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The Public Resource Management Game

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Abstract

Use of public resources for private economic gain is a longstanding, contested political issue. Public resources generate benefits beyond commodity uses, including recreation, environmental and ecological conservation and preservation, and existence and aesthetic values. We analyze this problem using a dynamic resource use game. Low use fees let commodity users capture more of the marginal benefit from private use. This increases the incentive to comply with government regulations. Optimal contracts therefore include public use fees that are lower than private rates. The optimal policy also includes random monitoring to prevent strategic learning and cheating on the use agreements and to avoid wasteful efforts to disguise noncompliant behavior. An optimal policy also includes a penalty for cheating beyond terminating the use contract. This penalty must be large enough that the commodity user who would gain the most from noncompliance experiences a negative expected net return.

Keywords: Renewable resources, public resources policy, optimal contracts

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1. Introduction

Fishing without a license; poaching big game; hiking and off-road vehicle use in fragile or protected areas; taking petrified wood, fossils, or Native American artifacts from public lands; cutting and hauling firewood in unapproved areas; and excess forage consumption by privately owned livestock are examples of a common resource management problem. Each of these activities reduces the quality of a public resource for other users. The economic problem is that individual users face incentives that are not socially optimal. To help finance the cost of protecting, improving, and policing public resources, individuals are charged fees to exploit public resources.

This paper uses livestock (privately owned cattle, sheep, and horses) grazing on federal lands to illustrate the nature of and solutions to this public resource use problem. Grazing and other commercial uses of federal land have been hotly contested for more than a century. For example, livestock graze on 262 million acres of federal land, 167 million acres administered by the Bureau of Land Management (BLM) and 95 million acres administered by the United States Forest Service (USFS) land (USDI, 2003; USDA, 2003) – a total land area larger than the Eastern seaboard plus Vermont, Pennsylvania and West Virginia. Roughly 28,000 livestock producers hold contracts to graze animals on federal lands, roughly 3% of all livestock producers in the United States, and 22% of the livestock producers in the eleven Western contiguous States (USDI-BLM, USDA-USFS, 1995). Fishing, hunting guide and outfitting operations, mining, timber harvesting, and petroleum and natural gas exploration, development, and extraction present similar management challenges and are other extensive uses of public resources.

One focus of the debate over the private use of public resources is the argument that commodity users are heavily subsidized. Figure 1 illustrates the discrepancy between public and private grazing fees in the eleven contiguous western states in constant 2009 dollars, using the implicit price deflator for gross domestic product to adjust for inflation.

Environmentalists, and some economists, have argued that higher use fees are linked to the quality of the environment associated with public resources. For grazing policy, this view is best articulated by President Clinton's Council of Economic Advisors:

> "The controversy over rangeland reform shows the importance of integrating pricing with regulation to use the Nation's resources more efficiently and strike a better balance between economic and environmental objectives.
>
> A central point of contention involves the fees that the federal Government charges ranchers to graze animals on federal land. These fees should reflect both the value of the forage used by an additional animal and the external environmental costs of grazing an additional animal ... Charging ranchers the marginal value of forage ... encourages efficient use of the range. By preventing overgrazing, it protects the condition of the range for future uses. It also promotes long-run efficiency in the industry ...
>
> Promoting efficiency thus means both increasing grazing fees and ensuring that federal grazing fees change from year to year in accordance with changes in rent on private grazing land."
>
> *Economic Report of the Presid*ent, 1994:182-83.

This paper develops an economic model of the dynamic game between a public resource management agency and private commodity users who exploit the resource. In the first stage of this game, the agency chooses the administrative rules, including the approved extraction rate, use fees, penalties for failing to comply with government regulations, and a monitoring strategy. These are announced publicly and the government commits to this policy for all time. In all later stages, commodity users choose extraction rates, which may or may not be consistent with the government's approved extraction rates, and the government pursues its monitoring and enforcement activities. All parties are risk neutral and form rational expectations, and the focus is on a subgame perfect Nash equilibrium.

2. A Model of Public Resource Management

In this section, we develop a dynamic economic model of the incentives and conflicts between a regulatory agency and public resource commodity users. Let $x(t)$ be the resource stock and let $s(t)$ be the extraction rate. Let A denote the set of all use allotments and I the set of commodity user types. For each $(a,i) \in A \times I$ the net return from commodity use is $v(s(t), x(t), a, i)$ and the net benefit to noncommercial use is $b(s(t), x(t), a)$. The commercial net returns function is increasing in (x, s), the noncommercial benefit function is increasing in x and decreasing in s, and both are twice continuously differentiable and jointly concave in (x, s). Noncommercial use benefits do not depend on the characteristics of the commercial user. Individual characteristics that determine his or her type, i, are vector-valued. The agency cannot identify, choose, or affect any commercial user's characteristics or type.

The equation of motion for the resource stock is

$$\dot{x}(t) = f(x(t), a) - s(t), \quad x(0) = x_0(a) \ \ fixed, \tag{1}$$

where the natural resource growth rate on allotment a, $f(x,a)$, is twice continuously differentiable in x, $f(0,a)=0$, $\partial f(0,a)/\partial x>0$, and $\partial^2 f(x,a)/\partial x^2 < 0 \;\; \forall \;\; x \geq 0$. A unique maximum sustainable stock level, $x^{msy}(a)>0$, satisfying $\partial f(x^{msy}(a),a)/\partial x=0$ exists for each $a \in A$ (Stoddard, Smith, and Box, p. 273; Libecap, p. 67).

