area [11].

2. *Crop Damage Compensation Programs*

The DNR administers the WWDP for damage caused by bear, deer, and geese to agricultural crops. Administration and compensation is funded with about $2 million annually by hunters from a $1 surcharge on all sport-hunting licenses sold in the state, a $12 charge on resident deer licenses, $20 on non-resident deer licenses, and, under extreme circumstances, by general state revenues. The USDA ADCP provides $528,000 annually for Canada goose abatement support in the

[8] The DNR has not seriously considered one measure suggested by wildlife ecologists as being most effective for controlling crop damage—restricting all Wisconsin goose hunting to HZ to force the fastest rate of goose dispersal—because hunters would then pay too high a price in terms of crowding at Horicon and the loss of alternative hunting areas.

[9] During the last several seasons the DNR has received annual emergency quotas of 4,500 tags to distribute directly to Horicon area farmers who, after using all on-farm damage abatement procedures as recommended by the DNR, have sustained $1,000 worth of damage before the season's close. Farmers may not sell or use the tags themselves, but must distribute them, two at a time, to hunters with valid permits.

[10] Ironically, the activity of the least efficient hunters (''sky-busters'') is reported to be the most effective of all. However, some farmers have suggested that hunters can be more of a nuisance than geese.

Horicon area. Participating farmers receive abatement assistance, and when possible, partial compensation for damages not prevented by recommended abatement practices. The current program relieves costs of damage by helping landowners purchase abatement equipment, providing technical assistance, assessing crop losses, and processing damage claims. Funds remaining after meeting administrative and abatement costs are divided among all eligible damage claimants (including for bear and deer damage) in proportion to their approved claims. Farmers are required to provide a specified level of abatement effort to be eligible for compensation. Farmers must enroll before the season starts and formally agree, by signed legal affidavit, to provide the recommended types and levels of abatement effort [6]. Specific steps for reporting damages, filing for damages, and assessing claims are as follows. Within 72 hours after each damage occurrence, the farmer must notify WWDP technicians; failure to do so makes the farmer ineligible to file a claim. A technician may recommend further specialized abatement activities and may provide labor for abatement effort. The technician performs a damage assessment using a standard formula to estimate expected crop yields before and after damages (random samples are taken on a grid over the field). A separate assessment is made for each occurrence.

III. MODELS OF ABATEMENT AND COMPENSATION

1. *Notation and Assumptions for Damages*

Assume $I \geq 2$ identical farming firms till the Horicon area.[11] This section presents a model of the amount of farmer i's potential crop quantity y^i that remains to be harvested at the end of the season.[12] For each farmer, realized harvest depends on total crop damage in the Horicon Zone and how total crop damage is distributed across farms within the HZ.

Total crop damage in the HZ is a function of the density of geese in the HZ. Define g as a seasonal, scalar index of goose density in the HZ; the index g comprises the estimated number of geese at Horicon, their arrival date, and their length of stay. Wildlife management policies and stochastic environmental influences on the population partially determine goose density in the Horicon area. Denote the target for the MVP of geese G and the allowable Wisconsin goose harvest (i.e., the number of tags distributed) T; these are set by flyway-wide management authorities. Public abatement effort through a state wildlife authority's management of hunting is reflected in q, a scalar index defined such that increasing q corresponds to more aggressive dispersal of geese from the HZ. Stochastic environmental factors that affect the total number of geese and the number of geese that roost in the HZ (e.g., temperature and rainfall) are denoted

[11] As noted earlier, geese concentrate at the marsh and farmers nearer the marsh are more susceptible to crop losses. Assuming farmers are homogeneous abstracts from spatial considerations for the sake of mathematical tractability.

[12] Unless noted otherwise below, the notational conventions followed are that superscripts label variables or functions with respect to farmers or random variables, while subscripts are reserved to denote partial derivatives of functions. Additionally, in this section, we refer to a ''state wildlife management authority'' rather than the Wisconsin DNR so as to not confuse actual practice with theoretical optima.

θ, which follows the probability distribution $F^{\theta}(\theta)$, assumed to be twice continuously differentiable.

The density of geese in the HZ is also responsive to the abatement efforts of farmers. Because geese return to the same roost at nightfall unless driven from a territory, the distribution of abatement efforts across farmers in the HZ is no less important than the aggregate level of effort. Thus, goose density in the HZ is a function of the mean abatement effort $\bar{a}$ among farmers, and s, the variance of abatement effort across farmers. Summarizing, we write

$$g = g(q, \bar{a}, s, T, G, \theta) \tag{1}$$

as the density of geese in the Horicon Zone. As indicated in the discussion, partial derivatives of the function g satisfy $g_q < 0$, $g_{qq} > 0$, $g_{\bar{a}} < 0$, $g_{\overline{aa}} > 0$, $g_s > 0$, $g_{\bar{a}s} < 0$, $g_G > 0$, and $g_T < 0$.

