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Addressing Additionality in REDD Contracts when Formal Enforcement is Absent[*]

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Abstract

This paper examines self-enforcing contracts (relational contracts) as a financial mechanism for reducing carbon emissions from deforestation and forest degradation (REDD) when formal enforcement is absent and the opportunity cost of the land (i.e., landholder type) is private information. We characterize the optimal contract and provide the parameters under which private enforcement is sustainable. The optimal payment scheme suggests that all payments should be made contingent on additional forest conservation at the end of the contracting period regardless of the information about landholder type available to the buyer. If forest conservation is sufficiently productive a first-best self-enforcing contract can be implemented when the buyer does not know landholder type. If the gains from forest conservation are small, relational contracts may still induce carbon sequestration below the first-best level for some or all landholder types, depending on the value of the relationship.

Keywords: contracts, incomplete enforcement, carbon sequestration, climate change, institutions, development.
JEL Codes: D86, K12, L14, O12, Q54, Q56.

1   Introduction

Carbon emissions from deforestation and forest degradation account for approximately twenty percent of greenhouse-gas emissions each year (Holloway and Giandomenico, 2009). Forest conservation may be a cost-effective option to mitigate climate change because deforestation is often only marginally profitable while forest conservation often leads to additional benefits in terms of biodiversity and local economic development (Angelsen, 2008; Sohngen and Beach, 2008). However, the implementation of a strategy for reducing emissions from deforestation and forest degradation (REDD) depends on the design of a financial mechanism that encourages landholders to adopt forest-management practices that contribute to climate goals. Effective REDD contracts not only reward those who reduce deforestation and forest degradation but also address technical issues such as additionality and permanence of the carbon offsets. Additionality means that a REDD mechanism must result in forest conservation that would not occur in the absence of such incentives, i.e., relative to the business-as-usual scenario. Permanence implies that both parties perform faithfully their contract obligations[1] (i.e., sequester carbon and make payments) for the duration of the contract.

The realities of the global carbon-contracting environment work against additionality and permanence. Asymmetric information about the cost of conservation impedes additionality. If the buyer does not know the landholder's opportunity cost, adverse selection may occur and he may contract with landholders who would conserve the forest without REDD incentives. As a consequence the contracted forestland would not meet additionality criteria. Furthermore, landholders may use their private information to extract information rents, which raises contracting costs and limits the effectiveness of the buyer's limited funds.

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[1]Some authors include risky events as non-permanence, e.g., forest fires that are purely natural. From a contracting perspective, this can be included in a contract so that even with a fire an individual fulfills their obligation.

Analysis of environmental payment programs has generated indirect evidence of the problems that arise because of hidden information (Ferraro, 2008; Kerr et al., 2004; Sanchez-Azofeifa et al., 2007; Strassburg et al., 2009). For example, Robalino et al. (2008) find that parcels enrolled between the years 2000 and 2005 in the Payment for Environmental Services Program in Costa Rica faced a low average deforestation threat, suggesting that enrolled parcels did not contribute much to additionality in carbon sequestration.

In addition, the lack of formal institutions to enforce contracts, or the prohibitive cost of accessing such institutions, impedes permanence. Many rapidly deforesting regions are located in countries where enforcement institutions are weak (Angelsen, 2008). Without efficient formal enforcement, self-enforcement becomes the sole means for ensuring contractual performance. Self-enforced contracts, also known as relational contracts, feature more constraints that limit the power of incentives and often erode efficiency compared to contracts enforced by third parties.

As a result of adverse selection and weak formal enforcement, REDD contracts may be inherently inefficient, which raises the possibility that economic frictions prevent forest conservation from addressing climate-change goals with promised efficiency. In this paper we design self-enforcing REDD contracts that can overcome adverse selection by leveraging two elements of the forest-conservation context that allow for stronger incentives. First, carbon sequestration is largely irreversible; once carbon stocks are released from forests, it takes substantial time to restore sequestered carbon levels. This slow reversibility limits the renegotiation possibilities for self-enforcing contracts and so provides additional limits and structure to the problem. In the parlance of contract theory, we need not worry about designing a renegotiation-proof contract because, if the landholder breaks the contract, the buyer has no incentive to renegotiate. Second, the landholder requires relatively few liquid resources to undertake conservation of established stands. Unlike afforestation schemes, which may involve significant initial cash expenses for plant material and ground preparation,

the costs of conservation are dominated by opportunity costs rather than by cash expenses. Hence, payments need not be front loaded to alleviate cash-flow constraints and can be made contingent upon performance.