Suppose that commercial user $i \in I$ maximizes the unencumbered discounted present value of profits from commercial use on allotment $a \in A$,

$$J_{\text{Private}}(a,i,x_0)=\max_{\{x(t),s(t)\}}\int_0^\infty e^{-rt}v(s(t),x(t),a,i)dt \tag{2}$$

subject to (1), where $r>0$ is the real discount rate. From optimal control theory, the commercial user's privately optimal wealth-maximizing use path satisfies (1) and the following differential equation for the harvest rate,[1]

$$\dot{s}_{\text{Private}}=\frac{(r-f_x)v_s-v_x-v_{sx}(f-s_{\text{Private}})}{v_{ss}}. \tag{3}$$

The long-run steady state satisfies $\dot{s}_{\text{Private}}=\dot{x}_{\text{Private}}=0$, so that,

$$s^\infty_{\text{Private}}(a,i)=f(x^\infty_{\text{Private}}(a,i),\ a) \tag{4}$$

and the private equilibrium value of the marginal product condition,

$$\begin{aligned}F(x^\infty_{\text{Private}}(a,i),a,i)=v_x(f(x^\infty_{\text{Private}}(a,i),a),x^\infty_{\text{Private}}(a,i),a,i)+\\ v_s\left(f(x^\infty_{\text{Private}}(a,i),a),x^\infty_{\text{Private}}(a,i),a,i\right)\times\left[f_x(x^\infty_{\text{Private}}(a,i),a)-r\right]=0.\end{aligned} \tag{5}$$

The condition $\partial F(x,a,i)/\partial x<0 \;\forall\; x\geq 0$ is sufficient for (5) to define a unique, globally stable, saddle point equilibrium.

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[1] Subscripts denote partial derivatives. Detailed derivations of all of the results presented in this paper are available from the authors upon request.

Now consider the socially optimal decision rule on allotment *a* for the same commodity user *i*. This decision rule includes both the commercial user's flow of net returns from exploitation of the resource and the flow of noncommercial use benefits.

The socially optimal resource use path is the solution to

$$J_{\text{Public}}(a,i,x_0) = \max_{\{s(t),x(t)\}} \int_0^\infty e^{-rt}\left[v(s(t),x(t),a,i) + b(s(t),x(t),a)\right]dt\ , \tag{6}$$

subject to (1). Again from optimal control theory, this path satisfies (1) and the following differential equation for the harvest rate:

$$\dot{s}_{\text{Public}} = \frac{(r-f_x)(v_s+b_s)-(v_x+b_x)-(v_{sx}+b_{sx})(f-s_{\text{Public}})}{v_{ss}+b_{ss}}. \tag{7}$$

The steady state now satisfies $s^\infty_{\text{Public}}(a,i) = f(x^\infty_{\text{Public}}(a,i),a)$ and the public management agency's value of the marginal product condition,

$$\begin{aligned} &G(x^\infty_{\text{Public}}(a,i),a,i) = v_x(f(x^\infty_{\text{Public}}(a,i),a),x^\infty_{\text{Public}}(a,i),a,i) \\ &+ b_x(f(x^\infty_{\text{Public}}(a,i),a),x^\infty_{\text{Public}}(a,i),a) \\ &+ \left[v_s(f(x^\infty_{\text{Public}}(a,i),a),x^\infty_{\text{Public}}(a,i),a,i) + b_s(f(x^\infty_{\text{Public}}(a,i),a),x^\infty_{\text{Public}}(a,i),a)\right] \\ &\times\left[f_x(x^\infty_{\text{Public}}(a,i),a)-r\right] = 0. \end{aligned} \tag{8}$$

Analogous to the private equilibrium, the condition $\partial G(x,a,i)/\partial x < 0\ \ \forall\ x \geq 0$ is sufficient for equation (8) to define a unique, globally stable, saddle point equilibrium.[2]

It follows from equations (5) and (8) that $\forall\ (a,i) \in A \times I,\ x^\infty_{\text{Public}} > x^\infty_{\text{Private}}$. In turn, it

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[2] The first-order conditions for the private and the social optima also are sufficient for an optimal use path for the associated optimal control problems due to the concavity of $v(\cdot,a,i)$, $b(\cdot,a)$, and $f(\cdot,a)$.

follows from this result that, $\forall\ x_0 > 0,$ the privately optimal harvest rate is higher than the socially optimal harvest rate. This is illustrated in Figure 2.

The economic intuition for this result is the following. Because the harvest rate has a negative marginal value to noncommercial users, the value of the marginal product for *s* is lower for society than for the commercial user. Similarly, because the resource stock has a positive marginal value to noncommercial users, society's value of the marginal product of *x* is higher than for the commercial user. Both effects work together, producing incentives for the commercial user to exploit the resource more intensively and harvest more stock than is socially optimal.

3. Optimal Commercial Use Contracts for Public Resources

Monitoring and enforcement by government agencies are costly activities. This is particularly true under incomplete information about user types. Also, monitoring and enforcement activities are not directly productive. They only have value to society insofar as they prevent unwanted or wasteful actions on the part of private resource users. As such, one goal of a rational government agency will be to minimize the cost of these activities.[3]

However, if an agency cannot monitor the use of public resources and effectively enforce its regulations for that use, then there may be no penalty for pursuing purely private incentives. Therefore, given the conflict of interest between society and private resource

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[3] For example, this portion of BLM and USFS budgets is essentially independent of commercial use fees collected. Approximately 50% of fees go to state legislatures to be distributed to counties as "Payment in Lieu of Taxes," 25-50% are earmarked for resource allotment improvement, and less than 25% return to the federal treasury. The General Accounting Office (1991) and the BLM estimate that the costs of monitoring grazing allotments greatly outweigh total grazing fees collected.

users established above, this section of the paper considers the issues of design, monitoring, and enforcement of commercial use contracts for public resources in the presence of imperfect monitoring and enforcement on the part of the government agency.