Total crop damage in the HZ is given by the function $d[g(q, \bar{a}, s, T, G, \theta)]$, where $d[\cdot]$ is assumed to be linear and increasing in g.[13]

For a given amount of crop damage in the Horicon Zone, the distribution of damage across farms is determined by the I-vector $\mathbf{a} = (a^1, a^2, \ldots, a^I)$, where a^i is an index of abatement effort that increases in farmer i's private efforts at dispersing geese through the use of fluorescent lights, propane cannons, patrols, and so forth, and an I-vector of random variables that influence the effectiveness of each farmer's abatement effort, $\boldsymbol{\varepsilon} = (\varepsilon^1, \varepsilon^2, \ldots, \varepsilon^I)$. Denote the joint probability distribution of $\boldsymbol{\varepsilon}$ by $F^{\varepsilon}(\varepsilon)$; we assume ε^i is independent of ε^j, for all $i \neq j$, $\boldsymbol{\varepsilon}$ is independent of θ, and $F^{\varepsilon}(\varepsilon)$ is twice continuously differentiable. Further, let the cost of abatement effort a^i to each farmer i be $c(a^i)$, and assume that the marginal cost of private abatement effort is positive ($c_{\mathbf{a}} > 0$) and increasing ($c_{\mathbf{aa}} > 0$).

From the preceding discussion, the quantity of crop damages suffered by farmer i is given by

$$m^i(\mathbf{a}, \varepsilon) d[g(q, \bar{a}, s, T, G, \theta)]. \tag{2}$$

Note carefully the interpretation of m^i; it gives the proportion of whatever goose crop damage takes place in the HZ that is visited on farmer i. Thus farmer i is able to harvest $y^i - m^i(\mathbf{a}, \mathbf{e}) d[g(q, \bar{a}, s, T, G, \theta)]$. We assume that partial derivatives of the function m^i satisfy $m^i_{a^i} < 0$, $m^i_{a^i a^i} < 0$, $m^i_{a^i, a^j} < 0$, and $m^i_{a^j} > 0$. In the sequel, we suppress, G and T as they are exogenous to the decisions made by actors in the model.

The sign of the total derivative of the product of functions in (2) with respect to a^i is somewhat subtle. The model of crop damages includes positive and negative externalities among farmers. To make the externalities explicit, observe that by definition, aggregate crop losses are the sum of crop losses across farmers in the HZ,

$$d[g(q, \bar{a}, s, \theta)] \equiv \sum_{j=1}^{I} m^j(\mathbf{a}, \varepsilon) d[g(q, \bar{a}, s, \theta)]. \tag{3}$$

[13] If damages are concave in g, then the policy that yields the least damages is to concentrate geese as much as possible, rather than disperse them. We thank Bill Even for calling this to our attention.

Differentiating the identity (3) with respect to a^i yields

$$d'[\cdot][g_{\bar{a}}(\cdot)\bar{a}_{a^i} + g_s(\cdot)s_{a^i}] = \sum_{j=1}^{I} m^j_{a^i}(\cdot)d[g(\cdot)] + m^j(\cdot)d'[\cdot][g_{\bar{a}}(\cdot)\bar{a}_{a^i} + g_s(\cdot)s_{a^i}]. \quad (4)$$

Because the sum across m^j is 1, the second term on the RHS of Eq. (4) is equal to the LHS. Therefore, the first term on the RHS of (4) sums to zero and represents the marginal effect of farmer i's effort in shifting geese among farms within the HZ; that is, it is the "own effect" of farmer i's abatement effort on her share of damages plus a negative externality. The second term on the RHS represents farmer i's marginal contribution to increased yields for all farmers by displacing geese from the HZ, a positive externality.

Below, we permit a state wildlife management authority to determine hunting regulations q after observing θ. Therefore, assume that the goose density function $g(\cdot)$ is separable in q, define the random variable $\tilde{g}$ with probability density function conditional on the dispersal of geese achieved through the mean of farmers' abatement efforts and the variance of abatement efforts across farmers as $\phi^{\tilde{g}}(\tilde{g} \mid \bar{a}, s)$, and write total damages as $d[g(q, \tilde{g})]$. Further, define the probability density function of m^i conditional on farmers' abatement effort as $\phi^{m^i}(m^i \mid \mathbf{a})$ for all $i = 1, \dots, I$. The probability density functions $\phi^{\tilde{g}}(\tilde{g} \mid \bar{a}, s)$ and $\phi^{m^i}(m^i \mid \mathbf{a})$ are derived from the distribution functions $F^{\varepsilon}(\varepsilon)$ and $F^{\theta}(\theta)$, and inherit independence (conditional on $\mathbf{a}$) from the independence of $\boldsymbol{\varepsilon}$ and θ; the joint probability density function of $(m^i, \tilde{g})$ conditional on $\mathbf{a}$ is $\phi^{m^i}(m^i \mid \mathbf{a})\phi^{\tilde{g}}(\tilde{g} \mid \bar{a}, s)$, for all $i = 1, \dots, I$. Further, we suppose that the distribution functions for each of these densities satisfies the monotone likelihood ratio property and the convexity of the distribution function property. Jewitt [16] shows that along with a condition on the agents' (i.e., farmers') utility functions provided below, these assumptions guarantee that the necessary conditions provided below for the solution to the principal−agent problem are sufficient conditions. Additionally assume that for all $\mathbf{a}$, the support of $\phi^{m^i}(m^i \mid \mathbf{a})$ is $[\underline{m}, \overline{m}]$, and the support for $\phi^g(g \mid \bar{a}, s)$ is $[\underline{g}, \bar{g}]$.[17]

