Optimal Contracts for Discouraging Deforestation with Risk Averse Agents

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Abstract

There is an emerging consensus that carbon emissions must be limited. An attractive approach to promoting carbon reductions is to encourage reductions in deforestation. But any such strategy must confront a basic problem: agents that might be induced to reduce their actions which would reduce forests have private information about their opportunity costs. This concern seems particularly likely to apply in situations where there are significant related risks, as agents seem highly likely to differ in their tolerance for risk. In this paper, I investigate a contracting scheme designed to mitigate the asymmetric information problem where agents are heterogeneous in their tolerance for risk. Mechanisms that recognize the potential insurance value associated with the acquisition of sequestration services, and that pay attention to landholders' private information about risk tolerance, offer a sensible way to approach the problem. These contracts are generally a cheaper approach to maintenance of forests than a simple, constant per-unit subsidy.

Keywords: Incentive Contracting; Risk aversion; Deforestation

1 Introduction

Reducing emissions of greenhouse gases to lessen the impact of future climate change is likely to result in large net benefits globally. However, reducing emissions will impose significant costs.[1] One way to reduce costs that has received a great deal of attention is the use of offsets, a particularly promising type of which involves carbon sequestration in forests.[2]

Despite their potential to reduce costs, offsets have a basic problem stemming from asymmetric information. Sellers of offsets have private information about their opportunity costs of mitigating or abating emissions. This implies that only the seller knows whether she would have undertaken the activity in the absence of a payment for the offset. This leads to the oft-expressed concern about "additionality": offsets are not true incremental adjustments if they would have happened anyway.[3] To legitimately use offsets to meet emissions reduction targets, such as those stipulated under international treaties, the government must be able to verify that they are additional. Procedures that fail to clearly identify the increment of sequestration produced have been soundly criticized (Richards and Andersson, 2001), and, thus, concerns about additionality have been a stumbling block for inclusion of offsets, particularly those from avoided deforestation, in international efforts to address climate change.[4]

[1] Nordhaus (2008) estimates the costs of achieving optimal abatement of greenhouse gas emissions through control of industrial CO_2 emissions as $2.2 trillion.

[2] Numerous studies have found that forest sequestration can be used to offset a substantial share of carbon emissions at costs that are similar to or lower than those associated with energy-based mitigation approaches (Richards and Stokes, 2004; van Kooten et al., 2004; Stavins and Richards, 2005).

[3] More generally, additionality arises whenever the government seeks to procure an impure public good from agents with private information. It has also been studied in the context of government subsidies for R&D and job creation (Picard, 2001; Gorg and Strobl, 2007).

[4] See Plantinga and Richards (2010) for discussion. Even when a private entity such as a regulated

One obvious aspect of asymmetric information in the problem of encouraging avoided deforestation is the potential for agents to have heterogeneous risk attitudes. Consider a landowner who is contemplating cutting down trees on a plot of land so as to convert the land to some alternative use. This alternative could be growing crops or some variant of real estate development; the important point is that the development in question is subject to some form of risk. Offset contracts in this setting have an interesting element generally absent in other incentive contracts schemes: they provide insurance in that they shields the landowner from any risk associated with the alternative land use. Naturally, the value of this insurance depends on the landowner's tolerance for risk. Highly risk-averse landowners are likely to place a high value on mitigating the risk associated with the outside option and so would accept relatively smaller payments to participate while less risk-averse landowners would require more substantial payments. As usual, the optimal contracting scheme is constrained by the need to induce truthful revelation of risk attitudes, which is done by allocating information rents to the privately informed agents. What is new here is the ability of government to reduce these information rents, and hence government expenditures, via the insurance that contracts offer risk averse landowners.

The optimal contract menu I derive in this paper achieves cost savings through two elements. First is the familiar feature of incentive contracts whereby the principal reduces payments distorting for the more easily attracted types. The second element is

emissions source purchases offsets, it faces the same problem as the government does with asymmetric information. As long as it is required to verify the purchase of additional offsets, a private entity will want to avoid paying for non-additional offsets as well as limiting its expenditures on the offsets that are additional. However, sellers have an incentive to exploit the asymmetric information by claiming to have high opportunity costs.

due to the presence of risk-aversion among agents: by capturing part of the insurance value that risk-averse landowners would otherwise realize. The combination of these elements renders optimal contracts substantially less expensive than a uniform per-unit subsidy – the policy instrument most commonly proposed in practice. This insurance dimension is absent from the extant literature on optimal offset contracts, which generally treats landowners as risk-neutral (Bourgeon et al., 1995; Montero, 2008; van Benthem and Kerr, 2013; Mason and Plantinga, 2013).