Assume that the distribution of commercial user types, $\Psi : I \to [0,1]$, is known to the agency and time invariant. Each commercial user with a commercial use contract is considered by the agency to be a random draw from this distribution. The agency is unable to observe, select, or influence *i* on any allotment, and is unable to learn *i* regardless of the resources committed to seeking this information.[4]

Under rational expectations, given information only about the distribution of commercial user types, the resource management agency will seek to maximize the expected discounted net benefits on each allotment,

$$\bar{J}_{Public}(a, x_0) = \max_{\{s(t),x(t)\}} \int_0^\infty e^{-rt} [\bar{v}(s(t), x(t), a) + b(s(t), x(t), a)] dt \,, \tag{9}$$

subject to (1), where the expectation is taken over the distribution of commercial user types,[5]

$$\bar{v}(s(t), x(t), a) = \int_{i \in I} v(s(t), x(t), a, i) d\Psi(i) \,. \tag{10}$$

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[4] If *I* is a general sample space (e.g., a linear vector space), then the map from a structural form of a game to a reduced form based on types is not invertible. As a result, models leading to simplifications such as the revelation principle, which is often applied when *i* is a scalar, do not apply in this setting.

[5] This is a *second best decision rule*. In particular, if the agency could know or learn *i*, but not choose or influence the commodity user's type, then it would first solve the decision problem in the previous section. If we then take expectations over types to determine the expected net benefit, it is clear that this will exceed the solution to (9) because the expected value of the pointwise maximum over *I* will always be at least as large as the maximum of the expected value over *I*. Moreover, if the agency could choose or influence the type, then it would be rational to select the optimal user for each allotment, which clearly dominates the average solution.

Now the long-run steady state satisfies $\overline{s}^{\infty}_{\text{Public}}(a) = f(\overline{x}^{\infty}_{\text{Public}}(a), a)$ and the government agency's *average value of the marginal product* condition,

$$\begin{aligned} & H(\overline{x}^{\infty}_{\text{Public}}(a), a) = \overline{v}_x(f(\overline{x}^{\infty}_{\text{Public}}(a), a), \overline{x}^{\infty}_{\text{Public}}(a), a) \\ & + b_x(f(\overline{x}^{\infty}_{\text{Public}}(a), a), \overline{x}^{\infty}_{\text{Public}}(a), a) \\ & + \left[\overline{v}_s(f(\overline{x}^{\infty}_{\text{Public}}(a), a), \overline{x}^{\infty}_{\text{Public}}(a), a, i) + b_s(f(\overline{x}^{\infty}_{\text{Public}}(a), a), \overline{x}^{\infty}_{\text{Public}}(a), a)\right] \\ & \times \left[f_x(\overline{x}^{\infty}_{\text{Public}}(a), a) - r \right] = 0. \end{aligned} \tag{11}$$

In this case, the condition $H_x(x, a) < 0 \;\forall\; x \geq 0$ is sufficient for equation (11) to determine unique, globally stable saddle point equilibrium.

The commercial user's choices for $x(t)$ and $s(t)$ are observed by the agency if and when the lease is monitored. To prevent the wasteful use of resources by a noncompliant commodity user to try to learn the timing and location of monitoring activities by the agency, the government's monitoring strategy needs to be random and statistically independent both across space (allotments) and across time. It needs to be independent across allotments so that a user cannot learn or predict the agency's behavior on his allotment by observing monitoring activities on other allotments. It needs to be independent across time so that users cannot learn or predict the agency's future behavior on the basis of their observations of past behavior.

Beyond the necessity of spatial and temporal statistical independence, two properties of a well-designed monitoring and enforcement strategy are required. Both are driven by the conjoint goals of minimizing the cost of monitoring and enforcement, to identify and address noncompliant resource patterns, and to create an economic environment in which commodity users operate in an intertemporally consistent and predictable way, whether or not they are compliant with the commodity use regulations. We analyze these in reverse order.

First, note that an independent, stationary Poisson process for monitoring each allotment is a feasible monitoring rule that induces a stationary exponential distribution for the waiting time until the next monitoring event. The stationary exponential distribution is the unique stochastic process for waiting times without memory. If the real discount rate is constant, then a time autonomous resource extraction problem for a noncompliant commodity user is created. This is, in fact, the *only* way that the government agency can create a time autonomous decision problem for noncompliant commodity users. By the monotonicity of optimal control paths with a single state variable, this leads to a predictable, and eventually observable, noncompliant resource use path.

Second, to permanently discourage noncompliant use of public resources, an optimal monitoring and enforcement policy will include a penalty function beyond terminating the commodity use agreement. Incentive compatibility, regardless of user type, requires this penalty to be large enough that the net present value of a compliant strategy exceeds the expected net present value of a noncompliant strategy.[6] The optimal penalty thus leads the commodity user who would gain the most from failing to comply with the use regulations to face an expected loss from noncompliance.

The commodity user's optimal decision regarding whether to cheat or comply with

[6] This argument assumes that the government collects taxes, fees, and fines efficiently and is efficient in the provision of government goods and services and other activities – including monitoring and enforcement of regulatory rules. It also assumes that there are no political or other barriers or limits to the size of regulatory fines. However, see section 4 of this paper for a discussion of extensions to the model in this respect.

the commodity use agreement in the first stage of play therefore becomes a subgame perfect Nash equilibrium strategy for all subsequent stages of the game. This permanently separates compliant and noncompliant users on all allotments. The government is then able to discover the entire extraction path at every monitoring date for each allotment.

Therefore, to create a dynamic decision rule for a noncompliant commodity user that is time autonomous, let $\mu(a)$ denote the constant hazard rate for inspection times.[7] Then the rational expectation of the distribution of agency monitoring times is determined by the exponential probability density function, $\varphi(t,a) = \mu(a)e^{-\mu(a)t}$. Once the agency monitors the allotment, it has complete information.[8] If the agency observes a stock that is below or a harvest rate that is above the socially optimal level, then it concludes that the permit has been violated. In that case, the government will permanently terminate the lease and impose an additional penalty.[9]

We now turn to two issues. First, does the commercial use fee affect the harvest rates of compliant or noncompliant commercial users? Second, does the commercial use fee affect the compliance choice?

