Optimal Monitoring and Offset Prices in Voluntary Emissions Markets

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Abstract

Carbon offset markets are modeled as an uninformed regulator who wishes to use a voluntary price instrument to reduce harmful emissions under varying degrees of private information. Regulators offer agricultural producers payments to reduce their emissions for some price per ton relative to the social price of carbon. Abstracting from distributional concerns or costly transfers, we derive optimal contracts for offsets contracts, minimizing welfare losses from adverse selection. The model shows how the level of monitoring and the prices offered should vary depending on the regulator's information. Although existing and proposed policies discount the price that offset producers receive relative to the social cost of carbon to account for the adverse selection, our model argues that optimal offset prices may be above the social cost of carbon for sufficiently high levels of monitoring. Our model also identifies and quantifies the types of firms that produce additional offsets for a given contract, offering guidance on how regulators might better target offset contracts.

1 Introduction

According to the United Nations IPCC, agriculture and deforestation together account for a quarter of global anthropogenic greenhouse gas emissions. However, under most proposals to cap emissions (such as

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Kyoto or the Waxman-Markey Bill in the United States), emissions from sources such as deforestation or agriculture are not capped. Instead, emissions reductions in these sectors are normally incentivized as carbon offset programs where firms receive payments in exchange for agreements to reduce, i.e., offset, emissions. Furthermore, a small but growing part of global climate mitigation efforts is in voluntary offsets markets which allow individuals or organizations to pay offset originators to make carbon reductions in their name. By observing Figure 1, from Ecosystem Marketplace and Bloomberg New Energy Finance, we can appreciate the size and growth of these markets. Before the "Great Recession" of the late 2000s, purchases of voluntary offsets more than doubled in volume annually, and the value of these markets grew at an even faster rate. As the global economy recuperates, that trend is expected to continue for the foreseeable future.

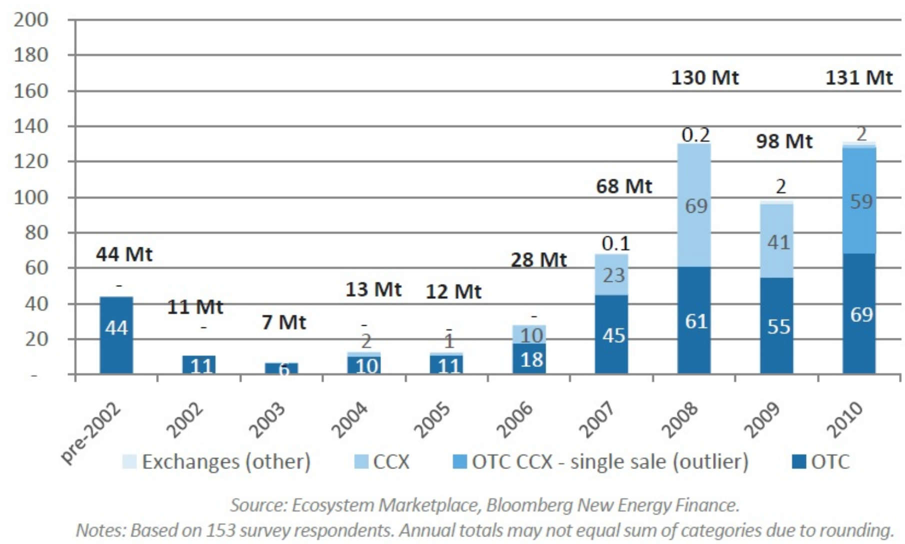

Figure 1 Historic Volume Growth of the Voluntary Carbon Offset Markets

However, there is still a general distrust of whether the greenhouse gas reductions from offset projects are "real" and many have expressed concern that allowing firms in capped sectors to use offsets to reduce their obligations threatens the integrity of cap and trade policies.

The U.S. Government Accountability Office (GAO) and the Congressional Research Service (CRS), among others, have identified permanence, leakage and additionality (collectively known as PLA) as the primary concerns that threaten the integrity of carbon offsets:

Permanence: Issues of permanency arise when some carbon reductions (such as afforestation) may be reversed at some point in the future (e.g., if the trees get cut down).

Leakage: The problem of leakage occurs when emissions reductions by one firm or industry indirectly cause emissions from another firm or industry to inefficiently increase.

Additionality: An offset is said to lack additionality if the carbon reduction would have happened anyway, without the payments from the offset purchaser.

Together, these three problems undermine the credibility of offsets markets and highlight the necessity of developing efficient strategies to deal with imperfect information.

The key insight is that the PLA concerns all arise from the inherent difficultly in measuring greenhouse gas emissions from sources like agriculture or deforestation. The difficulties in policy design arise due to asymmetric information, in other words, regulators have less accurate information about emissions than the offset originators. If the uncertainty were symmetric, then mismeasurements should average out; however, asymmetric information introduces the possibility of systemic biases. In this paper, we design a model of asymmetric information in which a regulator wishes to design a price instrument in order to incentivize the efficient production of carbon offsets by land owners that have private information about their heterogeneous characteristics.[1] The specific uncertainties are over the dimensions of land quality (which determines the opportunity cost of emissions reduction) and baseline emissions (which determines the amount of emission reductions the firms are capable of producing). The model predicts which types of firms are most likely to participate in offset programs, the extent of mismeasurement due to information asymmetries, and how offset contracts depend on the regulator's choice of monitoring.

In our model, we specifically focus on the concern of additionality, and address the concern often raised by emissions market designers that the unintended costs from additionality means we should disallow the use of agricultural offsets.

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[1] In the rest of the paper, we refer to land owners as firms.

Our model relates to the extensive literature on regulation in markets with asymmetric information. For example, Montero (1999 and 2000) deals with programs that allow firms to opt-in to emissions reduction programs, and highlights the trade-off between the efficiency gains of achieving lower cost abatement with the excess emissions that comes from adverse selection. Mason and Plantinga (2013), van Benthem and Kerr (2013) and Bento et al. (2014) each examine the issue of adverse selection.[2] Mason and Plantinga, use a non-linear contracting model where the regulator offers a two-part contract to address adverse selection to motivate their econometric model. However, their theoretical framework does not analyze the core issue that we address: how does welfare change under different levels of monitoring and information. Van Benthem and Kerr look at the effect of different levels of monitoring, but do not directly consider how monitoring affects contracts. Van Benthem and Kerr find that increasing the scale of voluntary opt-in programs to reduce emissions in unregulated sectors improves efficiency and reduces transfers to agents. Their focus is on how to balance the costs of adverse selection with the cost of transfers, rather than the role of information. Bento et al. (2014) compares three policies (baseline, trade ratios and limits) to deal with the additionality problem in offsets, but also does not consider monitoring and informational issues, focusing instead on distributional concerns. None of these papers directly address our main question: how do optimal contracts and welfare change when regulators operate under different information levels.

More broadly, this paper relates to the optimal monitoring literature. For example, Schmutzler and Goulder (1997) consider the trade-off between taxing inputs versus taxing emissions when monitoring is imperfect. While taxing agricultural emissions would achieve superior welfare outcomes, our model presumes a political constraint that agricultural offset contracts must be voluntary. Millock, Sunding, and Zilberman (2002) and Stranlund and Dhanda (1999), like us, allow the amount of monitoring to be a choice variable, but still consider only mandatory tax instruments rather than voluntary offsets. Regimes where emissions reductions are driven by offsets, however, differ fundamentally from regimes where emissions reductions are

[2] Jack (2013) also conducts a field experiment in Malawi to examine the one-shot allocation problem in environmental markets, and confirms the presence of information asymmetries in these markets and demonstrates that project design affects both the cost effectiveness and the environmental effectiveness of carbon offset projects.

mandatory; offset contracts must satisfy individual rationality constraints, otherwise firms will take their outside option.

In the voluntary offset regimes we study, firms are offered a take it or leave it offer of a particular price for the emission reductions they promise to produce. While the price is typically keyed to the prevailing emissions price in the market, regulators effectively vary the price offered to the firm through policies that discount the amount of credits a firm receives as a function of the quality. For example, firms that sell offsets based on landfill methane may get one full ton of offset credit for each ton of emissions they reduce, while firms that sell offsets based on afforestation often get less than a full ton of credit for each ton of claimed reductions. Credits are typically discounted based on the attributes of the offset originator. This paper thus provides guidance to regulators on how offsets should be discounted and priced. In our model, offsets may be discounted, to account for the additionality problem, but they may also be priced at a premium above the social cost of carbon because firms need to be paid an information rent in order to optimally produce offsets.

While more sophisticated contracts (as described for example by Mason and Plantinga (2013) or Montero (1999)) could reduce information rents and increase welfare relative to the linear contracts presented here, the contracts we study are designed to speak to the typical voluntary carbon offset regimes found in typical US and international proposals for cap and trade. These regimes typically offer a fixed price per ton of emissions, discounted for land quality. To that extent our contracts resemble the contracts in van Benthem and Kerr (2013) and Bento et al. (2014) as well as the Clean Development Mechanism (CDM) contracts defined under the Kyoto Protocol that are currently traded today (Peters-Stanley et al. 2011). Unlike previous models about the problem of additionality, the amount of information the regulator has about the land owner is a choice variable: the regulator chooses the optimal level of monitoring, which in turn affects the contracts offered.

Our model focuses on two dimensions of asymmetric information regarding a given area of land: the private (agricultural) productivity, and the suitability for public (offset) production. While the agricultural productivity of a land may be easy to observe in developed economies, the majority of agricultural offset production currently originates in Africa and Asia (Peters-Stanley et al. 2011) where land markets are often thin and information scarce (for example, land in China, the world's largest offset originator, is still technically collectively owned and buying and selling of agricultural land is prohibited). Furthermore, while this paper uses the term agricultural value for exposition, what we really care about is the private value of that land to the current owner. While the market value of the land and geographic estimates of land quality may provide a good signal for this value, any individual owner may have idiosyncratic value for that land that is unobserved (perhaps sentimental value, or private information about mineral rights or other non-agricultural uses).