2. *Agency Approaches to Crop Damage Abatement and Compensation*

a. Hunters' benefits and farmers' profits. The state wildlife management authority's goal is to choose a compensation/abatement contract with farmers that maximizes the aggregate welfare of hunters subject to an expected utility constraint for each farmer, which we take to be determined exogenously by political authorities. In the compensation/abatement contract, the management authority promises that after observing $\tilde{g}$, it will "transfer" all farmers $q = t(\tilde{g})$ in the form of hunting regulations that disperse geese more or less effectively and are more or less onerous to hunters. It also promises a payment per unit of lost harvest of $p(\tilde{g}, m^i)$ to each farmer $i = 1, \dots, I$, as a function of the proportion of total damages she suffered at the end of the season. We assume hunters are identical and adopt a

[14] Note that the monotone likelihood ratio property implies a higher observed yield for farmer i permits inference that farmer i supplied greater effort, while the invariance of the support of each distribution rules out the enforcement of contracts by setting high penalties for outcomes that can only be observed at effort levels that violate the contract.

representative agent approach in the objective function of the state wildlife management authority's optimization problem.

To develop a hunter's welfare, assume recreational benefits from geese using the Horicon Marsh accrue to each hunter according to the benefit function $\beta[g, q]$. Recreational benefits increase at a decreasing rate with the intensity of geese use at Horicon Marsh, (i.e., $\beta_g > 0$, and $\beta_{gg} < 0$), and decrease at an increasing rate with the stringency of hunting regulations (i.e., $\beta_q < 0$, and $\beta_{qq} < 0$). Given that the compensation/abatement contract promises a transfer of $t(\tilde{g})$, and supposing each hunter pays a license fee l, we write a hunter's utility as

$$u\{\beta[g(t(\tilde{g}), \tilde{g}), t(\tilde{g})] - l\} \tag{5}$$

with the utility function $u\{\cdot\}$ twice continuously differentiable, increasing, and concave to represent risk aversion (i.e., $u'[\cdot] > 0$ and $u''[\cdot] \leq 0$). The first term in the utility function incorporates the effect of the transfer $q = t(\tilde{g})$ on a hunter's utility; from (1), after the farmers commit to $\mathbf{a}$ and the management authority observes θ, the hunting regulations determine the index of goose intensity g in the HZ by their dispersal effect. The transfer also affects a hunter's utility by forcing higher opportunity costs on hunters as q increases. Total license fees finance compensation to farmers for crop losses and are therefore constrained to be greater than or equal to total expected compensation payments; we develop the budget constraint below.

Letting r be the price of output less the average of all but abatement costs, profit for any farmer i, except for abatement costs, is given by $ry^i - [r - p(\tilde{g}, m^i)]m^i d[g(q, \tilde{g})]$. Each farmer i receives utility given by

$$v\{ry^i - [r - p(\tilde{g}, m^i)]m^i d[g(q, \tilde{g})]\} - c(a^i), \tag{6}$$

where $v\{\cdot\}$ is assumed to be twice continuously differentiable, increasing, and concave to represent risk aversion for farmers.[15]

Events transpire as follows. The license fee, l, the population goal for Canada geese in the MVP, G, and the number of geese available for harvest in Wisconsin, T, are determined exogenously by a state legislature and flyway-wide management authorities, respectively. The state wildlife management authority then chooses an abatement/compensation contract to offer farmers. Subsequently, geese arrive at Horicon, farmers choose abatement effort, and θ is drawn; these events determine $\tilde{g}$. After observing $\tilde{g}$, the state wildlife management authority specifies hunting regulations q, hunters pay license fees and hunt, and $\boldsymbol{\varepsilon}$ is drawn, determining crop damages m^i for each farmer i. After observing what can be observed, the state wildlife management authority consummates the contract. Below, contracts that provide optimal abatement incentives for farmers are investigated under two informational environments: either the state wildlife management authority observes effort costlessly or it observes only the goose density $\tilde{g}$ and the damage proportions m^i, $i = 1, \ldots, I$. In its broad outlines, our model is similar to Holmström's [14] model, in which a single principal (here, the government) con-