In this paper, I focus my analysis on a government agency seeking to contract with private landowners to set parcels of land aside, guaranteeing the forests on that land will not be harvested. My theoretical model adapts a standard principal-agent framework (Laffont and Tirole, 1993; Salanié, 2005) to the problem at hand. The principal's objective is to maximize expected net societal benefits from afforestation and avoided deforestation (collectively, forestation), where forestation benefits are tied to an exogenously determined carbon price and costs are defined in terms of government expenditures. The problem may be regarded as one of adverse selection: the principal is assumed to know the distribution over landowners' opportunity costs, but not the realization for any particular individual; as a result, the amount of land any particular agent would have placed in forest absent a payment is not observed by the principal.[5] Marginal social benefits equal an exogenously determined value V that can be thought of as the marginal value of those forests in

[5] Viewed in this way, the problem is one of hidden information. van Benthem and Kerr (2013) consider a similar framework to mine, but do not consider the potential for the principal to reduce information rents by the use of two-part contracts; instead, they focus on the role of landowner size on contract efficiency. Using a variation of the law of large numbers, they argue that efficiency increases with the size of the landowner's holdings. Montero (2008) considers a problem in which the government wishes to buy a certain amount of offsets from a group of firms whose costs are private information; once a firm commits to a certain amount of offsets its actions can be perfectly monitored. In this framework, Montero constructs an auction mechanism that induces firms to perfectly reveal their cost curves.

reducing carbon stocks. As is common in the optimal contracting literature, each contract entails two ingredients, which I interpret as a price per unit of land set aside together with a land transfer from the agent to the Government. The nature of the optimal contracting scheme is related to key elements of the underlying distribution characterizing agents' risk attitudes. In general, the optimal contract scheme is considerably less expensive than a uniform payment scheme. The implication is that the contract scheme will generally be strongly welfare-enhancing. These results have considerable practical importance, as they suggest sequestration contracts need not require huge governmental outlays. These contracts also identify ex post how much of the forestation undertaken by each agent is additional relative to what they would have done without a contract. This is the information a regulatory agency needs to ensure proper accounting of offsets credits.

2 Model

Suppose there is a governmental agency, which I term the "principal," that is interested in preventing deforestation. Each unit of land kept in forest generates an amount of sequestration, which yields a benefit V to the principal. This induced benefit can naturally be thought of as a value of marginal product, which depends on the price of carbon (which can either be explicit, if a formal carbon market exists, or implicit, as with an emissions trading scheme) and the marginal product of forest land in a sequestration production function.[6] For expositional concreteness, I will occasionally refer to V as the "value of marginal product," with the understanding that this value is defined with respect to the

[6] This interpretation implicitly assumes that each acre of land stores the same quantity of carbon.

production of sequestration services. The land that may be placed in forest is managed by a private entity, whom we call the "agent." In practice, the principal will interact with a number of agents; in the description of the model presented below I focus on the interaction with a canonical agent. Agents are characterized by their risk attitude; for expositional concreteness, I assume each type of agent exhibits constant relative risk aversion, so that their von Neumann Morgenstern utility function is

$$u(\pi) = \pi^{1-\theta}. \tag{1}$$

In this framework, θ is the index of relative risk aversion, which is private information to the agent. I assume that agents differ only in terms of their risk preference. In particular, the size and shape of the land they might protect from deforestation is not correlated with type. The set of agent types is $\Theta = [\underline{\theta}, \overline{\theta}]$ where $0 \leq \underline{\theta} < \overline{\theta} < 1$.

While the principal does not know any particular agent's type, he does know the probability distribution function $f(\theta)$ over θ,[7] as well as the associated cumulative distribution function $F(\theta)$ and hazard rate

$$h(\theta) = \frac{f(\theta)}{1 - F(\theta)}.$$

I assume these functions are continuous in θ, and that $h'(\theta) > 0$.[8]

[7] This may not be an innocuous assumption. For an analysis of a model in which the governmental agency does not know this distribution with certainty, see Bushnell (2011). An alternative to employing the optimal contracting approach we outline here would be to set a baseline level of activity, and pay agents for levels in excess of that baseline (Horowitz and Just, 2011). This baseline approach might result from ignorance regarding the distribution of firm types, or it could reflect institutional constraints that preclude the use of a contracting scheme such as the one we derive below.

[8] The hazard rate is the conditional probability an agent's type belongs to the interval $[\theta, \theta + d\theta]$, given the agent is known to be of type θ or larger. The condition $h'(\theta) > 0$ holds for many distributions, including