Also, while we do have two dimensions of uncertainty, many of our results show that it is the productivity of the land *relative* to its carbon sequestration value that is most crucial for determining the contracts, akin to the one-dimensional uncertainty over opportunity cost in Mason and Plantinga (2013). Furthermore, our results can be compared to other papers with one dimension of uncertainty by setting either variance parameter to zero.

However, we believe our paper adds value by considering the agricultural uncertainty and emissions uncertainties separately. Our focus is on monitoring, and regulators implement different policies to monitor one vs the other. For example, offset originators and governments have struggled with the measurement of the density of vegetation in indigenous rainforests. While vegetation density does not affect the land's private value, which mostly depends on the land's potential for agricultural production once the indigenous vegetation is burned away, the baseline emissions levels and potential for sequestering carbon depends very much on that density measurement. Helping policy makers assess the value of such measurements, and how measurement affects optimal offset pricing is the goal of this paper.

The paper proceeds as follows: we set up the regulator's and the agents' maximization problem and study the optimal behavior of the agents. We then study the scenario in which the regulator can only use a voluntary price instrument to regulate the carbon offset market. We then consider the welfare loss in this scenario under different levels of information. The regulator can achieve first best with voluntary price contracts under full information (assuming transfers are costless).[3] We

[3] See the models in van Benthem and Kerr (2013) and Bento et al (2014) that consider offset policies when transfers are costly.

then derive conditions for optimal monitoring, under asymmetric information, when monitoring is costly. We show that although existing policies and the existing literature only considers offset prices below the social cost of carbon, we find that for sufficiently high levels of monitoring, offsets should be paid a premium, to compensate for information rents. Our model also identifies and quantifies the types of firms that produce offsets at various levels of monitoring, offering guidance on how regulators should target offset contracts.

2 General Model

2.1 Firms

There exists a continuum of profit maximizing firms, which are differentiated by their marginal cost of producing agricultural goods and their baseline emissions. These are modeled as a two-dimensional random variable. θ_i represents the quality of land to produce agricultural goods, while β_i represents the ability of the land to produce reductions in carbon emissions. You might think of β_i as the baseline level of emissions, and firms with higher β_i would yield more emission reductions when land is shifted away from agricultural use. Different land endowments have differing potentials to either reduce carbon emissions or sequester carbon. We will be agnostic as to where these reductions may come from and simply refer to the firm as "producing" offsets.[4]

Firm type, (θ_i, β_i) defined as follows: $\theta_i \in [\underline{\theta}, \bar{\theta}], \beta_i \in [\underline{\beta}, \bar{\beta}]$, θ_i and β_i are firm-independent and identically distributed over firms according to some joint cumulative distribution $G(\theta_i, \beta_i)$. For now we assume that the marginal densities $g_{\theta i}$ and $g_{\beta i}$ exist, while later on we shall make stronger assumptions over the distribution of θ_i and β_i. Firms are endowed with $\bar{R}$ amount of land, which can be devoted to either agriculture or offsets (denoted by R). Production is defined through the production functions $A(\bar{R} - R, \theta_i)$ and $F(R, \beta_i)$, which we assume to be increasing and concave in the first argument (amount of land allocated to production) and increasing in their respective quality parameter.

[4] See Figure 3 for a better understanding of the common carbon offset projects firms or land owners could possibly engage in.

2.2 Regulator

The regulator wishes to maximize some social welfare function, which we assume is the net sum of total profits from agriculture, the social benefit derived from offsets and the cost of "researching" firms (estimating (θ_i,β_i)). By adding the assumption that the price of the agricultural good is at a fixed equilibrium (which would be valid if, say, the agricultural good is perfectly substitutable with other consumption goods), we believe that this social welfare function accurately captures the welfare components that are subject to change with respect to the implemented policy of incentivizing offset production.

Furthermore, the regulator cannot observe (θ_i, β_i), so she estimates them: $(\tilde{\theta}_i, \tilde{\beta}_i)$, where $\tilde{\theta}_i = \theta_i + i(\varepsilon_i, m)$ and $\tilde{\beta}_i = \beta_i + j(\delta_i, m)$, where $\varepsilon_i \in [-\bar{\varepsilon}, \bar{\varepsilon}]$ and $\delta_i \in [-\bar{\delta}, \bar{\delta}]$ are random variables with a cumulative joint distribution $H(\varepsilon_i,\delta_i)$ and i and j are increasing functions in the error ε and δ and the level of regulator monitoring, m, and equal to zero when δ and ε are zero. An implicit assumption is that both $\tilde{\theta}_i$ and $\tilde{\beta}_i$ are elements in the support set of θ_i and β_i. The quality of these estimates, as seen in the error terms above, are determined by the regulator's monitoring level, m. The cost of monitoring is defined by $C(m)$, which we assume to be increasing and convex. The regulator's problem is to choose the level of monitoring and the price by which she will offer for offsets.

For the rest of the paper, without loss of generality, we forgo the *i* sub-index and observe the behavior of an arbitrary firm and what type of contract it will be offered.

2.3 Firm Behavior

Firms maximize profits given their characteristics and the contract they are offered. This contract is a given amount of offsets at a fixed price $\tilde{p}_f(\tilde{\beta}) > 0$ (which will depend on what type of firm the regulator believes it to be). Given a fixed price of the agricultural good, $p_a > 0$, the firm's maximization problem will be:

$$\hat{R}(\theta, \beta, \tilde{\beta}, p_f) = \operatorname{argmax}_{R \in \mathbb{R}_+} \{ p_a A(\bar{R} - R, \theta) + p_f(\tilde{\beta}) F(R, \tilde{\beta}) \} \quad (1)$$

Note that this objective function implies two important points: First, the only choice variable is land; specifically, whether to allocate it toward producing agricultural goods or toward producing offsets. Second, the profit the firm generates through producing offsets, and therefore its preferred allocation is actually a function of the type of land the regulator perceives it to be, rather than its actual type.

The firm's optimal behavior will be defined by the following first order condition:

$$p_a \frac{\delta A(\bar{R}-\hat{R},\theta)}{\delta R} = p_f(\tilde{\beta}) \frac{\delta F(\hat{R},\tilde{\beta})}{\delta R} \quad (2)$$

where $\hat{R}$ denotes the optimal allocation of land from the firm's perspective. An implicit assumption of this condition is that these two curves intersect at some value of R between 0 and $\bar{R}$ However, we can easily envision firms with such a high productivity of land, where $\forall R: p_a \frac{\partial}{\partial R} A(\bar{R}-R,\theta) > p_f(\tilde{\beta}) \frac{\partial}{\partial R} F(R,\tilde{\beta})$, such that these firms will never produce offsets, i.e. $\hat{R}=0$. For them, this first order condition does not apply, and they simply devote their land to produce agricultural goods. Let us define the fraction of firms that exhibit this characteristic by $\alpha_g>0$.

Though we will expand more on the regulator's behavior, we should note that for a given estimate $(\tilde{\theta},\tilde{\beta})$, the regulator believes that there is an optimal allocation of land $\tilde{R}$ that the firm should use for offset production, where $\tilde{R}=R(\tilde{\theta},\tilde{\beta},p_f)$, which solves the following optimization problem:

$$\tilde{R}(\tilde{\theta},\tilde{\beta},p_a,p_f) = \mathrm{argmax}_{\tilde{R}\in\mathbb{R}}\left\{p_a A\left(\bar{R}-\tilde{R},\tilde{\theta}\right) + p_f(\tilde{\beta})\, F\left(\tilde{R},\tilde{\beta}\right)\right\} \quad (3)$$

which is solved by the amount of land $R=\tilde{R}$ that satisfies the following first order condition:

$$p_a \frac{\delta A(\bar{R}-\tilde{R},\tilde{\theta})}{\delta R} = p_f(\tilde{\beta}) \frac{\delta F(\tilde{R},\tilde{\beta})}{\delta R} \quad (4)$$

This optimal amount of land for the regulator $\tilde{R}$ could be demonstrably greater than, less than, or ambiguous with respect to the firms preferred land allocation $\hat{R}$, and will depend on the relationship between the regulator's estimates $(\tilde{\theta},\tilde{\beta})$ and the actual values of (θ,β). We will also make reference to what we will call the "full information scenario" (where $\theta = \tilde{\theta}$ and $\beta = \tilde{\beta}$), which implies an $R^* = \tilde{R} = \hat{R}$.

Let us study one particular case depicted in Figure 2.

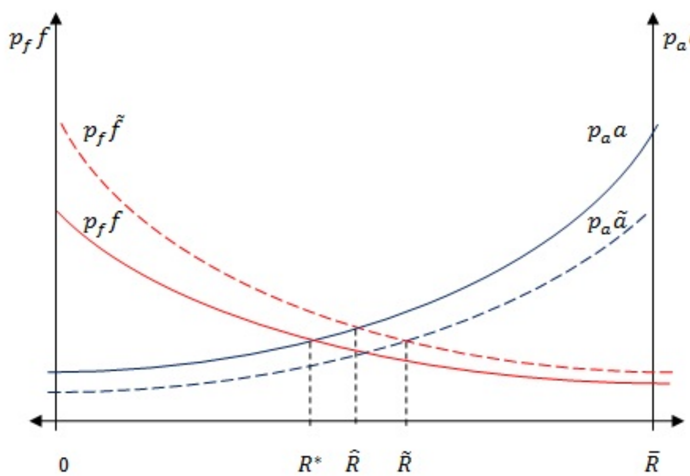

Figure 2: Real and Estimated Marginal Benefit Curves of Agriculture and Offset Production

The firm with the depicted marginal benefit curves is a firm for which the regulator has overestimated β and underestimated θ. This implies that the regulator believes the firm to have a lower agricultural marginal productivity of land than it actually has:

$$\theta > \tilde{\theta} \implies p_a a = p_a \frac{\delta A(\bar{R} - R, \theta)}{\delta R} > p_a \frac{\delta A\left(\bar{R} - R, \tilde{\theta}\right)}{\delta R} = p_a \tilde{a}, \quad \forall R \geq 0$$

and a higher offset marginal productivity of land:

$$\tilde{\beta} > \beta \implies p_f \tilde{f} = p_f \frac{\delta F\left(R, \tilde{\beta}\right)}{\delta R} > p_f \frac{\delta F(R, \beta)}{\delta R} = p_f f, \qquad \forall R \geq 0$$

In this case, the firm will always allocate more land to offset production than is efficient under perfect information, but less than what the regulator expects the firm to allocate. Mathematically, the regulator chooses $\tilde{R}$ such that $R^* < \hat{R} < \tilde{R}$.