[15] That an agent's utility is separable in effort is a standard assumption in principal–agent models that has the effect of ruling out income effects on the choice of effort. Jewitt [16, p. 1185] indicates that an additional assumption on $v\{\cdot\}$ required for the first order approach is that the transformation $\psi(z) \equiv v[v'^{-1}(1/z)]$ be concave for positive z.

tracts with multiple agents (here, farmers) whose effort inputs jointly determine an outcome. Following Holmström, we will suppose that if effort cannot be observed and contracted on directly, then the agents choose effort as a Nash equilibrium.

b. First-best risk sharing contracts. In this section, assume that the vector **a** of abatement efforts applied by farmers is costlessly observable by the state wildlife management authority. Since the abatement efforts of farmers are observable, they can be contracted on, and to achieve first-best risk sharing contracts the state wildlife management authority solves

$$\max_{\mathbf{a},\, t(\cdot),\, p(\cdot)} \int_{\underline{g}}^{\bar{g}} u\{\beta[g(t(\tilde{g}),\tilde{g}),t(\tilde{g})] - l\}\phi^{\tilde{g}}(\tilde{g}\,|\,\bar{a},s)\,d\tilde{g}$$

subject to

$$Nl - \sum_{i=1}^{I}\int_{\underline{g}}^{\bar{g}}\int_{\underline{m}}^{\overline{m}} p(\tilde{g},m^i)m^i d[g(t(\tilde{g}),\tilde{g})]\,\phi^{m^i}(m^i\,|\,\mathbf{a})\phi^{\tilde{g}}(\tilde{g}\,|\,\bar{a},s)\,dm^i\,d\tilde{g} \ge 0 \quad (7)$$

$$\int_{\underline{g}}^{\bar{g}}\int_{\underline{m}}^{\overline{m}} v\{ry - [r - p(\tilde{g},m^i)]m^i d[g(t(\tilde{g}),\tilde{g})]\}$$

$$\phi^{m^i}(m^i\,|\,\mathbf{a})\phi^{\tilde{g}}(\tilde{g}\,|\,\bar{a},s)\,dm^i\,d\tilde{g} - c(a^i) \ge R^0 \qquad \text{for } i = 1,\ldots,I,$$

where N is the number of hunters, the first constraint is a budget constraint, and the second set of I constraints consists of an expected utility constraint for each farmer. (Recall that both the license fee l and the level of expected utility for each farmer R^0 are determined exogenously by the state legislature.) Let μ be the multiplier on the budget constraint, and λ_i, $i = 1,\ldots,I$, denote the multipliers on the I participation constraints.

Clearly the management authority contracts the same effort from each farmer. To do otherwise both raises the costs of a given level of total abatement effort and, because it raises the variance of abatement effort across farmers, achieves less dispersal from a given level of total abatement effort than a symmetric profile of abatement effort across farmers. Therefore each of the I first order conditions for effort are the same, as are the multipliers λ_i, and the expectations $\mathrm{E}_{m^i}[\cdot]$, for $i = 1,\ldots,I$; unnecessary subscripts and superscripts are dropped below. Additionally, $\sum_{j=1}^{I}\phi_{a^i}^{m^j}(\cdot)\phi^{\tilde{g}}(\cdot) = 0$; that is, farmer i's effort benefits society only in its effect in removing geese from the HZ.[16] Using these facts, integrating over $\phi^{m^i}(\cdot)$ where possible, and assuming that constraints bind, one obtains the following characterization of the optimal level of each abatement effort, a^i, transfer function $t(q)$, and compensation schedule $p(\tilde{g},m^i)$

$$\int_{\underline{g}}^{\bar{g}} -\{\mu I\,\mathrm{E}_m[p(\tilde{g},m)]d[g(t(\cdot),\tilde{g})] + \lambda I\,\mathrm{E}_m[v\{\cdot\}]\}D_{a^i}^{\phi^{\tilde{g}}}\,d\tilde{g}$$

$$= \lambda c'(a) - \int_{\underline{g}}^{\bar{g}} u\{\cdot\}D_{a^i}^{\phi^{\tilde{g}}}\,d\tilde{g} \qquad (8)$$

[16] That is, one can derive the analog to Eqs. (3) and (4) by replacing Eq. (3) with the identity $\int_{\underline{g}}^{\bar{g}} d[g(q,\tilde{g})]\phi^{\tilde{g}}(\tilde{g}\,|\,\bar{a},s)\,d\tilde{g} \equiv \sum_{j=1}^{I}\int_{\underline{g}}^{\bar{g}}\int_{\underline{m}}^{\overline{m}} m^j d[g(q,\tilde{g})]\phi^{m^j}(m^j\,|\,\mathbf{a})\phi^{\tilde{g}}(\tilde{g}\,|\,\bar{a},s)\,dm^i\,d\tilde{g}$.

$$\mu Id'[\cdot]g_q(\cdot)\mathrm{E}_m\{p(\tilde{g},m)m\} + \lambda Id'[\cdot]g_q(\cdot)\mathrm{E}_m[v'\{\cdot\}[r - p(\tilde{g},m)]m]$$
$$= u'\{\cdot\}[\beta_g(\cdot)g_q(\cdot) + \beta_q(\cdot)] \quad (9)$$
$$\sum_{i=1}^{I} v'\{\cdot\}m^i = \frac{\mu}{\lambda}, \quad (10)$$

where, to decrease the length of the expressions, we have defined $D_{a^i}^{\phi^{\tilde{g}}} \equiv \phi_{\bar{a}}^{\tilde{g}}(\cdot)\bar{a}_{a^i} + \phi_s^{\tilde{g}}(\cdot)s_{a^i}$.