Indeed, we find that under the optimal REDD relational contract a landholder does not get paid until the end of the period regardless of her type and regardless of the information available to the buyer about the landholder's type. The optimal incentive provision is characterized by large contingent payments and base payments equal to zero because the base payment does not provide the landholder incentive to perform. Self-enforcement is negatively related to the total cost of forest conservation (the opportunity cost of the land and the reservation profits) and positively related to the value of the contracted carbon offsets. The higher the total cost of forest conservation is relative to net value of the carbon offsets contracted, the harder it is to achieve forest conservation.

When the buyer does not know the landholder's type and the value of the relationship is sufficiently productive, the model predicts that a first-best self-enforcing contract can be implemented for both types of landholder. The landholder with a lower opportunity cost of land (H type) benefits from an information rent because she is more efficient in providing forest conservation. However, if the gains from the relationship are small (i.e., the reservation profits are too high or the discount factor is small) but the self-enforcing constraint is still met for the efficient landholder, relational contracts may still induce forest conservation below the first-best level for either or both types, depending on how restrictive the self-enforcement constraint is. Asking for more forest conservation from the L-type landholder implies a higher payment for the H-type landholder such that she reveals her type. As a consequence, if the self-enforcement constraint is very restrictive, it is socially optimal to set forest conservation below the first-best level for both types, instead of having only one type producing forest conservation. If the self-enforcement constraint is less restrictive, the H type is induced to maintain more land in forest (below first-best) because she is more

efficient in providing carbon sequestration and requires a lower performance payment for each additional unit of land in forest conservation.

There is limited extant research to guide the contract design of conservation payments to ensure additionality of carbon offsets and long-term performance from landholders. There have been recent attempts to employ contract theory to design carbon-sequestration contracts. Examples include Gjertsen et al. (2010); Mason and Plantinga (2011); Palmer, Ohndorf, and MacKenzie (2009); van Benthem and Kerr (2010); Guiteras, Jack, and Oliva (2011); and Bushnell (2011). Gjertsen et al. (2010) model conservation agreements as dynamic relationships with renegotiation. In contrast, we assume that renegotiation is not reasonable given the slow reversibility of carbon stocks, so there is no gain from renegotiation. Mason and Plantinga (2011) investigate the optimal contract structure when landholders have private information about their opportunity costs and contracts are perfectly enforceable. Palmer, Ohndorf, and MacKenzie (2009) design carbon contracts in the context of afforestation and reforestation projects, which require up-front cash payments to ease landholders' liquidity constraints, and they assume there exists some probability of contract enforcement. van Benthem and Kerr (2010) study the trade-offs between efficiency, efficacy in deforestation, and payments when there is asymmetric information. However, they focus on a single baseline and on the conditions for which it is individually rational for carbon buyers and sellers to participate in a single-period contract. Bushnell (2011) explores the effect of adverse selection on carbon-offset markets, but he focuses on transactions of offsets between capped and uncapped firms and not on avoided deforestation and degradation. Guiteras, Jack, and Oliva (2011) use the Becker-DeGroot-Marschark mechanism to derive a simple menu of contracts to pay for forest offsets when landholder type is private information and contract enforcement is perfect. In contrast with those papers, this research proposes the use of self-enforcing contracts to overcome the multiple institutional frameworks in which REDD implementation is potentially embedded. This paper further contributes to the economics

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literature by deriving a contract that may be more suitable for markets in which opportunity cost predominates the costs of performing the task; as a consequence, the contract is characterized by back-loaded payments rather than up-front or base payments.

This paper also contributes to the literature on contract design for environmental services (Ferraro, 2008) and agri-environmental payment schemes (Chambers, 1992; Claassen, Cattaneo, and Johansson, 2008; Fraser, 2009; Latacz-Lohmann and Van derHamsvoort, 1997; Moxey, White, and Ozanne, 1999; Ozanne, Hogan, and Colman, 2001; Peterson and Boisvert, 2004; Spulber, 1988; Wu and Babcock, 1996; Yano and Blandford, 2009) by deriving the optimal self-enforcing contract under asymmetric information about the opportunity cost of land. Furthermore, this paper generates new ideas for tackling the optimal contract design to guarantee participation of landholders who have private information about potential land use, a necessary condition to ensuring long-term performance of carbon sequestration when formal institutions to enforce contracts may be unavailable. These ideas also benefit practitioners charged with implementing carbon sequestration contracts around the world.