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[7] Independent and stochastic monitoring in a static setting when the regulator is unable to differentiate among agents is analyzed in Viscusi and Zeckhauser (1979). In a dynamic setting, a constant hazard rate for monitoring times is equivalent to a stationary exponential distribution for the waiting time for the next monitoring date, regardless of the point in time in the commodity user's resource use path. The exponential distribution is the unique continuous distribution without memory in this sense.

[8] Perfect detection of violations once an agent is monitored is a common theme in environmental regulation (e.g., Viscusi and Zeckhauser).

[9] Costly monitoring and limited budgets have frequently been argued to lead to optimal enforcement strategies with random detection and penalties for violations (e.g., Becker 1968, Stigler 1970, and Polinsky and Shavell 1979).

3.1 Commercial Users' Decisions in a Regulated Environment

The Taylor Grazing Act of 1934 set much of grazing policy still in effect today. Public grazing fees have always been lower than private fees (LaFrance and Watts). As figure one illustrates for public lands grazing over the past fifty years, real public grazing fees have been well below private grazing lease rates for several decades. This suggests that enough time has past for a compliant commercial user to have reached the long-run equilibrium resource stock and harvest rate. Therefore, assume that $x_0(a) = \overline{x}^{\infty}_{\text{Public}}(a) \;\forall\; a \in \boldsymbol{a}$. The optimal compliant strategy is the sustained harvest rate $s(t,i) \equiv \overline{s}^{\infty}_{\text{Public}}(a) \;\forall\; t \geq 0$. The wealth of a compliant commercial user of type *i* on allotment *a* is

$$\begin{aligned} W_C(a,i) &= \int_0^{\infty} \left[v(\overline{s}^{\infty}_{\text{Public}}(a), \overline{x}^{\infty}_{\text{Public}}(a), a, i) - p_g \overline{s}^{\infty}_{\text{Public}}(a) \right] e^{-rt} dt \\ &= \frac{1}{r} \left[v(\overline{s}^{\infty}_{\text{Public}}(a), \overline{x}^{\infty}_{\text{Public}}(a), a, i) - p_g \overline{s}^{\infty}_{\text{Public}}(a) \right], \end{aligned} \tag{12}$$

where p_g is the commercial use fee.

On the other hand, the expected wealth of a noncompliant commercial user is partially determined by the frequency and timing of monitoring.[10] The first time that the agency monitors an allotment, any cheating is detected. To mask their cheating, noncompliant commercial users will pay $p_g \overline{s}^{\infty}_{\text{Public}}(a)$. Consequently, commercial use fee payments act like a fixed cost to avoid the direct revelation of noncompliance. The expected

[10] Becker (1968) and Stigler (1970) argue that individuals compare the expected benefits and costs of compliance with laws and regulations. Viscusi and Zeckhauser (1979) extend this to the regulation of profit-maximizing firms.

wealth for a noncompliant commercial user is [11]

$$\overline{W}_{NC}(a,i)=\int_0^\infty \mu(a)e^{-\mu(a)t}\left\{\int_0^t e^{-r\tau}\left[v(x(\tau;a,i),s(\tau;a,i),a,i)-p_g\overline{s}^\infty_{\text{Public}}(a)\right]d\tau\right\}dt\,. \quad (13)$$

Integration by parts lets us rewrite this as (Kamien and Schwartz 1991, pp. 61-62),

$$\overline{W}_{NC}(a,i)=\int_0^\infty e^{-(r+\mu(a))t}\left[v(s(t;a,i),x(t;a,i),a,i)-p_g\overline{s}^\infty_{\text{Public}}(a)\right]dt\,. \quad (14)$$

Note, in particular, that the integrand in (14), with $r+\mu(a)$ as the constant real discount rate in a noncompliant optimal control problem, is time autonomous. This implies that the noncompliant commodity user's optimal resource use path is monotone over time, so that a cyclical use path cannot complicate the agency's monitoring problem.

A noncompliant commercial user's optimal control path satisfies (1) and

$$\dot{s}_{NC}=\frac{[r+\mu(a)-f_x]v_s-v_x-v_{sx}(f-s_{NC})}{v_{ss}}. \quad (15)$$

The numerator in (15) is positive with no monitoring. This is because the long-run equilibrium resource stock in a privately optimal resource use path is lower than the long-run equilibrium resource stock in a socially optimal resource use path. Therefore, $\mu(a)>0$ increases the incentive for a noncompliant commercial user to exploit the resource more intensively.

The long-run steady state equilibrium for a noncompliant commercial user satisfies

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[11] Sharon (1967) and Srinivisan (1973) argue that tax evaders hide actions to avoid suspicion by regulators.

$s_{NC}^{\infty}(a,i) = f\left(x_{NC}^{\infty}(a,i),a\right)$ and

$$\begin{aligned} & v_x(s_{NC}^{\infty}(a,i), x_{NC}^{\infty}(a,i), a, i) + v_s(s_{NC}^{\infty}(a,i), x_{NC}^{\infty}(a,i), a, i) \\ & \times [f_x(x_{NC}^{\infty}(a,i), a) - (r + \mu(a))] = 0. \end{aligned} \tag{16}$$

It follows that the intertemporal harvest rate, the long-run equilibrium harvest rate, and the long-run equilibrium resource stock all are independent of the commodity use fee.[12] It also follows that $\partial x_{NC}^{\infty}(a,i)/\partial\mu < 0$. Thus, the long-run equilibrium stock is a decreasing function of the hazard rate for the first monitoring time, the intertemporal harvest rate is an increasing function of the hazard rate for the first monitoring time, and the commercial use fee plays no role in an optimal noncompliant commodity resource exploitation path.