Equation (8) reflects the fact that since abatement effort is contracted before random variables are drawn, the optimal level of abatement effort from each farmer is constant across states rather than state-contingent. The optimal level of abatement effort thus equates expected marginal benefits—the expected gain in hunter utility from abatement effort's effect in slackening the budget constraint and expected revenue constraint (i.e., abatement lowers damages and thus raises farmers' revenues)—with marginal costs—the direct costs of abatement effort and the expected decrease in hunter utility from fewer geese.

Equation (9) indicates that for any realization of $\tilde{g}$, the sum of the marginal benefits of abatement effort through hunting regulation is equated to the marginal cost of abatement effort through its effect in decreasing a hunter's utility. Thus (9) implies that, taking into account the goose density for the Horicon Marsh, the wildlife management authority will choose the optimal level of hunting abatement effort as a public good for farmers.[17] For example, the larger the realization of goose density, the greater the marginal benefit to farmers and the lower the marginal cost to hunters associated with increasing the stringency of regulations on hunters, so tougher hunting regulations are enacted when goose density is high. Equation (9) thus represents optimal risk sharing between hunters as a group and farmers as a group, given the nature of hunting regulations as a public good.

Optimal risk sharing between hunters and farmers does not peg the level of goose density and therefore does not peg aggregate damages, but Eq. (10) indicates that the payments to farmers will be structured such that the marginal utility of each farmer is the same, regardless of the draw of goose damages across farms.[18] After the level of goose damage is determined by the choice of farmer abatement effort in Eq. (8), the draw of goose density $\tilde{g}$, and the resulting choice of hunting regulations in (9), the revenue generated by license fees is used to make compensation payments to farmers such that each farmer has the same marginal (and given that farmers are identical, total) utility. This implies that all farmers will receive utility as if they suffered the same proportion of (smaller) damages and were not compensated for damages, which in turn implies that the larger a farmer's damages, the larger the payment per unit of damages she receives.[19]

[17] The representative agent approach obscures it, but of course, hunting regulations are a public ‘‘bad’’ for hunters as well as a public good for farmers, so the right hand side of (10) would be multiplied by N, the number of hunters, had we aggregated utility across hunters.

[18] To see this, note that since m^i appears inside $v'\{\cdot\}$ and $v\{\cdot\}$ is concave, the only way to ensure that average marginal utility on the LHS of (10) is constant across all draws of $\mathbf{m}$ is to structure payments such that each farmer has the same marginal utility, given total crop damages, regardless of the vector $\mathbf{m}$ that is drawn.

[19] The compensation function $p(g, \mathbf{m})$ is not constrained to be non-negative and, for some draws of $\mathbf{m}$, transfers among farmers will be required to equate marginal utilities across all farmers as in (10).

Finally, although we have suppressed the license fee l to conserve space, through the budget constraint the license fee is a determinant of the optimal abatement choices $\mathbf{a}$ and transfer $t(\tilde{g})$ as well as playing the obvious role of determining the funds available for redistributing income from hunters to farmers. Intuitively, the level of compensation paid to farmers per unit of lost crop is the price hunters pay for goose feed, and this price will of course affect the optimal level of public and private abatement.

c. Optimal incentive contracts under asymmetric information. In this section, suppose that the wildlife management authority observes $\tilde{g}$ (and therefore the total level of damages) and the vector of damage proportions, $\mathbf{m}$. Therefore contracting a level of effort from each farmer is not feasible because an individual farmer who reneged on the contract and suffered large damages could claim to have supplied effort diligently, but to have been victimized by bad luck (i.e., a large draw of ε^i). Below, we use the correlation between $\tilde{g}$, $\mathbf{m}$, and $\mathbf{a}$ in a Mirrlees–Holmström [9, 10, 13, 14, 16, 20, 23, 24] first-order approach to the principal–agent problem. Thus, the state wildlife management authority's task is to choose the compensation function $p(\tilde{g}, \mathbf{m})$ and transfer of public abatement $t(\tilde{g})$ that achieve an efficient trade-off between first-best risk-sharing and abatement incentives for farmers, given that farmers will behave non-cooperatively by choosing abatement efforts that are a Nash equilibrium.[20]