Of note in this scenario is that firms will always produce more agriculture and less carbon offsets than what the regulator expects:

$$\int_{\hat{R}}^{\bar{R}} p_a \frac{\delta A(\bar{R} - R, \theta)}{\delta R}\, dR > \int_{\tilde{R}}^{\bar{R}} p_a \frac{\delta A\left(\bar{R} - R, \tilde{\theta}\right)}{\delta R}\, dR$$
$$\Leftrightarrow \int_{\hat{R}}^{\bar{R}} \frac{\delta A(\bar{R} - R, \theta)}{\delta R}\, dR > \int_{\tilde{R}}^{\bar{R}} \frac{\delta A\left(\bar{R} - R, \tilde{\theta}\right)}{\delta R}\, dR$$

and since $\tilde{R} > \hat{R}$ and $\tilde{\theta} > \theta$ we have

$$A\left(\bar{R} - \hat{R}, \theta\right) > A\left(\bar{R} - \tilde{R}, \tilde{\theta}\right)$$

Analogously, $F\left(\hat{R}, \beta\right) < F(\tilde{R}, \tilde{\beta})$.

However, they are still producing more offsets and less agriculture than what would be expected in the full information case:

$$\int_{R^*}^{\bar{R}} p_a \frac{\delta A(\bar{R} - R, \theta)}{\delta R}\, dR > \int_{\hat{R}}^{\bar{R}} p_a \frac{\delta A(\bar{R} - R, \theta)}{\delta R}\, dR$$
$$\Leftrightarrow \int_{R^*}^{\bar{R}} \frac{\delta A(\bar{R} - R, \theta)}{\delta R}\, dR > \int_{\hat{R}}^{\bar{R}} \frac{\delta A(\bar{R} - R, \theta)}{\delta R}\, dR$$

and, since $\hat{R} > R^*$

$$\Rightarrow A(\bar{R} - R^*, \theta) > A\left(\bar{R} - \hat{R}, \theta\right)$$

By the same logic, $F(R^*, \beta) < F(\hat{R}, \beta)$.

For the case in which the regulator overestimates θ and underestimates β, we get the reverse case:

$$\begin{cases} R^* > \hat{R} > \tilde{R} \\ A(\bar{R} - R^*, \theta) < A(\bar{R} - \hat{R}, \theta) < A(\bar{R} - \tilde{R}, \tilde{\theta}) \\ F(R^*, \beta) > F(\hat{R}, \beta) > F(\tilde{R}, \tilde{\beta}) \end{cases}$$

Intuitively, this means that offset production is more land intensive than what the regulator anticipates, yet not as land intensive as it would be in the full information case.

2.4 Regulator's Behavior

The regulator will observe $(\tilde{\theta}, \tilde{\beta})$, noisy signals of the true (θ, β). Then, she will solve the welfare problem and offer a price $p_f(\tilde{\beta})$ for each ton of carbon emissions the regulator believes would be reduced given the regulator's best guess for β (we assume that the regulator's estimate of $\tilde{\theta}$ is not contractible). In a first-best world with perfect information, the price offered would equal the social benefit of reducing each ton of emissions, given by $p_e > 0$. However, given the uncertainties over land quality, the regulator will optimally distort the price to account the regulator's uncertainty about the true emissions reduction.

When solving her optimization problem, the regulator takes into account the expected ex post realization of how much land would actually be allocated, $\hat{R} = R(\theta, \beta, \tilde{\beta}, p_f)$. This decision is then an input into the regulator's social welfare maximization problem, where she must solve for the optimal level of monitoring and the price that she will offer for offsets production. The regulator's problem is thus given as follows:

$$\max_{m,p_f} V\big(\theta,\beta,\tilde{\theta},\tilde{\beta},p_f\big) \quad (5)$$

where

$$V\big(\theta,\beta,\tilde{\theta},\tilde{\beta},p_f\big) = \iint_{\theta,\beta}\left[\iint_{\varepsilon,\delta}\big[p_a A\left(\bar{R}-\hat{R},\theta\right) + p_e F(\hat{R},\beta) - C(m)\big]\, dH\,(\varepsilon,\delta)\right] dG\,(\theta,\beta) \quad (6)$$

$V(\theta,\beta,\tilde{\theta},\tilde{\beta},p_f)$ is the total expected welfare expression given the optimal reaction function of the firm, $\hat{R}$. Note that this implies that the regulator has full information about technology: she knows what the production functions look like. The only sources of uncertainty are the true characteristics of the firm, θ and β.

Given this setup, we can proceed to solve for the regulator's optimal carbon offset price and level of monitoring. The optimality conditions for the regulator (applying Leibniz's rule) are:

$$m^* : \iint_{\theta,\beta}\left[\iint_{\varepsilon,\delta}\left[\begin{pmatrix} -p_a\frac{\delta A(\bar{R}-\hat{R},\theta)}{\delta R} \\ +p_e\frac{\delta F(\tilde{R},\beta)}{\delta R}\end{pmatrix}\frac{d\tilde{R}}{dm} - C'(m^*)\right] dH\,(\varepsilon,\delta)\right] dG\,(\theta,\beta) = 0 \quad (7)$$

where

$$\frac{d\tilde{R}}{dm} = -\frac{\delta\tilde{R}}{\delta\tilde{\beta}}\frac{\delta j(\delta,m)}{\delta m}$$

and

$$p_f{}^* : \iint_{\theta,\beta}\left[\iint_{\varepsilon,\delta}\left[\begin{pmatrix} -p_a\frac{\delta A(\bar{R}-\hat{R},\theta)}{\delta R} \\ +p_e\frac{\delta F(\hat{R},\beta)}{\delta R}\end{pmatrix}\frac{\delta\hat{R}}{\delta p_f}\right] dH\,(\varepsilon,\delta)\right] dG\,(\theta,\beta) = 0 \quad (8)$$

Substituting (2) into (8), we can calculate the optimal price discount the regulator offers for a given firm' offsets (where p_e is the full price):

Proposition 1: *The optimum price contract offered to a firm observed to be type* $(\tilde{\theta}, \tilde{\beta})$ *is given by:*

$$p_f{}^* : \iint_{\theta,\beta} \left[\iint_{\varepsilon,\delta} \left[\begin{pmatrix} -p_f(\tilde{\beta}) \frac{\delta F(\hat{R},\tilde{\beta})}{\delta R} \\ +p_e \frac{\delta F(\hat{R},\beta)}{\delta R} \end{pmatrix} \frac{\delta \hat{R}}{\delta p_f} \right] dH\,(\varepsilon,\delta) \right] dG\,(\theta,\beta) = 0 \quad (9)$$

Recall that p_e is the marginal social benefit of each unit of carbon offsets. Note that the price that the regulator will offer is fully dependent on the offset production function, only depending on the agricultural production function in so far as that affects the land allocation decision of the firm. Here we can again see that if $\tilde{\beta} = \beta$, or in other words, $\delta = 0$, we could set $p_e = p_f$ and transform the firm's problem to the regulator's. However, since $\delta \neq 0$ in general, some loss in efficiency should be expected to occur:

Proposition 2: *The efficiency loss associated to asymmetric information with respect to the perfect information scenario*

$$\Delta = \hat{V} - V^* =$$

$$\iint_{\theta,\beta} \left[\iint_{\varepsilon,\delta} \begin{bmatrix} p_a\left[A\left(\bar{R} - \hat{R}, \theta\right) - A(\bar{R} - R^*, \theta)\right] \\ +p_e\left[F\left(\hat{R}, \beta\right) - F(R^*, \beta)\right] \end{bmatrix} dH\,(\varepsilon,\delta) \right] dG\,(\theta,\beta)$$

$$= 0 \qquad (10)$$

The loss of efficiency is due to the suboptimal allocation of land. This allocation of land contributes to efficiency reduction by distorting the level of both agricultural and offsets production. Specifically, welfare is a function of the decrease (or increase) of agricultural output caused by the inefficient allocation of land, and the difference between the actual realization of offsets production and the offsets that would have been produced with the optimal allocation of land.

2.5 Modeling Baseline Emissions

The model was set up with abstract functional forms, where the industry's production functions $A(-)$ and $F(-)$, coupled with each firm's type (θ, β) accounts for the firm's productivity in producing a private (agricultural) good and a public (offset) good respectively. The functional form was intentionally left general (as in Mason and Plantinga, 2013), since offset contracts—such as those drafted under the Kyoto Clean Development Mechanism (CDM)—tend to be complicated multi-faceted contracts that cover attributes that depend on the private production value of the land and the suitability of that land for offset production. For example, afforestation contracts typically are specificed conditional on market price, counterparty risk, performance risk, project risk, country risk, monitoring structures, and more (Schneck et al. 2011). Although these contracts are offered at a fixed price per unit of emissions (as in our model), these prices are contingent on both the private value and the public value of that land, that we parameterize using (θ, β).

One of the the most common types of offset parameters discussed in the literature and by policy makers is the level of baseline emissions assessed by the regulator (see van Benthem and Kerr, 2013 or Bento et al. 2014 for papers that specifically model regulator choice of baseline emissions).