3.2 Commercial Use Fees versus Compliance

At this point, we have established that the commercial use fee plays no role in the harvest rate choices of both compliant and noncompliant commercial users. It is equally clear that the wealth generated by either commercial use decision decreases with increased commercial use fees. We now turn to the issue of how a change in the commercial use fee affects the decision to comply with commercial use regulations. We find that increasing the commercial use fee decreases the incentive to comply with the terms of a public resource commercial use contract.

In the absence of a penalty function that is imposed when a noncompliant use path is first monitored, the commercial user's decision whether to comply with contract provi-

[12] One implication is that higher commodity use fees do not necessarily reduce extraction rates or improve the environment.

sions hinges on the expected net benefit from noncompliance, $R \equiv \overline{W}_{NC} - W_C$. The optimal decision rule is to comply if $R \leq 0$ and to cheat if $R > 0$. We analyze the qualitative properties of this decision rule by appealing to the dynamic envelope theorem and curvature results of LaFrance and Barney (1991). This gives the following results, which we will make use of below:

$$\frac{\partial \overline{W}_{NC}}{\partial \mu} < 0\,; \tag{17}$$

$$\frac{\partial^2 \overline{W}_{NC}}{\partial \mu^2} > 0\,; \tag{18}$$

$$\frac{\partial \overline{W}_{NC}}{\partial p_g} = -\frac{\overline{s}^{\infty}_{\text{Public}}(a)}{\left[r + \mu(a)\right]} < 0\,; \tag{19}$$

$$\frac{\partial^2 \overline{W}_{NC}}{\partial p_g \partial \mu} = \frac{\overline{s}^{\infty}_{\text{Public}}(a)}{\left[r + \mu(a)\right]^2} > 0\,; \tag{20}$$

$$\frac{\partial^2 \overline{W}_{NC}}{\partial p_g^2} = 0\,; \tag{21}$$

$$\frac{\partial W_C}{\partial p_g} = -\frac{\overline{s}^{\infty}_{\text{Public}}(a)}{r} < 0\,; \tag{22}$$

and

$$\frac{\partial W_C}{\partial \mu} = \frac{\partial^2 W_C}{\partial p_g \partial \mu} = \frac{\partial^2 W_C}{\partial p_g^2} = 0\,. \tag{23}$$

If $\mu(a) = 0$, it is clear that the optimal strategy is to cheat for any $p_g \geq 0$ since there is no penalty for doing so. It also follows from (17)–(23) that R is strictly increasing in the commercial use fee,

$$\frac{\partial R}{\partial p_g} = \frac{\mu(a)\overline{s}^{\infty}_{\text{Public}}(a)}{r\left[r+\mu(a)\right]} > 0 \ , \tag{24}$$

strictly decreasing in the hazard rate,

$$\frac{\partial R}{\partial \mu} = \frac{\partial \overline{W}_{NC}}{\partial \mu} < 0 \, . \tag{25}$$

As a result, on each allotment, for any $\mu(a) > 0$, there is a unique commercial use fee (which may be negative), $p_g(\mu(a), a, i)$, such that $R = 0$, and such that commercial user i is indifferent between complying and cheating. Differences across commercial users and allotments imply different ($\mu(a)$, p_g) pairs for which a given commercial user is indifferent between compliance and cheating on a given allotment. *Therefore, in the absence of any penalty function imposed when cheating is first detected, some commercial user types will cheat and others will comply with the resource use regulations.*

It also follows from (17)–(23) that the monitoring rate must increase with the commercial use fee to maintain a constant incentive for compliance on any given allotment,

$$\left.\frac{\partial \mu}{\partial p_g}\right|_{R=R^{\text{o}}} = -\frac{\partial R/\partial p_g}{\partial R/\partial \mu} > 0 \, . \tag{26}$$

Moreover, the monitoring rate must increase at an increasing rate, since

$$\left.\frac{\partial^2 \mu}{\partial p_g^2}\right|_{R=R^{\text{o}}} = \frac{2\left(\frac{\partial^2 R}{\partial \mu \partial p_g}\right)\left(\frac{\partial R}{\partial \mu}\right)\left(\frac{\partial R}{\partial p_g}\right) - \left(\frac{\partial^2 R}{\partial \mu^2}\right)\left(\frac{\partial R}{\partial p_g}\right)^2}{\left(\frac{\partial R}{\partial \mu}\right)^3} > 0 \, . \tag{27}$$

Thus, a constant compliance incentive and higher use fees require more monitoring expenditures. Moreover, monitoring costs are strictly convex in use fees. Conversely, low use fees are associated with lower monitoring costs, and the latter are not directly productive beyond their contribution to the prevention of undesirable resource use behavior.

4. Optimal Penalties

In this section, we analyze the properties of a penalty function that will permanently discourage noncompliance with public resource use regulations. Therefore, suppose that if at date t the agency observes that commercial user i on allotment a has been cheating on the public resource extraction path, then the lease is permanently terminated and the penalty $P(a)$ is imposed.[13] Throughout, we assume that the commodity user is self interested, has full information regarding the monitoring and enforcement strategy of the agency and the form of the penalty function, is risk neutral, and forms rational expectations. The government maximizes the expected discounted net present value of the sum of the commodity user's net returns, noncommodity user net benefits, and net government revenue.[14]

To specify the second best optimal use policy on any given allotment, first we iden-

[13] Section 43 CFR 4150.3 provides for penalties for willful unauthorized commercial use on federal lands to include the value of stock consumed – defined in 43 CFR 4150.3(c) as three times the private commercial use lease rate in the state where the violation occurs, the value of damage to public resource and other Federal property, the cost of detecting, investigating, and enforcing violations, and the cost of impounding the trespassing livestock.