Let $\phi^m(\mathbf{m} \mid \mathbf{a})$ be the joint probability density function for the I damage proportions $\mathbf{m}$. At the time farmers choose abatement efforts, the contract offered by the management authority is fixed. Thus to determine the optimal contract to offer the farmers, the management authority acts as a Stackelberg leader, taking into account that whatever (acceptable) contract is offered, each farmer will choose abatement effort by solving

$$\max_{a^i} \int_{\underline{g}}^{\bar{g}} \int_{\underline{m}}^{\overline{m}} \cdots \int_{\underline{m}}^{\overline{m}} v\{ry - [r - p^i(g, \mathbf{m})] m^i d[g(t(q), \tilde{g})]\}$$
$$\times \phi^m(\mathbf{m} \mid a^i, \mathbf{a}^{-i}) \phi^{\tilde{g}}(\bar{g} \mid \bar{a}(a^i, \mathbf{a}^{-i}), s(a^i, \mathbf{a}^{-i}))\, d\mathbf{m}\, d\tilde{g} - c(a^i).$$

The notation $(a^i, \mathbf{a}^{-i})$ is used to imply that firm i takes the abatement efforts of all other farmers (i.e., the vector $\mathbf{a}^{-i}$) as given when it chooses its own abatement effort. First-order conditions for this problem are given by equating expected marginal utility for each farmer i with marginal cost given the abatement choices of all other firms,

$$\int_{\underline{g}}^{\bar{g}} \int_{\underline{m}}^{\overline{m}} \cdots \int_{\underline{m}}^{\overline{m}} v\{ry - [r - p^i(\bar{g}, \mathbf{m})] m^i d[g(t(q), \tilde{g})]\}$$
$$\cdot [\phi^{\mathbf{m}}_{a^i}(\mathbf{m} \mid a^i, \mathbf{a}^{-i}) \phi^{\tilde{g}}(\tilde{g} \mid \bar{a}(a^i, \mathbf{a}^{-i}), s(a^i, \mathbf{a}^{-i}))$$
$$+ \phi^{\mathbf{m}}(\mathbf{m} \mid a^i, \mathbf{a}^{-i}) \phi^{\tilde{g}}_{a^i}(\tilde{g} \mid \bar{a}(a^i, \mathbf{a}^{-i}), s(a^i, \mathbf{a}^{-i}))]\, d\mathbf{m}\, d\tilde{g} = c'(a^i)$$

As before, $\phi^{\mathbf{m}}_{a^i}(\cdot) = 0$; that is, the sum of the effects of an increase in farmer i's abatement effort on the distribution of damages across farms must be zero. Thus,

[20] Given that each farmer's damages are a function of the vector of abatement efforts, it is trivial to show that the payment to each farmer will depend on the vector of damage proportions $\mathbf{m}$.

substituting $D_{a^i}^{\phi^{\tilde g}}$ as defined above, we write the Nash equilibrium first order condition as

$$\int_{\underline{g}}^{\bar g}\int_{\underline{m}}^{\overline{m}}\cdots\int_{\underline{m}}^{\overline{m}} v\big\{ry - \big[r - p^i(\tilde g, \mathbf{m})\big]m^i d\big[g(t(q), \tilde g)\big]\big\} \times \phi^{\mathbf{m}}(\mathbf{m}\,|\,\mathbf{a}) D_{a^i}^{\phi^{\tilde g}}\, d\mathbf{m}\, d\tilde g = c'(a^i). \tag{11}$$

Note that Eq. (11) implies farmers take account of their positive and negative externalities on each other in the Nash equilibrium; otherwise, each farmer's abatement effort would not be a best reply to all other farmers' choices of abatement efforts. But that does not mean abatement effort is chosen optimally from society's perspective because the marginal cost of abatement effort to farmers does not include the effects of abatement efforts on hunters utility. We assume that the Nash equilibrium is symmetric in abatement efforts across farms.[21]

From the preceding, the wildlife management authority's problem is given by

$$\max_{\mathbf{a},\, t(\cdot),\, p(\cdot)} \int_{\underline{g}}^{\bar g} u\big\{\beta\big[g(t(\tilde g), \tilde g), t(\tilde g)\big] - 1\big\}\phi^{\tilde g}(\tilde g\,|\,\bar a, s)\, d\tilde g \qquad \text{subject to} \tag{12}$$

$$Nl - \sum_{i=1}^{I}\int_{\underline{g}}^{\bar g}\int_{\underline{m}}^{\overline{m}}\cdots\int_{\underline{m}}^{\overline{m}} p^i(\tilde g, \mathbf{m}) m^i d\big[g(t(\tilde g), \tilde g)\big]\phi^{\mathbf{m}}(\mathbf{m}\,|\,\mathbf{a})\phi^{\tilde g}(\tilde g\,|\,\bar a, s)\, d\mathbf{m}\, d\tilde g \ge 0$$