To understand our model in the context of baseline policy, let $\underline{E}$ denotes the lowest level of emissions achievable from a given area of land, and let $\bar{E}$ be the counter-factual level of emissions that would have occurred absent an offset policy. In common usage, $\bar{E}$ would be considered the baseline, and the parameter β represents the maximum achievable emissions reduction, where $\beta = 0$ reflects land where no emission reductions are possible.

$$\beta = \bar{E} - \underline{E}$$

Since R reflects the proportion of the land devoted to offset production, we can write the offset production function as $F(R, \beta) = \beta R$. If the land owner maximally devotes the land to offset production, $R = 1$, the land achieves its maximum level of abatement and potentially earns the land-owner β offset credits.

Ideally, the regulator's assessment of β which we denote as $\tilde{\beta}$ would reflect the true baseline level of emissions: $\bar{E} - \underline{E}$. However, either due to political reasons, policy decision, or measurement error, the regulator's assessment of the baseline, $\tilde{\bar{E}}$, could be different than the true baseline such that

$$\tilde{\beta} = \tilde{\bar{E}} - \underline{E}$$

In particular, this interpretation of the parameters of the model lends itself to a linear functional form which also has the benefit of allowing us to produce closed form solutions to the model. Thus we focus on the linear case for the remainder of the paper. Furthermore, interpreting the offset productivity parameter as a measure of the baseline allows more direct comparison of our results with the prior literature, something we return to in the Discussion.

3 Linear Case

Consider the following functional form for the production function. Assume that production is linear in both agriculture and offsets. Specifically,

$$A(\bar{R} - R, \theta) = \theta(\bar{R} - R) \; and \; F(R, \beta) = \beta R$$

Given this assumption, the firms' maximization problem is now:

$$\max_{\hat{R} \in \mathbb{R}} \{ p_a \theta(\bar{R} - R) + p_f(\tilde{\beta}) \tilde{\beta} R \} \tag{11}$$

The linearity of the production functions implies a corner solution where the firm will only allocate land to agriculture *or* offsets, but not both. The firm's optimal land allocation is given by:

$$\hat{R} = \begin{cases} \bar{R}, & if \; p_f(\tilde{\beta})\tilde{\beta} > p_a \theta \\ R \in [0, \bar{R}], & if p_f(\tilde{\beta})\tilde{\beta} = p_a \theta \\ 0, & if \; p_f(\tilde{\beta})\tilde{\beta} < p_a \theta \end{cases} \tag{12}$$

Note that the conditions for each value of $\tilde{R}$ also define the fractions of firms that will produce either just agriculture or just offsets. Similarly, the allocations of land according to the regulator allowing for asymmetric information $\tilde{R}$ and with perfect information R^* are presented below:

$$\tilde{R} = \begin{cases} \bar{R}, & if\ p_f\ (\tilde{\beta})\tilde{\beta} > p_a\tilde{\theta} \\ R\ \epsilon\ [0, \bar{R}], & if p_f\ \ (\tilde{\beta})\tilde{\beta} = p_a\tilde{\theta} \\ 0, & if\ p_f\ (\tilde{\beta})\tilde{\beta} < p_a\tilde{\theta} \end{cases} \tag{13}$$

and

$$R^* = \begin{cases} \bar{R}, & if\ p_f\ (\beta)\beta > p_a\theta \\ R\ \epsilon\ [0, \bar{R}], & if p_f\ \ (\beta)\beta = p_a\theta \\ 0, & if\ p_f\ (\beta)\beta < p_a\theta \end{cases} \tag{14}$$

Now, let us define the measurement error the regulator experiences when trying to estimate $(\tilde{\theta}, \tilde{\beta})$. One of the implications of p_f only being a function of $\tilde{\beta}$ is that it is not necessary to specify a functional form for $\tilde{\theta}$. This is due to how profits are generated: agricultural profit is only function of the firm's real ability to produce agricultural goods. Let us define $\tilde{\beta}$ by imposing some structure on the information production function $j(\cdot)$:

$$\tilde{\beta}\ \equiv\ \beta + j(\delta, m) =\ \beta + \delta, where\ \delta \sim U\ \left[\frac{\underline{\beta} - \beta}{m+1}, \frac{\bar{\beta} - \beta}{m+1}\right] \tag{15}$$

The motivation behind the functional form of the upper and lower bound of the uniform distribution over δ is that we want to, in some sense, properly model monitoring. If the regulator does not perform any monitoring $(m = 0)$, we want her to have no good estimate for β: it can be any value between $\underline{\beta}$ and $\bar{\beta}$. On the other hand, as the regulator increases her level of monitoring, the bounds converge towards the real value, β. In other words, as monitoring goes to infinity, the measurement error goes to zero. Mathematically, $\lim_{m \to \infty} \delta(F_\beta(\beta), m) = 0$. Also, if we assume $\frac{\delta p_f\ (\beta)}{\delta\beta} > 0$, we can show that:[5]

$$\tilde{R} = R^*\ \Leftrightarrow\ \ p_f\ (\tilde{\beta})\ \tilde{\beta} = p_a\theta = p_f\ (\beta)\beta$$
$$\Leftrightarrow \tilde{\beta} = \beta\ \ \Leftrightarrow \delta = 0\ or\ m =\ \infty$$

[5] This condition is proven when solving the regulator's problem

In other words, the regulator can only know the true value of β in a world of asymmetric information by implementing infinite monitoring. This implies that we will always have a efficiency loss if there exists some uncertainty over β.

The linearity of the production functions also allows us to partition the space of firms of how firms will react to a given contract into three different types (which we will summarize in Figure 3):

Proposition 3: *For a linear production function, the behavior of firms depends only on how the regulator perceives the firm's capacity at producing offsets* $\tilde{\beta}$ *and their actual agricutlrual productivity* θ*. Firms can be partitioned by the following:*

I. All firms that satisfy $p_f\,(\tilde{\beta})\tilde{\beta} > p_a\theta$ will only produce offsets.
II. All firms that satisfy $p_f\,(\tilde{\beta})\tilde{\beta} < p_a\theta$ will only produce agriculture.
III. All firms that satisfy $p_f\,(\tilde{\beta})\tilde{\beta} = p_a\theta$ are indifferent between producing either good.

Note that this partition depends only on firms' actual agricultural productivity. Production of offsets yields only social benefits, and does not benefit the firm in any way; therefore their behavior depends only on agricultural productivity. The regulator cares about the true producitivty of offsets, but has no way to observe the true productivity β.

3.1 Regulator's Problem in the Linear Case

As before, the regulator first estimates the firm's decision and uses that expected outcome to calculate the welfare maximizing monitoring and offset prices. In the linear production technologies case, this welfare problem is as follows:

$$\max_{p,f,m} V\big(\theta, \beta, \tilde{\theta}, \tilde{\beta}, p_f\big) \qquad (16)$$

where

$$V(\theta,\beta,\tilde{\theta},\tilde{\beta},p_f) =$$
$$\iint_{\theta,\beta}\left[\iint_{\varepsilon,\delta}\left[p_a\theta\left(\bar{R}-\hat{R}\right)+\ p_e\beta\hat{R}-C(m)\right]dH\,(\varepsilon,\delta)\right]dG\,(\theta,\beta)$$
$$=\bar{R}\left[\iiint_{\theta,\beta,\delta}p_a\theta\;dH(\delta)\;dG(\theta,\beta)+P_e\beta dH(\delta)\;dG(\theta,\beta)\right]-\ C(m)$$

Assuming uniform distribution over all variables and assuming that $\underline{\beta} > \frac{P_a}{P_f}\,\underline{\theta}$ and $\overline{\beta} < \frac{P_a}{P_f}\,\overline{\theta}$, then we have:[5]

$$=\ \overline{R}\left[\left(\int_{\underline{\beta}}^{\overline{\beta}}\int_{\frac{\underline{\beta}-\beta}{m+1}}^{\frac{\overline{\beta}-\beta}{m+1}}\left[\int_{\frac{p_f}{p_a}(\beta+\delta)}^{\overline{\theta}}p_a\theta d\theta+\int_{\underline{\theta}}^{\frac{p_f}{p_a}(\beta+\delta)}p_e\beta d\theta\right]\frac{m+1}{\Delta\theta(\Delta\beta)^2}\;d\delta d\beta\right)\right]-c(m)$$

Solving for this integral and simplifying we get:

$$=\frac{\overline{R}}{\Delta\theta}\left[\left[\frac{p_a\overline{\theta}^2}{2}-\frac{p_f^2}{P_a(m+1)}+\left(\frac{m^2+1}{2(m+1)}\;E(\beta^2)+\frac{m}{m+1}\;E(\beta)^2\right)\right]+\left[\frac{p_ep_f}{p_a(m+1)}\;\left[E(\beta)^2+mE(\beta^2)\right]-p_e\,\underline{\theta}\,E(\beta)\right]\right]-\ C(m)$$

From this equation we can derive the new first order conditions:

$$p_f^*:\frac{\overline{R}}{\Delta\theta}\left[-\frac{2p_f}{p_a(m+1)}\left(\frac{m^2+1}{2(m+1)}\;E(\beta^2)+\frac{m}{m+1}\;E(\beta^2)\right)+\frac{p_e}{p_a(m+1)}\;\left[E(\beta)^2+mE(\beta^2)\right]\right]=0 \quad (17)$$

$$m^*:\frac{\overline{R}}{\Delta\theta}\frac{p_e^2}{p_a}\;Var\;(\beta)\left[p_e+\ p_f+\ m\left(p_e-p_f\right)\right]=\ C'(m) \quad (18)$$

From (17) we can solve for the optimal offset price, p_f^* substituting (19) into (18) gives us the optimal price and optimal level of monitoring:

Proposition 4: *The optimal price and level of monitoring given linear prodution functions for firms and uniform measurement error is given by:*

$$p_f^* = p_e \frac{[E(\beta)^2(m+1)^2 + Var\,(\beta)(m^2+m)]}{[E(\beta)^2(m+1)^2 + Var\,(\beta)(m^2+1)]} \tag{19}$$

:

$$\frac{\bar{R}}{\Delta\theta}\frac{p_e^3}{p_a}\, Var\,(\beta)\, \frac{[E(\beta^2)+E\,(\beta)^2]\,[E\,(\beta)^2 + m\,E\,(\beta^2)]}{[E(\beta^2)(\,m^2+1) + 2E\,(\beta)^2\,m]^2} \;= C'(m) \tag{20}$$

Note that the optimal offset price that is offered by the regulator depends solely on the expected value of β, the uncertainty of β (as captured by its variance), and the amount of monitoring that the regulator will choose. Hence, $p^*{}_f$ is set equal to the marginal social benefit of each unit of carbon offset adjusted to reflect the regulator's uncertainty over the quality of the land in the production of offsets. Given this solution for $p^*{}_f$, we can graph the firms that produce either agricultural goods or carbon offsets on the (θ, β, δ) plane. The defining property for firms which are indifferent between producing either good is $p_f(\beta + \delta) = p_a\theta$. We can gain some intuition by graphically depicting this equilibrium condition.