To focus the discussion, I suppose the contractual relation in question is one where the agent may sell the principal an easement for a fraction of her land x; in this way, questions of permanence are finessed. If the agent sells a fraction x of her land she collects a known payment $R(x)$ for that parcel.[9] The value associated with any residual fraction of land $1-x$ is stochastic. One can think of uncertain future payoffs associated with transforming the land into some alternative use, perhaps croplands or development; the value associated with that future alternative is unknown. For simplicity, I suppose there are two possible values the land may take after this uncertainty is resolved, namely p_1 and p_2; the probabilities of these outcomes are λ and $1-\lambda$, respectively. I define for later use

$$\overline{p} \equiv \lambda p_1 + (1-\lambda) p_2,$$

the expected value of the stochastic payment. An agent of type θ that opts out of any easement contract, and so places all her land in the risky category, obtains a payoff equal to her expected utility

$$\begin{aligned} EU_0(\theta) &= \lambda u(p_1) + (1-\lambda) u(p_2) \\ &= \lambda p_1^{1-\theta} + (1-\lambda) p_2^{1-\theta}. \end{aligned}$$

The principal's goal is to maximize expected net social surplus, which is the sum of the imputed value of land placed into easement, Vx, plus the expected utility earned by the agent, $EU(x,p;\theta)$, less the net cost of acquisition, which depends on the social cost

the one I employ in the empirical application below.

[9] It will occasionally be expositionally convenient to think of this payment as combining a per-unit payment p and a transfer T, so that $R(x) = p(x)x - T(x)$. At first blush, this would seem to introduce an extra degree of freedom. But as I note below, the agent's optimal choice of x can be expressed in terms of p and T. Thus, there is a unique combination of p and T that would correspond to R, subject to the constraint that x is privately optimal for the agent given that combination of p and T.

of raising a dollar of government funds, $\mu > 1$.[10] Thus, the principal's objective functional is

$$\Omega \equiv \int_{\underline{\theta}}^{\overline{\theta}} \Big(Vx(\theta) - \mu R(\theta) + EU(x,p;\theta)\Big) f(\theta) \mathrm{d}\theta,$$

where $x(\theta)$ is the amount of land an agent of type θ places in forest and $R(\theta) = R(x(\theta))$ is the payment to the agent. Note that the agent's type is the only source of randomness in the principal's objective function. I assume that the value to the principal and social cost of funds are such that $V < \mu\overline{p}$; if this were not true the problem would be trivial, in that the principal would offer a per-unit price of $\overline{p}$ to all agents (possibly with a fixed transfer from the agent), and so acquire all land.

3 Landowner Behavior

Because landowners are risk averse, they can benefit from selling part of their land to the government. Doing so allows the landowner to shed some of the risk associated with the uncertain potential future payoffs. The value of reducing this risk will differ by amount of land sold and by the agent's attitudes towards risk. In particular, if the landowner is

[10] The marginal cost of public funds summarizes the distortion in resource allocation that arises when the government funds its expenditures by raising taxes (Dahlby, 2008, p. 1). While its particular value depends on a host of assumptions regarding labor market elasticities, inter-temporal consumption elasticities and taxation method, their seems to be a consensus that the value will be larger than 1.1. For example, Browning (1987) estimates its value as between 1.1 and 4.0; Ballard and Fullerton (1992) find values between 1.1 and 1.99 (if funds are raised by increasing marginal tax rates); and Dahlby (2008, Table 6.1, p. 150) suggests a range between 1.150 and 1.557. In a numerical evaluation of environmental taxes, Bovenberg and Goulder (1996, Table 4) suggest that realistic values might fall between 1.11 and 1.41. While these various pieces of evidence suggest a broad range of potential values, most estimates fall below 1.5; our choice of 1.3 represents something of a compromise between the lower bound of 1.1 and this apparent upper bound of 1.5.

able to sell a fraction x at an average price $\tilde{p}$, her expected utility becomes

$$EU(x,\tilde{p}) = \lambda u\Big((1-x)p_1 + \tilde{p}x\Big) + (1-\lambda)u\Big((1-x)p_2 + \tilde{p}x\Big).$$

For the specified amount of land to be transferred, the agent's reservation price p^r sets this expected utility equal to the *ex ante* expected utility EU_0:

$$\lambda u\Big((1-x)p_1 + p^r x\Big) + (1-\lambda)u\Big((1-x)p_2 + p^r x\Big) = \lambda u(p_1) + (1-\lambda)u(p_2).$$

With the iso-elastic utility function in (1), p^r is implicitly defined by

$$\lambda\Big((1-x)p_1 + p^r x\Big)^{1-\theta} + (1-\lambda)\Big((1-x)p_2 + p^r x\Big)^{1-\theta} = \lambda p_1^{1-\theta} + (1-\lambda)p_2^{1-\theta}. \qquad (2)$$

In general, this reservation price is upward-sloping in x, and $p^r = \overline{p}$ at $x = 1$ for all θ, *i.e.*, at the actuarially fair price. Although all agents equally value the last increment of land, more risk averse types would accept lower prices for smaller fractions. Alternatively, viewing the principal's purchase as a form of insurance, more risk averse agents would be willing to pay more for insurance, particularly when the level of insurance is large. Moreover, so long as the worst outcome p_2 yields a positive payoff, the reservation price for the first increment of land is positive, and declining in θ, the index of relative risk aversion.