The structure of the paper is as follows. Section two presents the relational-contracts model. Section three presents the case of perfectly enforceable contracts and symmetric information. Section four derives the optimal relational contract and the sustainability of self-enforcement when parties have symmetric and asymmetric information. Finally, section five presents conclusions.

2　The Model

Consider two risk-neutral parties, a buyer and a landholder, who have the opportunity to trade carbon offsets at dates $t = 0, 1, 2, 3 \ldots$. The buyer is interested in the additionality and permanence of carbon offsets to comply with REDD objectives.[2] He offers a landholder

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[2]In this paper we apply the relational contracting model to address the pure objective of carbon sequestration. See Cordero Salas and Roe (2012) for a version that includes a framework with other REDD

a payment through a contract to avoid changing land use, but he prefers to pay only for the land that otherwise would become deforested.

Although in practice a buyer may interact with many landholders, in this model we consider a representative landholder. The landholder possesses forest land and is interested in adopting the land use that maximizes her economic returns. She can conserve the forest, or she can change the land use to a non-forest activity such as agricultural and timber harvesting, resulting in carbon emissions. The landholder is characterized by her type,[3] which is private information given by $\theta \in \{\theta_L, \theta_H\}$. In the absence of REDD payments, the landholder allocates θ of her land to forest and the rest to other economic activities. An L-type landholder keeps θ_L of her land in forest, while an H-type landholder keeps θ_H in forest, where $\theta_H > \theta_L$. The landholder's type determines the opportunity cost of placing fraction ℓ of her land in forest, $c(\ell, \theta)$. We assume that the cost of keeping additional land in forest is increasing and convex—$dc/d\ell > 0$ and $d^2c/d\ell^2 > 0$—and $c(\theta, \theta) = 0$. Furthermore, because the agent keeps land in forest in the absence of carbon payments and a L-type landholder keeps less land in forest than an H-type, then the cost is decreasing in type, $dc/d\theta < 0$, $d^2c/d\ell d\theta < 0$. That is, an L-type landholder has a higher opportunity cost for the land than an H-type landholder, who keeps a larger fraction of her land in forest when the price for

co-benefits often included in REDD+, such as distribution.

[3]The landholder's type is the amount of land a landholder places in forest absent any carbon payments. Given the returns of her land, a landowner determines the opportunity cost of placing additional land in forest. For example, if the landowner is a farmer, she deforests her land when the returns from farming are positive and keeps the forest if the returns of farming are non-positive absent carbon payments. If the landowner is a timber producer, she keeps the forest if the returns from harvesting timber are not positive. If the landholder has a high return on the non-forest activity, she has little incentive to keep the forest, and in the model she is referred as an L-type landholder. In contrast, if the returns of the non-forest activity are small, the landowner does not have much incentive to deforest and therefore she is an H-type landholder. In practical terms, knowing if the landowner is a farmer or a timber producer provides information about the landholder's type; however, historical information about land-use patterns or specific characteristics of the products and markets in which the landowner participates may better estimate the landholder's type. Furthermore, a landholder's type is important if the landowner is a government. For instance, if the government has a strong conservation policy, it represents an H-type landholder, while if the government is characterized by low conservation effort then it is an L-type landholder. Contracting with governments may decrease the information asymmetry about the landholder's type because the type may be easier to observe through government-conservation history and policies.

forest conservation is zero. The buyer does not observe the landholder's type before offering a contract, but he knows that a landholder is H-type with probability α and L-type with probability $1 - \alpha$.

Figure 1 shows the timing of actions and decisions. At the beginning of period t, the buyer offers the landholder a menu of contracts that include a compensation scheme that the landholder is entitled to if she maintains fraction ℓ of her land in forest. Compensation consists of a base payment, p_t, and a contingent payment, $b_t : \ell \to \Re$, where ℓ is the observed forest land. Forest land and its carbon stocks are observable by both parties, but they are not enforceable because it is too costly for a neutral third party to verify (for example, a court in a developing country may not have the means or technology for verifiability, and in some places it is more difficult to verify than in others, including within developed countries.). Consequently, the contracted area in forest, ℓ^*, may differ from the delivered quantity, ℓ_t, and it may also differ from $\overline{\ell}$ depending on the benefit and cost of forest conservation.[4] Let $\ell_t \in \mathcal{L} = [\theta_L, \overline{\ell}]$ denote the set of land amounts kept in forest in period t, where $\overline{\ell}$ represents the land in forest at the beginning of the period given the initial land use. Because there are only two types of landholders, θ_L represents the minimum amount of land any landholder keeps in forest given the opportunity costs.