Figure 3 shows the parallelepiped which defines the continuum of firms, as well as the plane that divides it into firms that produce agriculture goods or and those that produce carbon offsets. Specifically, the firms below the plane produce agriculture goods while the firms above it produce carbon offsets.

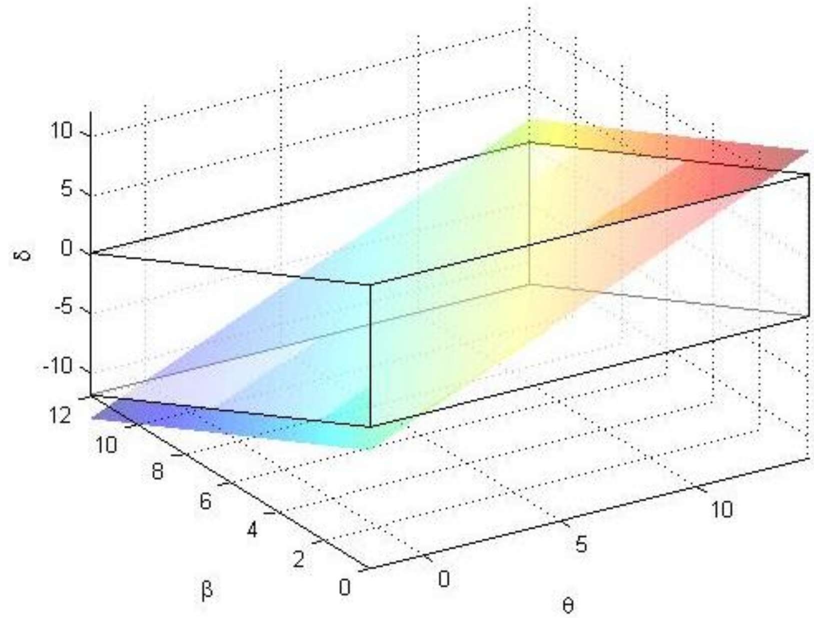

Figure 3 3D Continuum and Division of Firms over (θ,β,δ)

2D Continuum and Division of Firms over (θ,β)

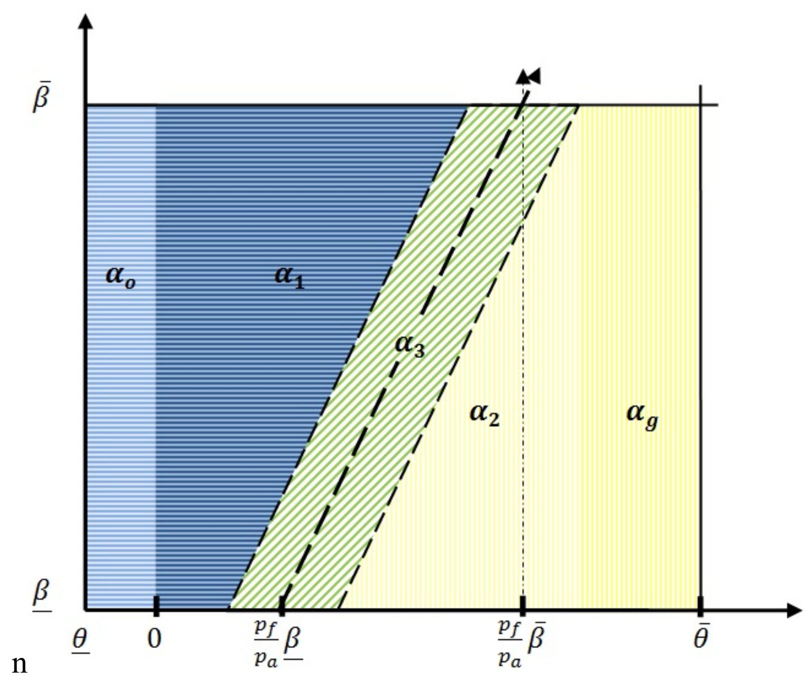

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Figure 4 2D Continuum and Division of Firms over (θ,β)

Futhermore, Figure 4 shows the cross-section of the (θ, β, δ) body of firms when $\tilde{\beta} = \beta$. For illustrative purposes, we assume $m = 1$. Firms in the area labeled α_O are those that will always choose to produce carbon offsets. For them, $p_f(\tilde{\beta})\tilde{\beta} > p_a\theta$ for all price levels since θ is negative. Without a carbon offset policy, these firms would have "produced" offsets anyway since not producing agriculture goods is their optimal choice and thus are non-additional. Firms in α_1 will also choose to produce carbon offsets, given the p_f being offered. For these firms, the offsets are additional but a lower offset price would have sufficed. Firms in α_2 and α_g will choose to continue to produce agriculture goods since the price of offsets being offered by the regulator results in lower returns from offset production than from agriculture. For firms in α_g, this will always be the case since for these firms, $p_f(\tilde{\beta})\tilde{\beta} < p_a\theta$ holds.

3.2 Comparative Statics: Optimal Monitoring and Offset Price

Figure 5 plots the ratio of the optimal offset price (derived from Proposition 4) and social cost of emissions p_f^*/p_e against the level of monitoring, m. The main intuition for this inverted-U relationship is that the offset price is pushed in opposing directions by two desiderata by the regulator. Since some fraction of offsets produced in the imperfect information regime will be spurious, the regulator would like to pay a lower price for offsets. At the same time, in order to incentivize some high value offset producers who possess private information to participate in the program, the regulator also needs to pay an information rent, which pushes the price of offsets higher. Which effect dominates depends on the degree of monitoring. For moderate levels of monitoring, the need to provide information rents outweighs the desire to account for the lower quality of the offsets being produced leading to firms being paid a greater amount than the social value of the offsets they produce. At $m = 1$, the regulator will pay the farmer exactly the marginal environmental benefit gained from that offset $p_f^* = p_e$. Finally, as monitoring approaches infinity $m \to \infty$ and we approach full information, the optimal carbon offset price approaches the marginal benefit of environmental protection $p_f^* \to p_e$.

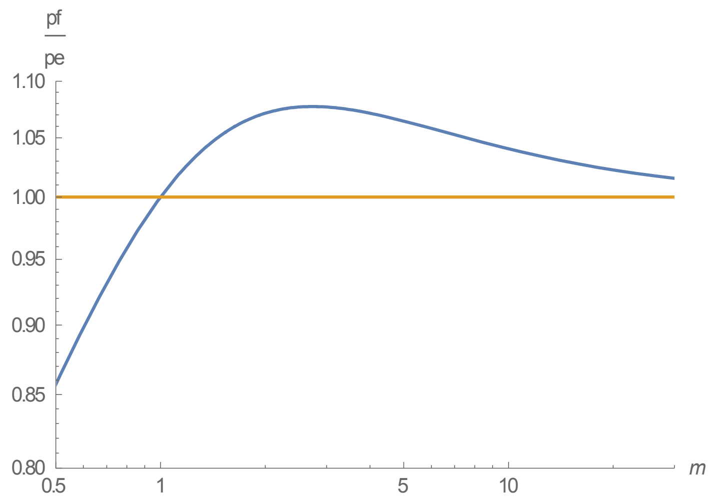

Figure 5 The optimal offset price relative to the social cost of emissions, as a function of the monitoring level on a log-log scale, for a regulator that has unit uniformly distributed uncertainty.

Another result that can be derived from the optimality conditions for monitoring is that the need for monitoring decreases as the difference between $\underline{\beta}$ and $\bar{\beta}$—the variation in quality of land with respect to production of carbon offsets—becomes smaller. We can prove that m goes to zero in the limit: if $\overline{\beta} = \underline{\beta} = B$, we have

$$\left[\frac{\bar{R}}{\Delta\theta}\frac{p_e^2}{p_a}\frac{2}{(m+1)^3}\right] * 0 = 0 = C'(m^*)$$

By the assumption that $C(m)$ is increasing and convex, we know that $C'(m) = 0 \Leftrightarrow m = 0$. The price of offsets at the limit then becomes $p_f = p_e[E(\beta)^2/E(\beta^2)] = p_e$. As expected, this is the same outcome seen with perfect monitoring, since in both cases, the regulator has perfect information and is able to price the offsets exactly at their environmental value.

On the other hand, as the variation over agricultural soil quality shrinks, the relative value of monitoring increases. To see this, note that as $\Delta\theta \to 0, C'(m) \to \infty \Leftrightarrow m = \infty$. Intuitively, as firms become more similar in terms of agricultural quality, the p_f each is willing to accept also becomes more similar. Thus, the regulator will need to choose an offset price more carefully so as to ensure that the proportion of firms that accept it will not be excessively high or low. Because of this, monitoring becomes increasingly valuable.

Finally, since $m \geq 0$, we know that $[E(\beta)^2(m+1)^2 + Var(\beta)(m^2+m)]/[E(\beta)^2(m+1)^2 + Var(\beta)(m^2+1)] < 1$ if and only if $m < 1$. This implies that the optimal p_f will be below p_e –i.e. offsets should be purchased at a discount – if $m < 1$ and above p_e – i.e. offsets should be offered a premium – if $m > 1$. More importantly, the price p_f is increasing over the range $m \in [0, 1 + \sqrt{(2)}\sqrt{((E(\beta^2) + E(\beta)^2))/E(\beta^2)}]$, and decreasing over $m > \sqrt{(2)}\sqrt{((E(\beta^2) + E(\beta)^2))/E(\beta^2)}$ (See Figure 5). Intuitively, for low levels of monitoring, the regulator must increase the incentive to firms in order to generate higher participation in the program. As monitoring increases, however, the offset price converges downwards to the social benefit p_e due to the increased quality of information.