I illustrate these effects in Figure 1. The diagram is based on an example with equally likely states ($\lambda = \frac{1}{2}$), where the outcomes are $p_1 = .9, p_2 = .1$. Thus, the expected value of a unit of land is $\overline{p} = \frac{1}{2}$. In this diagram, I show the reservation prices for three types of agents, with risk aversion parameters $\theta = \frac{1}{4}$ (the dashed curve), $\frac{1}{2}$ (the solid curve) and $\frac{3}{4}$ (the curve marked with dots, short dashes and long dashes). A key point here is that more risk averse agents would supply land more elastically and at lower prices than would relatively risk tolerant agents. That agents differ in terms of their supply elasticities suggests that a buyer might be able to benefit from price discrimination, in particular by demanding a larger transfer payment from more risk averse agents.

To expand on this theme, imagine an agent with index of relative risk aversion θ who has been offered a payment scheme $R(x)$. Such an agent would wish to transfer the amount of land:

$$x^*(\theta) = \textbf{argmax} \left\{ \lambda\Big((1-x)p_1 + R(x)\Big)^{1-\theta} + (1-\lambda)\Big((1-x)p_2 + +R(x)\Big)^{1-\theta} \right\}.$$

Proceeding directly, it is straightforward to characterize the optimal amount x^*:

$$\lambda\Big((1-x^*)p_1 + R(x^*)\Big)^{-\theta}\Big(R'(x^*) - p_1\Big) + (1-\lambda)\Big((1-x)p_2 + R(x^*)\Big)^{-\theta}\Big(R'(x^*) - p_2\Big) = 0. \quad (3)$$

The behavioral rule in eq. (3) serves as a constraint on the principal's choice of contracts.

Before moving on to a discussion of the principal's optimal menu of contracts, I note that if the contract is linear, so that $R = px - T$, there is an equivalence between contracts quoted as combinations (p, T) and contracts quoted as combinations (x, R). In this case, the optimal level of land transferred to the principal can be expressed as

$$x(p, T; \theta) = \frac{p_1\Lambda(p) - p_2 + T(1-\Lambda(p))}{p_1\Lambda(p) - p_2 + p(1-\Lambda(p))}, \quad (4)$$

where

$$\Lambda(p) = \left[\left(\frac{1-\lambda}{\lambda} \right) \left(\frac{p-p_2}{p_1-p} \right) \right]^{\frac{1}{\theta}}.$$

It is easy to see that $\Lambda \leq 1$ when $p \leq \overline{p}$, as is the case here, with strict inequality when $p < \overline{p}$. Moreover, when $p \in (p_2, p_1)$, again as will be the case in this problem, then Λ is strictly positive.

4 Optimal contracts

The government wishes to maximize its objective functional Ω, expected net social surplus. To accomplish this goal it designs a menu of contracts of the form $\{x(\theta), R(\theta)\}$. The choice of contract menu is subject to an incentive compatibility constraint: intuitively, an agent can guarantee a positive payoff by imitating a lower type agent; to induce the agent to accept the contract intended for his type, the agent must receive some of the rent, commonly referred to as an *information rent* in the literature.

To characterize this incentive compatibility constraint, I denote the expected utility earned by a type θ agent who chooses the contract intended for a type $\hat{\theta}$ agent by $EU(\hat{\theta}, \theta)$. The incentive constraint requires that each type of agent finds it optimal to select the contract intended for her type, *i.e.*, that EU is maximized at $\hat{\theta} = \theta$. Making use of the functional form in eq. (1), the impact of a slight change in the announced type upon payoffs can be expressed as

$$\partial EU(\hat{\theta}, \theta)/\partial\hat{\theta} = \lambda \partial \pi_1(\hat{\theta})^{1-\theta}/\partial\hat{\theta} + (1-\lambda)\partial\pi_2(\hat{\theta})^{1-\theta}/\partial\hat{\theta},$$

where

$$\pi_k(\hat{\theta}) = p_k\left(1 - x(\hat{\theta})\right) + R\left(\hat{\theta}\right).$$

The incentive compatibility constraint is that this marginal effect vanishes when evaluated at $\hat{\theta} = \theta$. Straightforward algebra yields:

$$\left[\lambda\pi_1^{-\theta} + (1-\lambda)\pi_2^{-\theta}\right]R'(\theta) = \left[\lambda p_1\pi_1^{-\theta} + (1-\lambda)p_2\pi_2^{-\theta}\right]x'(\theta).$$

Then, since $R(\theta) = R(x(\theta))$, one may derive:

$$R'(x) = \left(\frac{\lambda\pi_1^{-\theta}}{\lambda\pi_1^{-\theta} + (1-\lambda)\pi_2^{-\theta}}\right)p_1 + \left(\frac{\lambda\pi_2^{-\theta}}{\lambda\pi_1^{-\theta} + (1-\lambda)\pi_2^{-\theta}}\right)p_2. \tag{5}$$

As this constraint must be satisfied for all θ, it induces a differential equation for $R(x)$; the solution to this differential equation gives the revenue function $R(x)$ that the principal's optimal contract menu must honor.