$$\int_{\underline{g}}^{\bar g}\int_{\underline{m}}^{\overline{m}}\cdots\int_{\underline{m}}^{\overline{m}} v\big\{ry - \big[r - p^i(\tilde g, \mathbf{m})\big]m^i d\big[g(t(\tilde g), \tilde g)\big]\big\} \times \phi^{\mathbf{m}}(\mathbf{m}\,|\,\mathbf{a})\phi^{\tilde g}(\tilde g\,|\,\bar a, s)\, d\mathbf{m}\, d\tilde g - c(a^i) \ge R^0, \qquad \text{for } i = 1, \dots, I$$

$$\int_{\underline{g}}^{\bar g}\int_{\underline{m}}^{\overline{m}}\cdots\int_{\underline{m}}^{\overline{m}} v\big\{ry - \big[r - p^i(\tilde g, \mathbf{m})\big]m^i d\big[g(t(q), \tilde g)\big]\big\}\phi^{\mathbf{m}}(\mathbf{m}\,|\,\mathbf{a}) D_{a^i}^{\phi^{\tilde g}}\, d\mathbf{m}\, d\tilde g - c'(a^i) = 0, \qquad \text{for } i = 1, \dots, I.$$

Except for the fact that the compensation payment per unit of crop loss depends on the entire vector of damage proportions **m**, the first constraint and the second set of I constraints are the same as in the first-best case considered earlier; the third set of I constraint is the first order condition for the Nash equilibrium in abatement efforts from Eq. (11).

Let μ be the multiplier on the first constraint, λ_i, $i = 1, \dots, I$ be multipliers on the second I constraints, and ω_i, $i = 1, \dots, I$ be the multipliers on the third I constraints. Then, after eliminating own effects and externalities that sum to zero, noting that the equilibrium choice of abatement efforts by farmers is symmetric and therefore the multipliers on all firms are the same (and dropping the subscripts

[21] Because all farmers are identical, symmetry of the Nash equilibrium is likely to be less of a problem than uniqueness. We are unaware of any results that would guarantee the firms choose the Nash equilibrium with symmetric efforts, and must therefore unfortunately leave that implementation question open.

on multipliers), and integrating over $\phi^{\mathbf{m}}(\mathbf{m} \mid \mathbf{a})$ wherever possible, the optimal incentive contract is characterized by the first order conditions

$$\int_{\underline{g}}^{\bar{g}} \{-\mu I \mathrm{E}_{\mathbf{m}}[p(\tilde{g},\mathbf{m})m] d[\cdot] + \lambda I \mathrm{E}_{\mathbf{m}}[v\{\cdot\}]\} D_{a^i}^{\phi^{\tilde{g}}} \, d\tilde{g}$$

$$= -\int_{\underline{g}}^{\bar{g}} u\{\cdot\} \, d\tilde{g} - \sum_{j=1}^{I} \omega_j \int_{\underline{g}}^{\bar{g}} \mathrm{E}_{\mathbf{m}}[v\{\cdot\}] D_{a^j a^i}^{\phi^{\tilde{g}}} \, d\tilde{g} + \omega_i c''(a) + \lambda c'(a) \quad (13)$$

$$\mu I d'[\cdot] g_q(\cdot) \mathrm{E}_{\mathbf{m}}\{p(\tilde{g},\mathbf{m})m\} + \lambda I d'[\cdot] g_q(\cdot) \mathrm{E}_{\mathbf{m}}[v'\{\cdot\}[r - p(\tilde{g},\mathbf{m})]m]$$

$$+ \omega d'[\cdot] g_q(\cdot) \sum_{i=1}^{I} \mathrm{E}_{\mathbf{m}}[v'\{\cdot\}[r - p(\tilde{g},\mathbf{m})]m] \frac{D_{a^i}^{\phi^{\tilde{g}}}}{\phi^{\tilde{g}}}$$

$$= u'\{\cdot\}[\beta_g(\cdot) g_q(\cdot) + \beta_q(\cdot)] \quad (14)$$

$$\sum_{i=1}^{I} v'\{\cdot\} m^i \left(\lambda + \omega \frac{D_{a^i}^{\phi^{\tilde{g}}}}{\phi^{\tilde{g}}} \right) = \mu \quad (15)$$

Equations (13), (14), and (15) correspond identically to Eqs. (8), (9), and (10) except for the new derivatives introduced by the constraint that the farmers choose abatement efforts as in a Nash equilibrium; contrasting the two sets of first order conditions indicates the costs that asymmetric information imposes on the optimal choices of abatement effort, hunting regulations and risk-sharing among farmers.

The new term in Eq. (13) is the sum of the second order conditions for utility maximization at the Nash equilibrium for each firm. This term indicates how rapidly first order conditions change around the Nash equilibrium, and thus indicates how costly it is to impose the optimal level of effort, given that the level of effort is implemented as a Nash equilibrium.