The optimal level of monitoring is defined implictly in Equation 20 and depends on the cost of monitoring. As expected, the convexity of the cost function means the opimal monitoring level goes up as the costs of monitoring increase, and goes up as the value of monitoring goes up (due to a higher social cost of emisssions, p_e or a higher $Var(\beta)$ or a lower p_a).

We can also use Equation 20 to derive conditions on when offsets should be priced at a discount and when offsets should be priced at a premium. Recall that in our model, $m^* = 1$ corresponds to the cutoff, below which, the offset price p_f should be discounted below the social cost of emissions p_e, and above which, the offset price should be raised above. Then from Equation 20, the optimal level of monitoring is equal to 1, if and only if:

$$\frac{\bar{R}}{\Delta\theta}\frac{p_e^3}{p_a} Var(\beta) = 4\, C'(1) \qquad (21)$$

Equation 21 tells us that when you have either higher social costs of emissions, higher uncertainty about offsets, or lower value for the agricultural good, it is more likely that offset prices should be set at a premium,.

We can also see when the regulator crosses this $m^* = 1$ threshold in Figure 6 which plots the optimal level of monitoring m^* derived from Equation 20 as a function of the variance of the uncertainty about offset quality $Var(\beta)$. As the error in monitoring increases, the optimal level of monitoring increases as well.

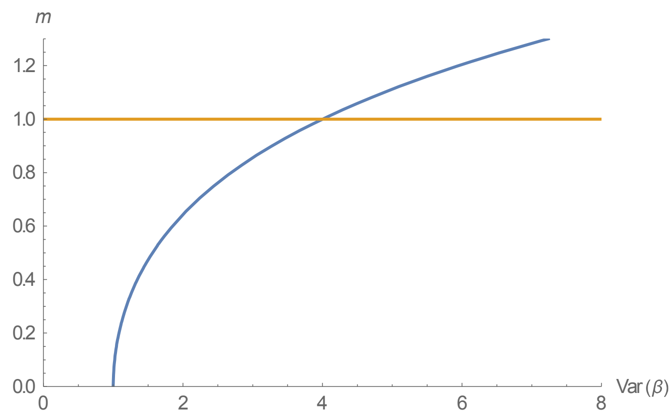

Figure 6 The optimal monioting level as a function of the Variance of the Regulator's Information about the quality of offset production.

3.3 Welfare

We now explore the results of this model as the level of information and the price mechanism vary between extremes

3.3.1 No Price Mechanism

With no price mechanism, which necessarily means no information, the resulting welfare is

$$V_0 = \frac{\bar{R}}{\Delta\,\theta}\left[\frac{p_a\,\overline{\theta}^2}{2} - p_e \underline{\theta}\, E\,(\beta)\right]$$

3.3.2 No Information with Price Mechanism

With no information, but assuming the linear contract studied above, we have a welfare level of

$$V_{NI} = \frac{\bar{R}}{\Delta\,\theta}\left[\frac{p_a\,\overline{\theta}^2}{2} + \frac{p_e^2}{2p_a}\frac{E\,(\beta)^4}{Var\,(\beta) + E\,(\beta)^2} - p_e \underline{\theta}\, E\,(\beta)\right] \qquad (22)$$

Notice that implementing a price mechanism always results in an increase in welfare:

$$\Delta V = V_{NI} - V_0 = \frac{\bar{R}}{\Delta\,\theta}\frac{p_e^2}{2p_a}\left[\frac{E\,(\beta)^4}{Var\,(\beta) + E\,(\beta)^2}\right] > 0$$

Even though the regulator does not monitor and therefore has no reliable information on the specific values of β, implementing the price mechanism is welfare increasing. This result is driven by the assumption that the regulator knows the distribution of β. However, this assumption reflects the fact that although a regulator may not know the exact quality of a given piece of land, she has access to plenty of data to potentially form an informed prior over land quality.

3.3.3 Perfect Information

With perfect information (without the need to monitor), we have

$$V_{PI} = \frac{\bar{R}}{\Delta\,\theta}\left[\frac{p_a\,\bar{\theta}^2}{2} + \frac{p_e^2}{2p_a}[Var\,(\beta) + E\,(\beta)^2] - p_e\underline{\theta}\,E\,(\beta)\right] \quad (23)$$

Hence, the maximum welfare loss attributable to not implementing the price mechanism is

$$\Delta V = V_{PI} - V_0 = \frac{\bar{R}}{\Delta\,\theta}\frac{p_e^2}{2p_a}[Var\,(\beta) + E\,(\beta)^2] > 0$$

3.3.4 Asymmetric Information

We have already computed the level of welfare associated with having asymmetric information – we did this when solving for the regulator's optimization problem – but it is useful to note the welfare gain by implementing the price mechanism:

$$\Delta V = V_M - V_0 = \frac{\bar{R}}{\Delta\,\theta}\frac{p_e^2}{2p_a}\left[\frac{[E(\beta)^2 + mE\,(\beta^2)]^2}{2[(m^2+1)\,E\,(\beta^2) + 2mE\,(\beta)^2]}\right] - C(m)$$

$$= \frac{\bar{R}}{\Delta\,\theta}\frac{p_e}{2p_a}\frac{p_f}{m+1} - C\,(m)$$

This allows us make our final observation on the optimal choices of m and p_f: $C(m)$ must be such that $\Delta V(m^*) > 0$, or, $C(m^*) < \frac{\bar{R}}{\Delta\theta}\frac{p_e}{2p_a}\frac{p_f}{m^*+1}$. In other words, if the cost of monitoring is too high, the regulator will rationally choose not to monitor.

3.4 Additionality

Firms which produce offsets are characterized by the condition $p_a\theta < p_f\tilde{\beta}$. However, firms that satisfy the property $\theta < 0$ would have produced offsets anyway. Since the regulator cannot exclude any firm from participating (her only available instrument is to offer an implicit price for offsets where the per unit offset price is the same offered to all firms but the estimation of offsets quantity production is firm specific), we have a number of non-additional offsets. Intuitively, since the agricultural production drops out of the regulator's decision, as seen above, the firm's opportunity cost of entering into an offsets contract with the regulator is not accounted for. Hence, firms whose agricultural production functions are such that they would not produce agricultural goods will always enter into a profitable contract with the regulator and get paid for doing what they would have done absent the carbon offsets program.

To see how this additionality problem is affected by information, let us again examine each scenario of information:

3.4.1 No Price Mechanism

$$F_0 = \bar{R}\int_{\underline{\beta}}^{\bar{\beta}}\int_{\underline{\theta}}^{0}\frac{\beta}{\Delta\beta\Delta\theta}\,d\theta d\beta = -\bar{R}\frac{\underline{\theta}}{\Delta\theta}\,E\,(\beta) \tag{24}$$

F_0 is the number of offsets produced with no price mechanism (i.e. no regulation). Note that this number is positive, since $\underline{\theta} < 0$ by assumption (there is a positive number of firms that have no incentive to farm their land). These are the non-additional offsets.

3.4.2 No Information with Price Mechanism

$$F_{NI} = \int_{\underline{\beta}}^{\overline{\beta}} \int_{\underline{\beta}-\beta}^{\overline{\beta}-\beta} \int_{\underline{\theta}}^{\frac{p_f}{p_a}(\beta+\delta)} \frac{\beta}{(\Delta\beta)^2\,\Delta\theta}\, d\theta\, d\delta\, d\beta = -\frac{\underline{\theta}}{\Delta\theta} E(\beta) + \frac{p_f}{p_a}\frac{E(\beta)^2}{\Delta\theta}$$
$$= \underbrace{-\bar{R}\frac{\underline{\theta}}{\Delta\theta}E(\beta)}_{\text{Non Additional Offset}} + \underbrace{\frac{p_e}{p_a}\frac{\bar{R}}{\Delta\theta}\left[\frac{E(\beta)^4}{Var(\beta)+E(\beta)^2}\right]}_{\text{Additional Offset}} \tag{25}$$

where we have plugged in for $p_f(m=0)$. Here we can see that by implementing the program, even with no additional information on land quality, we can increase the number of offsets produced. Since the second term, the additional offsets, is strictly positive for positive prices and nonnegative average emissions reduction capability, any price mechanism results in a number of firms reallocating some land from agricultural production to offsets production.

3.4.3 Perfect Information

$$F_{PI} = \int_{\underline{\beta}}^{\overline{\beta}} \int_{\underline{\theta}}^{\frac{p_e}{p_a}(\beta+\delta)} \frac{\beta}{\Delta\beta\,\Delta\theta}\, d\theta\, d\beta = \underbrace{-\bar{R}\frac{\underline{\theta}}{\Delta\theta}E(\beta)}_{\text{Non-Additional Offset}} + \underbrace{\frac{p_e}{p_a}\frac{\bar{R}}{\Delta\theta}\left[Var(\beta)+E(\beta)^2\right]}_{\text{Additional Offset}} \tag{26}$$

The other information extreme, where the regulator has perfect information, shows an increase in the number of offsets produced.[6] Thus, the no information case always results in an inefficiently low production level of offsets.