I next define the information rents earned by an agent of type θ as

$$\nu(\theta) \equiv EU(\theta,\theta) - EU_0(\theta).$$

Making use of this construct, the principal's objective functional may be rewritten as

$$\Omega \equiv \int_{\underline{\theta}}^{\overline{\theta}} \left[Vx(\theta) - \mu R(x(\theta)) + EU_0(\theta)\right]f(\theta)\mathrm{d}\theta - \int_{\underline{\theta}}^{\overline{\theta}} -\nu(\theta)f(\theta)\mathrm{d}\theta.$$

The optimal contract scheme is subject to the incentive compatibility constraint. Since all payments are linked to the payments offered to the least risk-averse agent, it follows that the optimal scheme reduces this agent's information rents to zero, *i.e.*, $v(\underline{\theta}) = 0$; this forms a sort of boundary condition. Then, applying integration by parts to the second integral while noting that $v(\theta)(1 - F(\theta)) = 0$ at both $\theta = \overline{\theta}$ (since $F(\overline{\theta}) = 1$) and $\theta = \underline{\theta}$ (since $v(\underline{\theta}) = 0$) yields[11]

$$\Omega = \int_{\underline{\theta}}^{\overline{\theta}} \left\{ Vx(\theta) - \mu R\left(x(\theta)\right) + EU_0(\theta) + v'(\theta)\left(\frac{1 - F(\theta)}{f(\theta)}\right)\right\} f(\theta)\mathrm{d}\theta. \tag{6}$$

It is now straightforward to derive the elements in the optimal menu of contracts: one simply maximizes Ω element by element, for each value of θ. Because the contract choice induces a level of land, one can view the problem as one of determining the principal's optimal level of x at each θ, subject to the behavioral constraint posed by eq. (4). Taking this interpretation, one obtains the first-order conditions for an interior solution:

$$V - \mu R'(x) + \frac{1 - F(\theta)}{f(\theta)} \frac{\partial v'(\theta)}{\partial x} = 0. \tag{7}$$

Notice that this condition dictates $R'\left(x(\overline{\theta})\right) = V/\mu$, as by definition $F(\overline{\theta}) = 1$.

The optimal contract scheme can also be thought of as the solution to a system of two first-order differential equations, one induced by the observation that the left-hand side of eq. (7) must not change as θ is varied, and the other given by the incentive constraint eq. (5). The solution to this system of differential equations is pinned down by two boundary conditions. One boundary condition is induced by the stipulation that $v(\underline{\theta}) = 0$, while the other comes from the requirement that $p(\overline{\theta}) = V/\mu$.

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11 Details regarding the information rent function, and the effect of x upon marginal information rents, are relegated to Appendix A.

5 Graphical Illustration

To illustrate the mechanics of the optimal contracting scheme, consider a stripped down version of the problem, with two agent types: $\theta \in \{.25, .75\}$. The risky prospect landowners start with is described by the two prices $p_1 = .9, p_2 = .1$, which I suppose are equally likely. With these parameters, it is easy to check that the *ex ante* expected utilities are $EU_0 = .551$ for $\theta = .25$ and $EU_0 = .768$ for $\theta = .75$. The first aspect of the optimal contract scheme is the restriction that the least risk-averse agent earn zero information rents, *i.e.*, that she is indifferent between accepting the contract or not accepting the contract. This means the optimal contract for the agent of type $\underline{\theta}$ leaves her on the iso-expected utility curve that goes through the initial payoff combination (the point labeled "endowment" in the figure). At this contract, the type $\underline{\theta}$ sells some land but retains most of it; as a result, the payoff she would earn in state 1 (where the unit value of land turns out to be p_1) is much larger than the payoff she would earn in state 2 (where the unit value of land turns out to be p_2). The combination of these payoffs is indicated as "induced by contract for type $\theta = .25$ in the figure. Because the other type of agent can also adopt this contract, she must obtain the same expected utility as at this contract; this realization places the optimal contract for the type $\overline{\theta}$ agent on the iso-expected utility curve labeled "$EU_1(\theta = .75)$." The optimal per-unit payment to this type of agent, V/μ, reflects the value of land to the principal, as well as the social cost of funds, and induces the type $\overline{\theta}$ agent to transfer most (though not all) of her land to the government. Accordingly, the payoff she would earn in state 1 (where the unit value of land turns out to be p_1) is only slightly larger than the payoff she would earn in state 2 (where the unit value of land turns out to be p_2). The combination of these payoffs is indicated as "induced by contract for type $\theta = .75$ in the figure.