The base payment, p_t, is paid independently of the final outcome. Although in practice landholders who depend on the land returns may find REDD contracts more attractive if the base payment is paid at the beginning of the period, we assume that landholders are not liquidity constrained. Furthermore, because the contracts are on forest conservation there are no upfront costs associated with the activity, in contrast with afforestation projects, in which there is an upfront investment. The contingent payment is considered a *bonus*, a per-unit payment used to reward forest conservation.[5] Since the contingency payment depends

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[4]The intuition is that the contracted area in forest, ℓ^*, depends on the marginal benefit and marginal cost of keeping additional land as forest. It may be the case that the marginal cost of keeping $\overline{\ell}$ is greater than its marginal benefit. Therefore, it is optimal to contract for $\ell^* < \overline{\ell}$.

[5]The optimal contract is designed to reward equally for either avoiding deforestation or avoiding forest
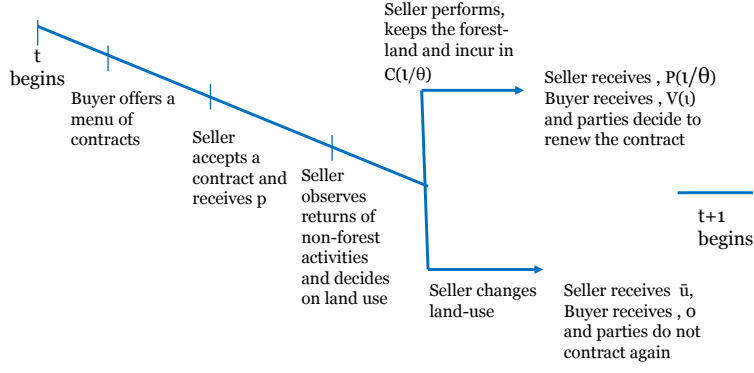
Figure 1: Timing line

on an unverifiable measure, it is not a legally binding obligation.

After observing the compensation scheme, the landholder decides whether to accept the buyer's offer. If the landholder accepts she receives p; observes the returns of alternative land uses, including non-forest activities; and decides to adhere to the contract or to change the land use by keeping only θ amount of land in forest.

If she decides to avoid deforestation and degradation, she incurs the opportunity cost for forest protection, $c(\ell_\theta, \theta)$. The landholder's profit is $U_{t\theta} = P_t(\ell_{t\theta}) - c_t(\ell_{t\theta}, \theta)$, where $P_t(\ell_{t\theta}) = p_{t\theta} + b_t(\ell_{t\theta})$ is the buyer's total payment to the landholder. At the end of period t, the landholder's forest land generates a direct net benefit for the buyer, $V_t(\ell_{t\theta})$, where $V'(.) > 0$, $V''(.) \leq 0$, and $V(\theta) = 0$. That is, the buyer only gets a benefit for additional land placed in forest relative to the business-as-usual scenario, and the benefit is net of the buyer's cost of observing the landholder's performance.[6] He also chooses whether to pay $b_t(\ell_{t\theta})$. The buyer's profits are given by $\pi_t = V_t(\ell_{t\theta}) - P_t(\ell_{t\theta})$. The total joint surplus is

degradation. The idea that the contracts are self-enforcing is that they give incentives to the landowners to not remove wood for markets or personal use. However, we acknowledge that in practice there are likely big cost differences in observing deforestation and degradation. As a consequence, REDD contracts may be more effective in reducing deforestation than forest degradation.

[6]We assume that the buyer's net value of the conservation is positive for a certain level of observation costs. The key focus here is on third-party verifiability, which we assume is prohibitively expensive or impossible.

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defined by $S(\ell_{t\theta}, \theta) = V(\ell_{t\theta}) - c(\ell_{t\theta}, \theta)$, and ℓ_θ^* maximizes the surplus for each type.