3.4.4 Asymmetric Information

$$F_m = \bar{R} \int_{\underline{\beta}}^{\overline{\beta}} \int_{\frac{\underline{\beta}-\beta}{m+1}}^{\frac{\overline{\beta}-\beta}{m+1}} \int_{\underline{\theta}}^{\frac{p_f}{p_a}(\beta+\delta)} \beta \frac{(m+1)}{(\Delta\beta)^2\,\Delta\theta}\, d\theta\, d\delta\, d\beta$$
$$= -\bar{R}\frac{\underline{\theta}}{\Delta\theta}E(\beta) + \frac{p_f}{p_a}\frac{\bar{R}}{\Delta\theta}\left[\frac{E(\beta)^2 + mE(\beta^2)}{m+1}\right] \tag{27}$$
$$= \underbrace{-\bar{R}\frac{\underline{\theta}}{\Delta\theta}E(\beta)}_{\text{Non-Additional Offset}} + \underbrace{\frac{p_e}{p_a}\frac{\bar{R}}{\Delta\theta}\frac{\left[E(\beta)^2+mE(\beta^2)\right]^2}{(m^2+1)E(\beta^2)+2mE(\beta)^2}}_{\text{Additional Offset}}$$

[6] This result follows from $E(\beta^2)=Var(\beta)+E(\beta)^2$.

Under asymmetric information and the inclusion of an offset price mechanism, the number of additional offsets is a function of how much monitoring the regulator chooses. When $m = 0$, we confirm our result for no information. Also, when $m \to \infty$, the number of additional offsets converges to $p_e/p_a \ 1/\Delta\theta E(\beta^2)$, the number of offsets when the regulator has full information. One last note: the number of additional offsets is increasing in m, which also confirms our intuition that as we increase monitoring, the number of offsets increases. This occurs because adverse selection is reduced (firms with low values of β drop out and firms with higher values of β opt in), but, as we shall see in the next segment, this occurs through two mechanisms: a shift in the behavior of existing firms due to the higher monitoring which increases the optimal price, and a corresponding shift in the composition of firms that are attracted into the offset market.

3.5 Division of Firms

Let us now study which and how many firms opt in under each scenario of information quality. We derive closed form expressions for these quantities. The number of firms in each scenario will differ depending on the amount of information the regulator has (in other words, it will depend on m). It is also important to note that under each of these scenarios we have several forms of inefficiency that can occur (see Table 1).

Table 1: Types of Firms and Causes of Inefficiency

Firms	**Action**
$p_e\beta < p_a\theta < p_f\tilde{\beta}$	Produce offsets when agriculture would be optimal
$p_f\tilde{\beta} < p_a\theta < p_e\beta$	Produce agriculture when offsets would be optimal
$p_a\theta < p_f\tilde{\beta} < p_e\beta$	Produce offsets, but compensation is less than optimal
$p_a\theta < p_e\beta < p_f\tilde{\beta}$	Produce offsets, but compensation is more than optimal

3.5.1 No Price Mechanism

Recall that we have assumed that firms are distributed uniformly over the relevant ranges of the (θ, β) space. Hence, we can normalize the number of firms with respect to the total area of firms (which is equal to $\Delta\beta\Delta\theta$). This can perhaps be seen more easily by noting that since we assumed a continuum of firms distributed evenly over a specific area, the integral of the joint cumulative distribution function is equal to 1. After this, we simply multiply by the relevant area. Our normalized number of firms, α_0, who will be producing offsets with or without a price mechanism is

$$\alpha_0 = \Delta\beta\Delta\theta \int_{\underline{\beta}}^{\overline{\beta}} \int_{\underline{\theta}}^{0} \frac{1}{\Delta\beta\Delta\theta} d\theta\, d\beta = \int_{\underline{\beta}}^{\overline{\beta}} \int_{\underline{\theta}}^{0} 1\, d\theta\, d\beta = -\underline{\theta}\, \Delta\beta \quad (28)$$

This is precisely the number we get by observing that the number of firms that would never produce agriculture even if the policy were not implemented is the rectangle with sides $\Delta\beta$ and $(0 - \bar{\theta}) = \bar{\theta}$.

3.5.2 No Information with Price Mechanism

$$\begin{aligned} \alpha_{NI} &= \Delta\beta\Delta\theta \int_{\underline{\beta}}^{\overline{\beta}} \int_{\underline{\beta}-\beta}^{\overline{\beta}-\beta} \int_{\underline{\theta}}^{\frac{p_f}{p_a}(\beta+\delta)} \frac{1}{(\Delta\beta)^2\, \Delta\theta}\, d\theta\, d\delta\, d\beta \\ &= \Delta\beta \left[-\underline{\theta} + \frac{p_f}{p_a} E\,(\beta) \right] \\ &= \underbrace{-\underline{\theta}\, \Delta\beta}_{\alpha_0} + \underbrace{\frac{p_e}{p_a}\, \Delta\beta \frac{E\,(\beta)^3}{Var\,(\beta) + E\,(\beta)^2}}_{\alpha_1} \end{aligned} \quad (29)$$

The additional firms that produce offsets, given by α_1 (see Figure 4) can be interpreted as a trapezoid with parallel sides of length $p_f/p_a\underline{\beta}$ and $p_f/p_a\bar{\beta}$, and height $\Delta\beta$. Then, after plugging in for p_f when $m = 0$, we get our final expression for α_1

3.5.3 Perfect Information

$$\alpha_{PI} = \Delta\beta\Delta\theta \int_{\underline{\beta}}^{\overline{\beta}} \int_{\underline{\theta}}^{\frac{p_e}{p_a}\beta} \frac{1}{\Delta\beta\,\Delta\theta}\, d\theta d\beta = -\underline{\theta}\,\Delta\beta + \frac{p_e}{p_a}\,\Delta\beta\, E(\beta) \quad (30)$$

Given a regulator with perfect information implementing a price mechanism, the share of firms that enter into carbon offset contracts will always be larger than in the no information case.[7] Equation (30) helps with the interpretation of α_1: as $Var(\beta) \to 0,\ \alpha_{NI} \to \alpha_{PI}$. This is consistent with our previous result—monitoring becomes less and less important as the uncertainty over β is reduced.

3.5.4 Asymmetric Information

$$\begin{aligned} \alpha_M &= \Delta\beta\Delta\theta \int_{\underline{\beta}}^{\overline{\beta}} \int_{\frac{\underline{\beta}-\beta}{m+1}}^{\frac{\overline{\overline{\beta}}-\beta}{m+1}} \int_{\underline{\theta}}^{\frac{p_f}{p_a}(\beta+\delta)} \beta\,\frac{(m+1)}{(\Delta\beta)^2\,\Delta\theta}\, d\theta\, d\delta\, d\beta \\ &= \Delta\beta\,\left[-\underline{\theta} + \frac{p_f}{p_a}\,E\,(\beta)\right] \qquad (31) \\ &= \underbrace{-\underline{\theta}\,\Delta\beta}_{\alpha_0} + \underbrace{\frac{p_e}{p_a}\,\Delta\beta\,\frac{(m+1)\left[E\,(\beta)^2 + mE\,(\beta^2)\right]E(\beta)}{2\,mE\,(\beta)^2 + (m^2+1)E\,(\beta^2)}}_{\alpha_1+\,\alpha_3} \end{aligned}$$

The same geometric interpretation made above can be made here: the additional number of firms in the general case of asymmetric information is given by the trapezoid $\alpha_1 + \alpha_3$ seen in Figure 4. Note, however, that changes in m lead to changes in p_f. This results in more firms opting in than in the no information scenario. As m increases, p_f will also increase. A higher p_f will make it more desirable for some firms to enter. However, as m increases the range over which β is estimated is reduced. This implies that the total payment to the firm to produce carbon offsets, which is a function of both the offsets price and the regulator's estimation of the quantity of offsets produced by the land, can either increase or decrease.

It turns out that for $m \in [0, \overline{m}]$, $\overline{m} = 1 + \sqrt{2}\frac{\sqrt{E(\beta^2)+E(\beta)^2}}{E(\beta^2)}$, the number of firms that opt in increases: the net effect of increasing the price is that more firms, even firms which are not necessarily good at producing offsets, will opt in. However, for $m > \overline{m}$, we observe that

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[7] This is implied by $Var(\beta)=E(\beta^2)-E(\beta)>0$.

the number of firms in the program decreases gradually: there is a weeding out process of bad firms, and even though there is a net reduction in firms, the fact that the remaining firms are the better ones at producing offsets will imply a greater number of total offsets. Also note that at $m = 1$, we have the same number of firms as when $m = \infty$, though the the composition of firms will differ leading to differing levels of total offset production.

To summarize, we find adverse selection for all values of m, but, as m increases, this adverse selection converges to zero. For the range $m \in [0, \bar{m}]$ there is a net increase in firms that opt in. We can describe this range as "casting a wider net", and, as we move along $m \in [\bar{m}, \infty)$, firms that should not have opted in but chose to for small levels of m, begin to opt out..

3.6 Summary of Results and Relationship to Prior Literature

Perfect information achieves first best. *Under perfect information, the regulator is able to implement the first-best option of pricing offsets at the price* p_e*, the marginal social benefit from a unit of carbon offset. This follows from the regulator's ability to perfectly discriminate. She will not purchase any offsets from firms which fall into the region* $p_e \underline{\beta} < p_a \theta$ *nor will any firm sell offsets if they are in the region* $p_e \bar{\beta} < p_a \theta$*.*

Welfare under this regime is

$$V_{PI} = \frac{\bar{R}}{\Delta\,\theta}\left[\frac{p_a\,\bar{\theta}^2}{2} + \frac{p_e^2}{2p_a}[Var\,(\beta) + \,E\,(\beta)^2] - \,p_e\underline{\theta}\,E\,(\beta)\right]$$

The number of firms which will opt in will be

$$\alpha_{PI} = \,\Delta\beta\Delta\theta\int_{\underline{\beta}}^{\bar{\beta}}\int_{\underline{\theta}}^{\frac{p_e}{p_a}\beta}\frac{1}{\Delta\beta\,\Delta\theta}\,d\theta\,\,d\beta = \,-\underline{\theta}\,\Delta\beta + \frac{p_e}{p_a}\,\Delta\beta\,E(\beta)$$

And the number of offset produced is

$$F_{PI} = \underbrace{-\,\bar{R}\frac{\underline{\theta}}{\Delta\theta}E\,(\beta)}_{\text{Non-Additional Offset}} \quad + \underbrace{\frac{p_e}{p_a}\frac{\bar{R}}{\Delta\theta}\,[Var\,(\beta) + \,E(\beta)^2]}_{\text{Additional Offset}}$$

This serves as a benchmark for our other information conditions.