Next, consider an example with three agent types. Figure 3 illustrates the mechanics. As with two types, the least risk-averse agent is induced to select a contract that leaves her on the iso-expected utility curve that goes through the endowment point, and the most risk-averse agent is induced to select a contract that pays her V/μ per unit of land, and at which she chooses to sequester most of her land. Also as in the two agent type example, the most risk-averse agent winds up on an iso-expected utility curve, labeled as $IC_{\overline{\theta}}$ in the figure, that goes through the payoff combination the next less risk averse agent chooses. I call this other agent type θ_2 below. With three agent types, the type θ_2 agent type is more risk averse than the type $\underline{\theta}$ agent, and so this type of agent is induced to select the contract induces a profit combination that lies on *her* iso-expected utility curve that goes through the payoff combination the least risk averse agent winds up with. This curve is labeled as $IC_{\theta=\theta_2}$ in the figure.

In general, the price paid to the type $\overline{\theta}$ agent, together with the incentive compatibility constraint, induces a family of sequences of combinations of price and transfer for all agent types; every member of this family is associated with a particular price paid to the least risk averse agent type. The optimal contract scheme picks out the sequence in this family that delivers the largest expected payoff to the principal.

6 Conclusion

Carbon offsets are a promising approach to reducing the global costs of climate change mitigation, but additionality presents significant obstacles. Besides additionality concerns, it is important that payments do not impose substantial costs on government; otherwise international efforts to promote such schemes will likely be compromised. In particular, I think it is important to recognize that offset contracts provide a variant of insurance in that they allow landholders to shed some of the risk associated with holding the land. I think it highly unlikely that landholders are homogeneous with respect to their risk tolerance. Moreover, an agent's risk tolerance is quintessentially private information. Accordingly, I think there is a real concern that poorly designed mechanisms will be unnecessarily expensive vehicles for delivering forest sequestration services.

Mechanisms that recognize the potential insurance value associated with the acquisition of sequestration services, and that pay attention to landholders' private information about risk tolerance, offer a sensible way to approach the problem. In this paper, I have proposed such a contracting scheme. The scheme I propose will encourage carbon offsets from forestation at minimal cost to the government, subject to the landholders having private information about their risk attitudes. These contracts typically leave some rents in landowners' hands, and so are second-best in nature. But the contracts are generally a cheaper approach to maintenance of forests than a simple, constant per-unit subsidy.[12]

While I analyze optimal contracts when the government purchases offsets, one can imagine cases in which private agents would be the buyers. For example, if energy producers are subject to emissions restrictions, they may be allowed to substitute lower-cost offsets for emissions reductions. In this case, the regulating agency will want to ensure

[12] In a national-scale simulation, Mason and Plantinga (2013) find that for given increases in forest area government expenditures with contracting are about 40% of those with subsidies. In absolute terms, contracts lower expenditures by over $5 billion per year when applied to 60 million acres of land. Since the contracting scheme does not satisfy the equi-marginal principle, private opportunity costs are necessarily higher than under the uniform subsidy. However, we find that this difference is small (about $100 million for a 60 million acre increase) relative to the reductions in expenditures.

that the offsets are additional since non-additional offsets would effectively relax the emissions controls. In this setting, non-additional offsets would be inexpensive and, thus, particularly appealing to emissions sources. If the private agent acts as a monopsonist in the offset market, as the government does in our model, our contracting scheme is a direct remedy for this problem. The regulating agency could require private buyers of offsets to structure contracts following our design. Conditional on their purchasing only additional offsets, private buyers would want to implement our scheme because it minimizes their costs. Future research is needed to investigate the performance of contracts in a competitive market with many private purchasers of offsets.

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Appendix A

Making use of eqs. (1) and (5), the effect of a small change in θ upon information rents can be expressed as:

$$\begin{aligned} v'(\theta) &= \frac{\partial EU(\hat{\theta},\theta)}{\partial \theta}|_{\hat{\theta}=\theta} - EU_0'(\theta) \\ &= \lambda\Big[\ln(p_1)p_1^{1-\theta} - \ln(\pi_1)\pi_1^{1-\theta}\Big] - (1-\lambda)\Big[\ln(\pi_2)\pi_2^{1-\theta} - \ln(p_2)p_2^{1-\theta}\Big]. \end{aligned} \quad (8)$$

One may then derive the marginal impact of x upon marginal information rents as

$$\begin{aligned} \frac{\partial v'(\theta)}{\partial x} &= \lambda p_1 \pi_1^{-\theta}\Big[1+(1-\theta)\ln(\pi_1)\Big] + (1-\lambda)p_2\pi_2^{-\theta}\Big[1+(1-\theta)\ln(\pi_2)\Big] \\ &-\Big\{\lambda\pi_1^{-\theta}\Big[1+(1-\theta)\ln(\pi_1)\Big] + (1-\lambda)\pi_2^{-\theta}\Big[1+(1-\theta)\ln(\pi_2)\Big]\Big\}R'(x). \end{aligned}$$