[14] Throughout this section, the assumption is that the government is efficient at tax, fee, and fine collection, and at providing government goods and services. This implies that the user fee is a cost to the commodity user and a benefit to society with equal and opposite weights in the social planner's objective function, regardless of the commodity user's compliance decision. It also implies that a noncompliant user's penalty imposed by the agency at the first monitoring time is a cost to the commodity user and a benefit to society, with equal and opposite weights in the planner's problem. As a result, both of these terms drop out of the social planner's objective functional.

One could extend the model to include an increasing, convex cost of imposing and collecting the penalty P, say $c_P(P),\ c_P(0)=0,\ c_P'(0)=1,\ c_P''(P)\geq 0\ \forall\ P\geq 0$, possibly with an upper limit due to political constraints, so that $\lim_{P\nearrow P^{\max}} c(P)=\infty.$ These extensions complicate the analysis and are the subject of ongoing work. In particular, if the upper limit $P^{\max}$ is binding, a positive rate of noncompliance can exist in equilibrium.

tify the expected net benefits to commodity users, noncommodity users, and society. The expected wealth of a noncompliant commercial user is

$$\overline{W}_{NC}(a,i) = \int_0^\infty \mu(a)e^{-\mu(a)t}\left\{\int_0^t e^{-r\tau}\left[v(x(\tau),s(\tau),a,i) - p_g\overline{s}^\infty_{Public}(a)\right]d\tau - e^{-rt}P(a)\right\}dt\,. \qquad (28)$$

The leading term in the outer integral is the probability density function for the first monitoring time. As noted above, this distribution is without memory and therefore leads to a time autonomous decision rule for the noncompliant commodity user, regardless of his or her type, if and only if it is generated by a stationary exponential distribution, i.e., $\phi(a,t) = \mu(a)e^{-\mu(a)t}$, for some constant $\mu(a) > 0$. The integral inside the braces is the discounted present value for the noncompliant commodity user for the period of time that he or she is not observed out of compliance with the terms of the resource use contract. The last term inside the braces is the present value of the additional penalty assessed on the noncompliant user at the first monitoring time. Integrating by parts in a manner similar to the previous section lets us rewrite this as

$$\overline{W}_{NC}(a,i) = \int_0^\infty e^{-(r+\mu(a))t}\left[v\big(s(t),x(t),a,i\big) - p_g\overline{s}^\infty_{Public}(a) - \mu(a)P(a)\right]dt. \qquad (29)$$

Note that, as in section 3.1 above, with the constant real discount rate equal to $r+\mu(a)$, this objective functional is time autonomous.

Our primary interest is in the marginal commodity user who has been in compliance for long enough to reach the second best socially optimal steady state, and who considers the net benefit of a noncompliant strategy from that point onward. The Hamilton-Jacoby-Bellman equation for this infinite horizon time autonomous optimal control problem can be written in the form,

$$\begin{aligned}[r+\mu(a)]\overline{W}_{NC}(a,i) = \Bigg[& v\Big(s_{NC}(0,a,i), \overline{x}^{\infty}_{\text{Public}}(a), a, i\Big) - p_g \overline{s}^{\infty}_{\text{Public}}(a) \\ & + \frac{\partial \overline{W}_n(a,i)}{\partial x}\bigg|_{\overline{x}^{\infty}_{\text{Public}}(a)} \times \Big[f(\overline{x}^{\infty}_{\text{Public}}(a), a) - s_{NC}(0,a,i) \Big] \Bigg] - \mu(a)P(a). \end{aligned} \tag{30}$$

The first term in the square brackets on the right-and-side of this equation, which appears on the first line, is the current flow of net returns obtained from moving from the compliant long-run equilibrium $\left(\overline{s}^{\infty}_{\text{Public}}(a), \overline{x}^{\infty}_{\text{Public}}(a)\right)$ to the noncompliant extraction path beginning at $\left(s_{NC}(0,a,i), \overline{x}^{\infty}_{\text{Public}}(a)\right)$ for user type *i* on allotment *a*. The second term in the square brackets, which appears on the second line, is the shadow price of the resource stock at time 0 and the compliant long-run equilibrium level $\overline{x}^{\infty}_{\text{Public}}(a)$ times the negative net growth rate of the resource stock that results from the more intensive extraction rate of a noncompliant strategy. The last term on the right-hand side is the product of the (constant) hazard rate for the first monitoring time times the penalty for being caught in a noncompliant strategy.

Recall from the previous section that the wealth of a compliant user at the long-run equilibrium solution is

$$W_C(a,i) = \frac{1}{r}\Big[v(\overline{s}^{\infty}_{\text{Public}}(a), \overline{x}^{\infty}_{\text{Public}}(a), a, i) - p_g \overline{s}^{\infty}_{\text{Public}}(a) \Big] \geq 0 \ \forall \ i \in I. \tag{31}$$

The inequality on the right-hand side is a necessary condition for incentive compatibility when the agency cannot identify, choose, influence, or learn the commodity user's type. This condition simply says that the discounted present value of the net benefit flow from compliant commodity use on any given allotment is positive for all possible commodity users. Thus, incentive compatibility places an *upper bound* on the use fee,

$$p_g \le \inf_{i \in I} \frac{v(\overline{s}^{\infty}_{\text{Public}}(a), \overline{x}^{\infty}_{\text{Public}}(a), a, i)}{\overline{s}^{\infty}_{\text{Public}}(a)}. \tag{32}$$

In other words, incentive compatibility requires that the commercial use fee must be less than the minimum all across user types of the average value product of the harvest rate.