In each of our information conditions, we have a term for non-additional offsets in our equation for offsets produced. Van Benthem and Kerr (2013) call these “spurious” offsets and finds that the number of spurious offsets increase as the observation error increases. We see the same in our results, but only in terms of uncertianty over land quality, θ. The number of spurious (non-additional) offsets does not vary as monitoring varies (as it does in van Benthem and Kerr) because the regulator knows in expectation the true quantity of emissions reductions.

The no information baseline. *Under no information, the regulator is only able to implement the worst case scenario of the price instrument. The regulator will offer the price* $p_f^* = p_e \left[\frac{E\,(\beta)^2}{Var\,(\beta) + E(\beta)^2}\right] < p_e$

This implies that there are firms that would have produced offsets under perfect information, but will not under no information. This is the main source of adverse selection. Welfare under this regime is

$$V_{NI} = \frac{\bar{R}}{\Delta\,\theta}\left[\frac{p_a\,\bar{\theta}^2}{2} + \frac{p_e^2}{2p_a}\frac{E\,(\beta)^4}{Var\,(\beta) + E(\beta)^2} - p_e\underline{\theta}\,E\,(\beta)\right]$$

The number of firms which will opt in is

$$\alpha_{NI} = -\underline{\theta}\Delta\beta + \frac{p_e}{p_a}\,\Delta\beta\,\frac{E\,(\beta)^3}{Var\,(\beta) + E\,(\beta)^2}$$

And the number of offsets produced will be:

$$F_{NI} = \int_{\underline{\beta}}^{\bar{\beta}} \int_{\underline{\beta}-\beta}^{\bar{\beta}-\beta} \int_{\underline{\theta}}^{\frac{p_f}{p_a}(\beta+\delta)} \frac{\beta}{(\Delta\beta)^2\,\Delta\theta}\, d\theta\, d\delta\, d\beta$$

$$= \underbrace{-\bar{R}\frac{\theta}{\Delta\theta}E(\beta)}_{\text{Non-Additional offset}} \quad \underbrace{+\frac{p_e}{p_a}\frac{\bar{R}}{\Delta\theta}\left[\frac{E(\beta)^4}{Var(\beta)+E(\beta)^2}\right]}_{\text{Additional offset}}$$

It is instructive to compare the no-information case in our model with the model of Mason and Plantinga (2013). Their regulator also has no information about the land, but is able to achieve something closer to first best by offering a sophisticated menu of contracts that offers different prices for different quantities produced, inducing land owners to reveal their true type. Our regulator is limited to offering a linear contract that pays a constant price for each unit of assessed emissions reductions.

Optimal Pricing and Monitoring with Imperfect Information.
Under the price instrument, the regulator will implement the following optimal discount of offset contracts and the following level of monitoring:

$$p_f^* = p_e \frac{[E(\beta)^2(m+1)^2 + Var(\beta)(m^2+m)]}{[E(\beta)^2(m+1)^2 + Var(\beta)(m^2+1)]}$$

$$\frac{\bar{R}}{\Delta\theta}\frac{p_e^3}{p_a} Var(\beta) \frac{[E(\beta^2)+E(\beta)^2]\,[E(\beta)^2 + m^* E(\beta^2)]}{[E(\beta^2)(m^{*2}+1) + 2E(\beta)^2 m^*]^2} = C'(m^*) \tag{32}$$

The optimal level of monitoring is $m^* > 0$. *The optimal offset price* p_f *can be either greater than or less than* p_e.

The reason why the offset price offered by the regulator may be either higher or lower than the social cost of emissions (in contrast to van Benthem and Kerr where equilibrium prices are always lower than the social cost), is because when the regulator has worse information about the quality of the offsets, the regulator would like to pay less because the offsets are of lower quality, but the regulator needs to pay more, to draw in the high quality offset producers.

For low levels of information, the regulator cares mostly about avoiding spuroius offsets. With perfect information, the optimal ratio of offset price to the social cost of emissions asymptotes back to one. The price paid for an offset is maximized at $\bar{m} \geq 1$, the point where the regulator can start to rely on monitoring to induce the right firms to participate, rather than offering a higher price to everybody.

As in the no information case, the imperfect information case will produce a sub-optimal allocation, though it is a welfare improvement over the no information case and, as shown below, the case in which no price mechanisms are introduced. Welfare under this scenario is

$$V_m = \frac{\bar{R}}{\Delta\theta}\left[\begin{array}{l}\left[\frac{p_a\bar{\theta}}{2} - \frac{p_f^2}{p_a(m+1)}\left(\frac{m^2+1}{2(m+1)}\,E\,(\beta^2) + \frac{m}{m+1}\,E\,(\beta)^2\right)\right] \\ + \left[\frac{p_e p_f}{p_a(m+1)}\,[E\,(\beta)^2 + \,m\,E\,(\beta^2)] - p_e\underline{\theta}\,E\,(\beta)\,\right]\end{array}\right] - C\,(m^*)$$

Observe that $V_M(m^* = \infty) = V_{PI}$ and $V_M(m^* = 0) = V_{NI}$. From our previous comparison of welfare between no information and perfect information combined with m^* being an interior solution, we know that $V_{PI} > V_M(m^*) > V_{NI}$.

The number of firms that opt in are

$$\alpha_M = -\underline{\theta}\,\Delta\beta + \frac{p_e}{p_a}\,\Delta\beta\,\frac{(m+1)[E\,(\beta)^2 + \,mE\,(\beta^2)]\,E(\beta)}{2\,mE\,(\beta)^2 + \,(m^2+1)E\,(\beta^2)}$$

And the number of offsets produced are

$$F_M = \underbrace{-\,\bar{R}\frac{\underline{\theta}}{\Delta\theta}E\,(\beta)}_{\text{Non-Additional Offset}} + \underbrace{\frac{p_e}{p_a}\frac{\bar{R}}{\Delta\theta}\,\frac{[E\,(\beta)^2 + \,mE\,(\beta^2)]^2}{(m^2+1)E\,(\beta^2) + \,2\,mE\,(\beta)^2}}_{\text{Additional Offset}}$$

These three sets of results show how welfare, offset production, and firm participation varies as the degree of regulator information varies. The perfect information and no-information case offer upper and lower bounds, and serve as limiting cases for the imperfect information model with monitoring.

Offset programs always increase welfare. *If no offset program is implemented, by construction* $p_f = 0$ *and* $m = 0$.

Welfare under this scenario is

$$V_0 = \frac{\bar{R}}{\Delta\,\theta}\left[\frac{p_a\,\bar{\theta}^2}{2} - \,p_e\underline{\theta}\,E\,(\beta)\right]$$

We can compare V_0 to V_{NI} to determine if, with respect to the entire range of firms, it is desirable to implement such a program:

$$V_{NI} = \frac{\bar{R}}{\Delta\,\theta}\left[\frac{p_a\,\bar{\theta}^2}{2} + \frac{p_e^2}{2p_a}\frac{E\,(\beta)^4}{Var\,(\beta) + E(\beta)^2} - \,p_e\underline{\theta}\,E\,(\beta)\right] > \frac{\bar{R}}{\Delta\,\theta}\left[\frac{p_a\,\bar{\theta}^2}{2} - p_e\underline{\theta}\,E\,(\beta)\right] = V_0$$

$$\Leftrightarrow \frac{\bar{R}}{\Delta\,\theta}\frac{p_e^2}{2p_a}[Var\,(\beta) + \,E\,(\beta)^2] > 0$$

Hence, it is always beneficial as a whole to implement the price instrument, even if the regulator has no additional information besides her prior over distributions. The number of firms that produce offsets are

$$\alpha_0 = \Delta\beta\Delta\theta\,\int_{\underline{\beta}}^{\bar{\beta}}\int_{\underline{\theta}}^{0}\frac{1}{\Delta\beta\Delta\theta}\,d\theta\,d\beta = -\,\underline{\theta}\,\Delta\beta$$

And the number of offsets produced are

$$F_0 = \bar{R}\,\int_{\underline{\beta}}^{\bar{\beta}}\int_{\underline{\theta}}^{0}\frac{\beta}{\Delta\beta\Delta\theta}\,d\theta d\beta = \,-\bar{R}\,\frac{\underline{\theta}}{\Delta\theta}\,E\,(\beta)$$

We emphasize this result because policy makers sometimes use the problem of additionality to advocate disallowing offset markets from carbon trading programs. Here, as in Bento et al. (2014), we note that constraining offset markets reduces welfare. However, it is important to note that this result depends crucially on the assumption that either transfers are costless, or that the regulator is indifferent to distributional concerns. The models of Van Benthem and Kerr (2013) and Bento et al. (2014) deal with these distributional concerns directly, and find that this added constraint may make such offset programs untenable.

4 Conclusion

In carbon offset markets an uninformed regulator who only has a voluntary price instrument at her disposal offers a contract that compensates private agents for producing carbon offsets while reducing adverse selection and welfare losses. Our results hold under varying degrees of uncertainty. The first-best solution is achievable under perfect information or free monitoring. Under asymmetric information and for positive costs of monitoring, we can identify the inefficiencies generated from the additionality problem created by problems of adverse selection. We show that the net social benefit of an offsets program is positive under the assumption of costless transfers.

The main contribution to the literature on the pricing of carbon offsets is to show how the price depends on the level of monitoring, and to offer guidance to policy makers on optimal investment in monitoring, on setting the price of offsets based on the level of monitoring, and on targeting and customizing offset contracts to individual landowners as a function of observable land quality. Unlike prior work that shows how offsets should be discounted, we derive conditions for when offset sellers should be paid a premium relative to the social cost of carbon: when the information rents are high and monitoring is sufficiently accurate. While we hope these results help the design and structure of new offset programs, we acknowledge that more work needs to be done, in particular, integrating these results with models including non-linear contracts and incorporating costly governmental transfers.

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