Combining with eq. (5), one then has

$$\frac{\partial v'(\theta)}{\partial x} = (1-\theta)\Big\{\lambda\pi_1^{-\theta}\ln(\pi_1)\,[p_1 - R'(x)] + (1-\lambda)\pi_2^{-\theta}\ln(\pi_2)\,[p_2 - R'(x)]\Big\}. \quad (9)$$

To facilitate an explanation of the monotonically negative relation between the elasticity of agents' willingness to supply land and relative risk aversion, suppose that $p_2 = 0$. Then $EU_0 = \lambda p_1^{1-\theta}$ and $EU(x,p^r) = \lambda\Big(p_1 + (p^r - p_1)x\Big)^{1-\theta} + (1-\lambda)\Big(p^r x\Big)^{1-\theta}$. Setting these equal gives the implicit relation that defines p^r:

$$1 = \lambda\Big(1 + (\frac{p^r}{p_1} - 1)x\Big)^{1-\theta} + (1-\lambda)\Big(\frac{p^r}{p_1}x\Big)^{1-\theta}.$$

Let $\tau \equiv \frac{p^r}{p_1}x$, and totally differentiate with respect to τ and x to get

$$0 = \lambda\left(1 - x + \tau\right)^{-\theta}[d\tau - dx] + (1-\lambda)\left(\tau\right)^{-\theta}d\tau.$$

It follows that

$$\begin{aligned}\frac{p^r}{p_1} + \frac{x}{p_1}\frac{dp^r}{dx} = \frac{d\tau}{dx} &= \frac{\lambda\left(1 - x + \tau\right)^{-\theta}}{\lambda\left(1 - x + \tau\right)^{-\theta} + (1-\lambda)\left(\tau\right)^{-\theta}} \\ &= \frac{\lambda}{\lambda + (1-\lambda)\left(1 + \frac{1-x}{\tau}^{\theta}\right)},\end{aligned}$$

which is clearly decreasing in θ. Finally, it is easy to see that the elasticity of supply with respect to p^r is positively related to this expression.