An optimal penalty function $P(a)$ discourages any commercial user, regardless of his or her type, from choosing a noncompliant strategy. Therefore, incentive compatibility also requires

$$\begin{aligned}\sup_{i \in I} \Bigg\{ & v\Big(s_{NC}(0,a,i), \overline{x}^{\infty}_{\text{Public}}(a), a, i\Big) - \left(\frac{r+\mu(a)}{r}\right) v(\overline{s}^{\infty}_{\text{Public}}(a), \overline{x}^{\infty}_{\text{Public}}(a), a, i) \\ & + \left(\frac{\mu(a)}{r}\right) p_g \overline{s}^{\infty}_{\text{Public}}(a) + \left.\frac{\partial \overline{W}_{NC}(a,i)}{\partial x}\right|_{\overline{x}^{\infty}_{\text{Public}}(a)} \Big[f(\overline{x}^{\infty}_{\text{Public}}(a), a) - s_{NC}(0,a,i) \Big] \Bigg\} \le \mu(a) P(a).\end{aligned} \tag{33}$$

This is an algebraic transformation of the compliance condition $\overline{W}_{NC} - W_C \le 0 \ \forall \ i \in I$ in the previous section, extended here to include the penalty function. This places a lower bound on the product of the constant hazard rate for monitoring times the penalty that is imposed on a noncompliant user. In other words, a lower monitoring rate – which by (26) is associated with a lower user fee – requires a higher penalty for noncompliance in order to permanently discourage noncompliant resource exploitation by all commodity users.

Intuitively, on each allotment the penalty for being caught and punished pursuing a noncompliant resource use program has to be large enough that the discounted present value of the expected net benefit from cheating is nonpositive for any user, regardless of type. This implies that almost all (that is, all except for a set of measure zero) commercial users on all allotments optimally choose a compliant strategy in a subgame perfect Nash equilibrium.

5. Conclusions

Commercial use of public resources is a source of intense conflict and political debate. A primary source of this conflict is the diversity of interest groups competing for the benefits generated by those resources. Property rights and use rights are not well defined and it is unlikely that this will change in the foreseeable future. There also is ample evidence that commercial users of public resources pay use fees that generically have the appearance of large subsidies. We analyze this economic problem through a dynamic natural resource management game.

Low use fees let commercial users capture more rents from commodity use of public resources. This increases the incentive to comply with mandated harvest rates and other regulations. Optimal contracts thus include use fees that are lower than what are typically described as competitive rental rates in a private market.

Furthermore, an optimal contract includes random monitoring of the resource use path of the commodity user. Randomness and independence prevent strategic learning by noncompliant users. This avoids wasteful efforts to disguise their noncompliant behavior.

An optimal public resource use policy also includes a penalty function for noncompliance beyond permanently terminating the use contract. The penalty that is assessed for being caught and punished for noncompliant behavior must be large enough that the commercial user who would profit the most from cheating has a negative expected return from doing so.

In closing, it is at least somewhat interesting to note that these attributes of an optimal public resource management program appear to reflect many aspects of the longstanding approach to public grazing policy on Federal lands. As figure 1 illustrates, Federal grazing fees have remained low in real terms relative to private rental rates throughout the Western United States for the past 100 years. BLM and USFS range conservationists randomly monitor the grazing activities of public grazing leaseholders in each grazing season. The incidence of major disputes on Federal grazing lands which resulted in penalties being assessed is extremely low – less than a handful of cases have occurred in the eleven Western states in the last 30 years. Finally, the penalties assessed in the most widely publicized of these disputes were very large – in addition to permanently terminating the grazing lease, all capital improvements on the leased land were confiscated and the trespassing ranchers' livestock were rounded up and sold at auction. This appears to represent at least an approximate and practical application of the principle of extracting any and all of the net benefits that these ranchers could have gained from pursuing noncompliant resource extraction strategies.

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Figure 1. Real Public and Private Grazing Fees.