The optimal transfer of hunting regulations, $t(\tilde{g})$, is characterized in Eq. (14). Equation (14) differs from Eq. (9) by the last term on the RHS of (14). This term includes $D_{a^i}^{\phi^{\tilde{g}}}/\phi^{\tilde{g}}$, and is positive if $D_{a^i}^{\phi^{\tilde{g}}} > 0$ (recall that farmers are identical). Thus an incentive to abate is provided by rewarding farmers as a group with more stringent hunting regulations than in (9) for observations of $\tilde{g}$ that are more likely as a^i increases and penalizing farmers with less stringent hunting regulations than in (9) for observation of $\tilde{g}$ that are less likely as a^i increases. The reason farmers are punished or rewarded as a group is that the correlation between $\tilde{g}$ and $\mathbf{a}$ is through group statistics as well as because q is a public good.

Deviations from optimal risk-sharing among farmers (i.e., Eq. (10)) are also used to provide incentives for abatement effort in Eq. (15). Since $D_{a^i}^{\phi^{\tilde{g}}}/\phi^{\tilde{g}}$ evaluated at the optimal level of effort in (13) is the same for each farmer i, the term in parentheses is a constant across draws of $\mathbf{m}$. Thus for an observation of $\tilde{g}$ that is more likely to have been realized at a combination of $\bar{a}$ and s on the same level set of $\phi^{\tilde{g}}(\tilde{g} \mid \bar{a}, s)$ as the $\bar{a}$ and s $(= 0)$ implied by the optimal abatement effort vector $\mathbf{a}$, an individual farmer i will be rewarded the higher her damage proportion m^i.

Although the compensation payments implied by (15) use relative performance evaluation (i.e., each farmer's payment depends on all farmer's damage proportions), they are quite different than rank-order tournaments discussed in previous literature. For example, Green and Stokey [8] provide a principal−multiple-agent model in which as the distribution of the common shock (i.e., θ in our model) becomes more diffuse, compensation payments that increase with an agent's rank among all agents (i.e., tournaments) outperform individual contracts. In their model, the reason tournaments can perform well is that the additional noise from the common shock (which the principle cannot observe and thereby design a contract around) weakens incentives in individual contracts, and can be screened out in a tournament. In the present model, since $\tilde{g}$ is observed, it does not matter whether or not θ is observed.[22] Indeed, here we find that as the number of agents grows large, the principal's leverage over an agent decreases, quite the opposite of their result that as the number of agents grows large the principal's welfare under the optimal tournament approaches that obtained under the first-best contract. Here, the problem induced by large numbers of agents is that at the optimal abatement choice, each farmer only affects the outcome through the mean of abatement effort, and thus her effect diminishes in order $1/I$.

IV. CONCLUSION

While the model above is somewhat stylized for mathematical tractability (identical firms, etc.), it has at least three implications for damage compensation programs that are likely to be robust:

(1) Payments to farmers should be linked to observables that are correlated with farmers' abatement effort. The WWDP currently goes much farther in tying compensation to abatement effort than other compensation programs that we are aware of by requiring farmers to supply abatement effort in order to receive any compensation. But additional information could be used. For example, in the course of researching determinants of population dynamics, wildlife biologists routinely gather data on wildlife populations that constitutes observation of the random variables associated with goose density in the model above. To provide incentives for abatement by farmers, tables that indicate how compensation payments will be contingent on total damages for a given beginning-of-season realization of the goose population could be distributed to farmers.

(2) To the extent that farmers are identical with respect to the effects of their abatement efforts, payments to farmers should be made so as to provide insurance within farmers as a group. Currently in the WWDP, farmers are paid a fixed percentage of the market price, which implies that the risk associated with random allocation of geese across farms is not insured against.

(3) Because the compensation a farmer receives depends on group statistics, the cost of providing incentives to achieve a given level of damages increases rapidly as the group size increases. Other crop predation settings (e.g., the re-introduction of wolves in the west) that involve fewer farmers than suffer losses in the Horicon Zone are likely to be less costly to address.

Toward generalizing the agency approach to other wildlife problems, observe that the key role played by hunters regulations in the model is in risk pooling. Extensions of the same idea to other settings thus depends on identifying groups of

[22] Even if θ were observed, since abatement efforts are not observed, individual farmers could accuse other farmers of the shirking that led to the suboptimal level set of $\tilde{g}$ in the mean and variance of abatement effort.

recreational users whose benefits are positively correlated with farmers' losses, and identifying a control variable that allows transfers between these recreational users and farmers.

Finally, the benefits and costs of prevailing alternatives (e.g., government ownership, markets for lease hunting and ownership of croplands by private hunting clubs) to forced transfers between recreational users and farmers should be weighed.[23] While that task is outside the scope of the present paper, the analysis above indicates that well-structured compensation/abatement programs address the inter-farm negative externality inherent in abatement technologies, but may be an expensive method for achieving the optimal level of abatement in situations in which large numbers of individuals suffer crop losses.

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