Figure 1: The Relation of Agents' Reservation Prices to Risk Aversion

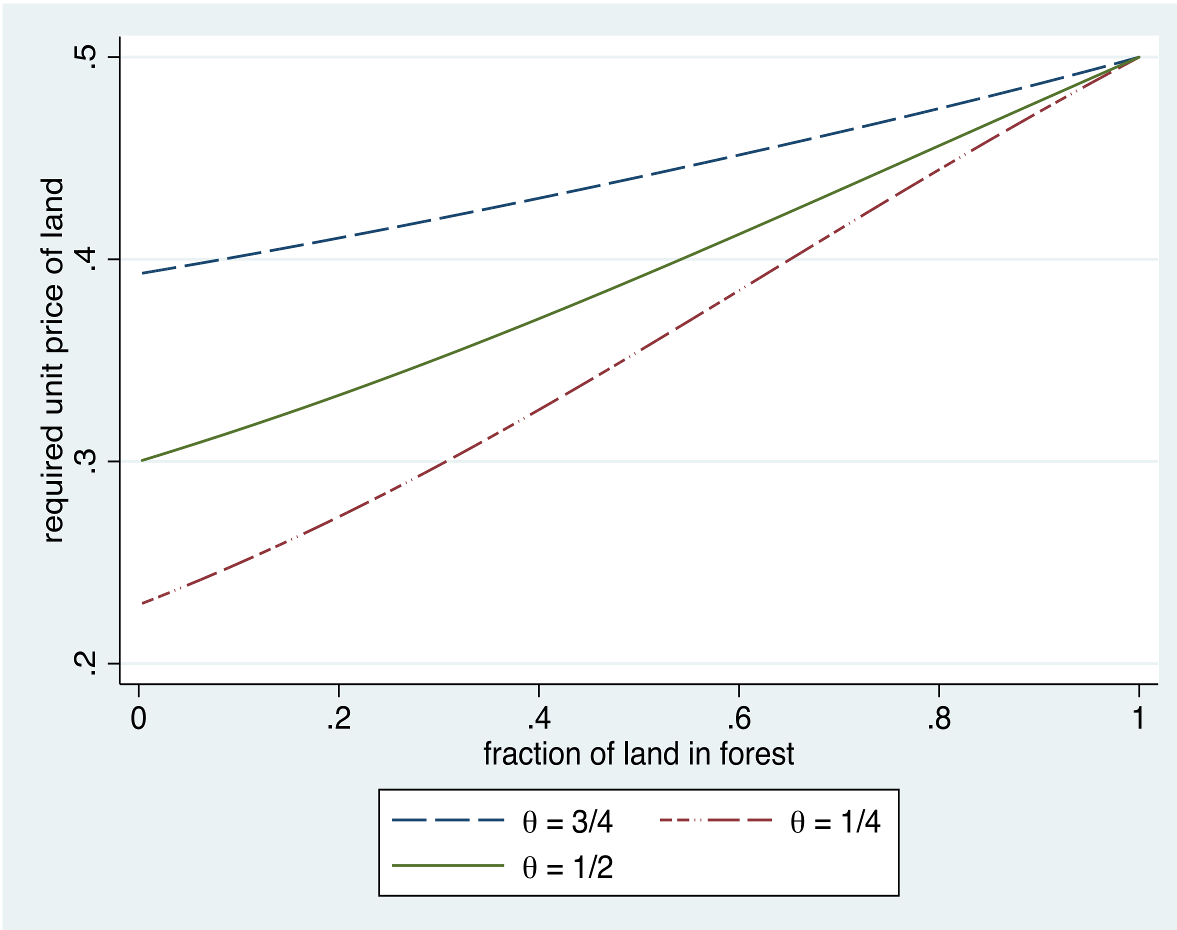

Figure 2: Optimal contracts with two types of agents

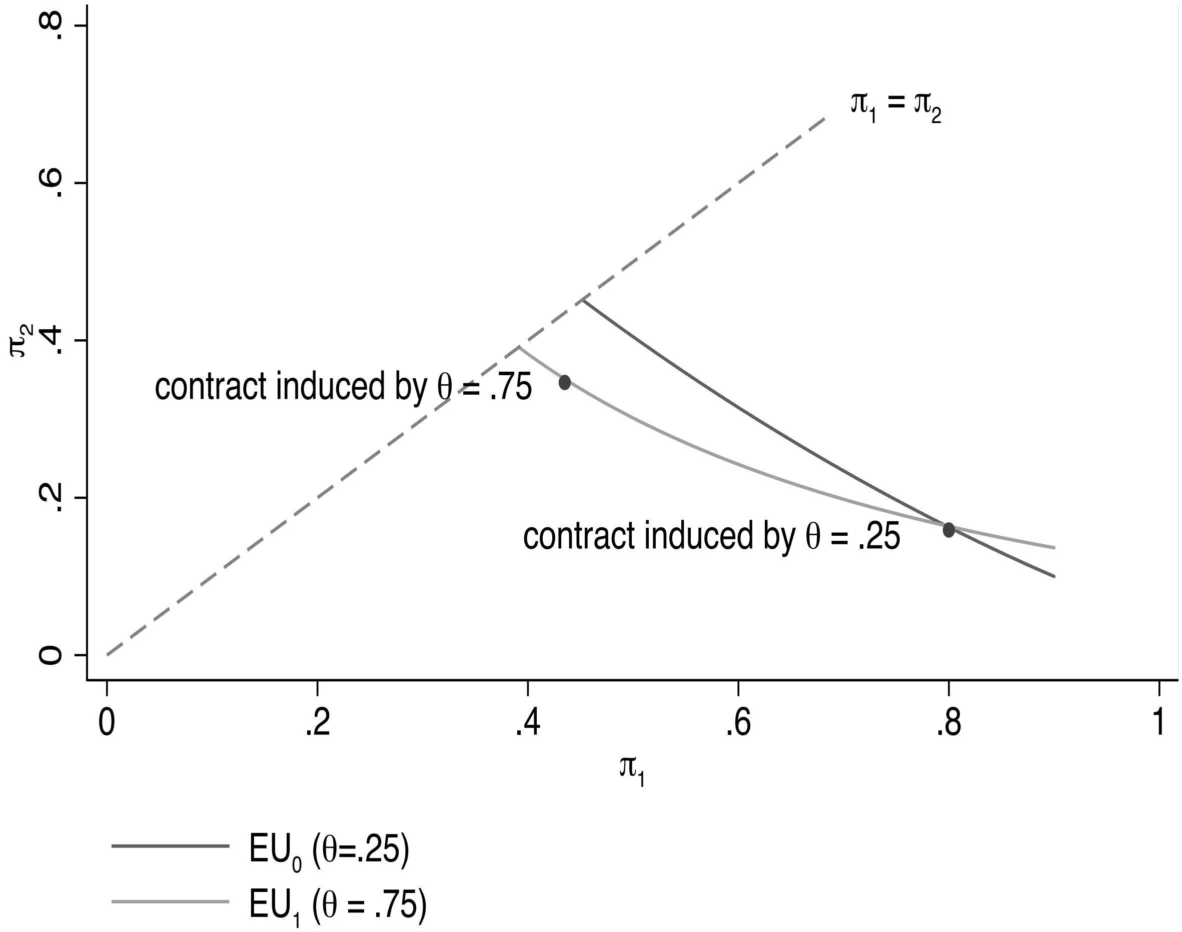

Figure 3: Optimal contracts with three types of agents