2009 $ per Animal Unit Month

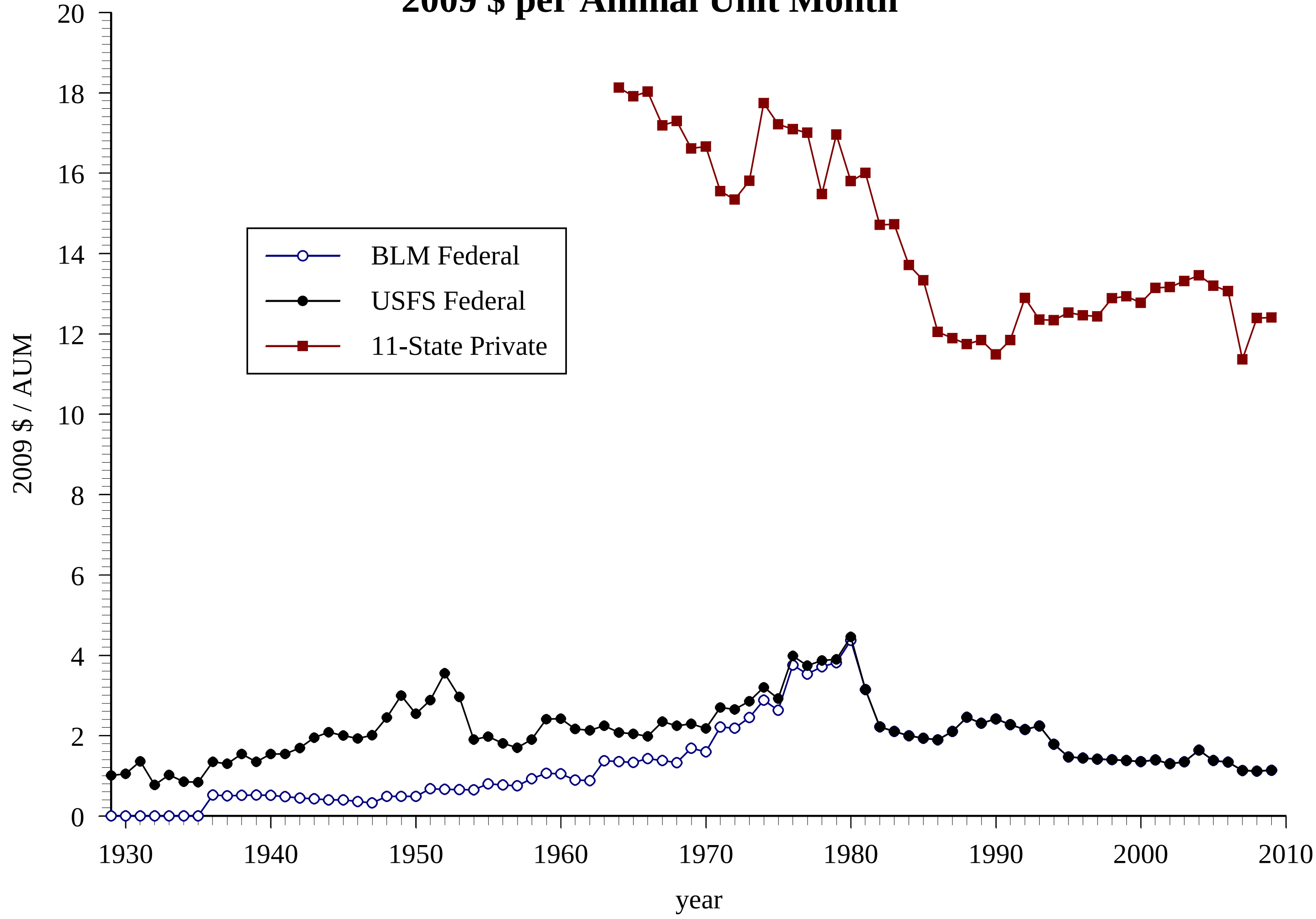

Figure 2. Phase Diagram for Public and Private Optimal Grazing Paths.

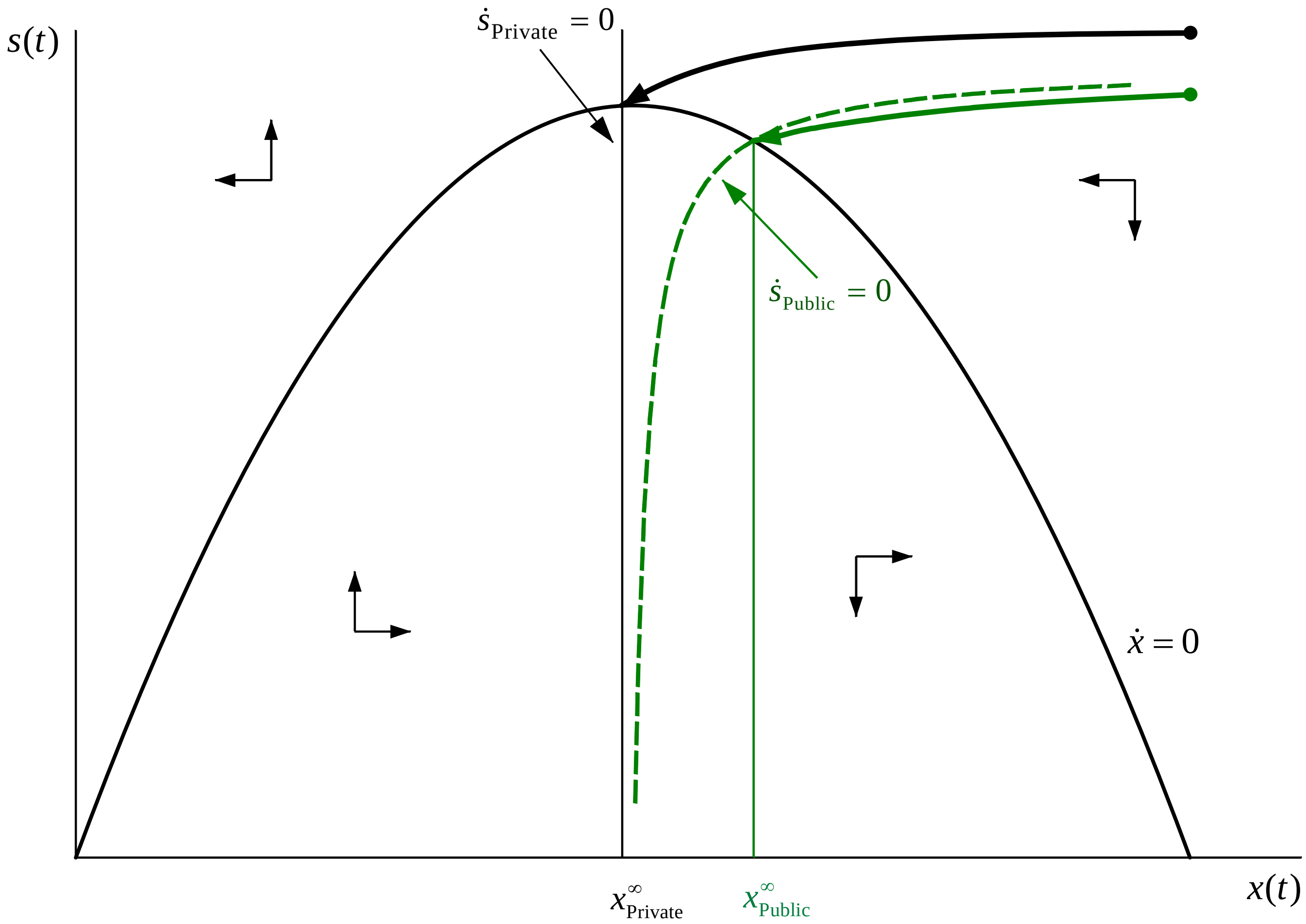

Figure 3. Long-Run Equilibrium Dynamic vmp(x).