If the landholder rejects the contract, she does not keep additional land in forest, only θ; trade does not occur; the landholder receives the profits from the non-forest activity $\bar{u}$; and the buyer receives $\bar{\pi}$, which is the value of alternative carbon credits. The sum of the fixed payoffs, $\bar{s} = \bar{u} + \bar{\pi}$, is the social value of the outside options. The net social surplus from carbon sequestration is given by $S(\ell_t, \theta) - \bar{s}$, and we assume that for both θ, $\max_{\ell_\theta} S(\ell_\theta, \theta) > \bar{s} \geq 0 \geq S(\theta_L, \theta)$.

This sequence of events repeats in each period t, and over the course of repeated interactions the parties know only the past actions of their previous trading partners, allowing for the creation of relationships. In addition, the party's objective is to maximize the future discounted stream of payments, where the common discount factor is $\delta \in (0, 1]$.

Specifically, the landholder's objective is to maximize her present discounted profit, given as

$$(1) \qquad \sum_{t=0}^{\infty} \delta^t \left\{ d_t(P_t(\ell_\theta, \theta) - c(\ell_{t\theta}, \theta)) + (1 - d_t)\bar{u} \right\},$$

and the buyer's objective is to maximize his present discounted profit,

$$(2) \qquad \sum_{t=0}^{\infty} \delta^t \left\{ d_t(V(\ell_{t\theta}) - P(\ell_{t\theta}, \theta)) + (1 - d_t)\bar{\pi} \right\},$$

where $d_t = 1$ if the landholder accepts the contract and trade occurs in period t and $d_t = 0$ if the landholder rejects the contract and no trade occurs.

3 First-Best REDD Contracts

Consider the case in which forest land and carbon stocks are contractible and there is not asymmetry of information between the buyer and the landholder about the landholder's type.

The buyer offers the landholder a contract according to her type in which the most efficient production levels are obtained by equating the buyer's marginal value and the landholder's marginal cost. The contract could explicitly include the area in forest and a single base payment in exchange for the carbon delivered by the forest land. Contingent payments are not necessary because a formal court enforces the contract. If parties breach the contract, they incur a formal penalty assumed large enough to motivate performance. Consequently, the buyer proposes a type-dependent contract defined as $y_{t,\theta} = \langle P_{t,\theta}, \ell_{t,\theta} \rangle$ that maximizes his stream of future payoffs subject to the participation of the landholder in the contract. The landholder accepts the contract and avoids deforestation and degradation for the additional land if and only if the benefits she obtained from the contract U_θ^* are greater than her reservation profits. The landholder's individual rationality constraint (IRC) is given by

$$(3) \qquad\qquad U_\theta^* = P_{t,\theta} - c(\ell_t, \theta) \geq \overline{u},$$

and the buyer solves the following maximization program for each landholder

$$(4) \qquad \max_{P_\theta, \ell_\theta} \left(\frac{V(\ell_\theta) - P_\theta}{1 - \delta} \right)$$
$$\text{subject to} \quad P_\theta = \overline{u} + c(\ell_\theta, \theta) \text{ and } \ell_\theta \in [\theta_L, \overline{\ell}].$$

Substituting the landholder's IRC into the buyer's profit option, we obtain the following first order condition for each type:

$$(5) \qquad\qquad V'(\ell_\theta^*) = c'(\ell_\theta^*, \theta)$$

Both landholder types keep the optimal additional land in forest, ℓ_L^* and ℓ_H^*, if their net social value is nonnegative, $S(\ell_L^*) - \overline{s} \geq 0$ and $S(\ell_H^*) - \overline{s} \geq 0$. Furthermore, the net social value is greater for the H-type than for the L-type because the H-type has a lower opportunity cost

for the land and therefore is more efficient in producing carbon offsets through maintaining more land in forest.[7] The optimal contract is given in Proposition 1.

Proposition 1. *If REDD contracts are perfectly enforceable and there is symmetric information about the landholder's type, the buyer pays compensation equal to $P = \overline{u} + c(\ell_H^*, \theta_H)$ to an H-type landholder and $P = \overline{u} + c(\ell_L^*, \theta_L)$ to an L-type landholder during date t, each landholder maintains ℓ_H^* and ℓ_L^* area of land in forest respectively, and each party gets profits*

$$\tag{6} \pi^* = \frac{V(\ell_\theta^*) - c(\ell_\theta^*, \theta) - \overline{u}}{1 - \delta} \quad and$$

$$\tag{7} U_\theta^* = \frac{\overline{u}}{1 - \delta}.$$

A formal mechanism enforces the optimal contract, which implements full conservation of additional forest, and each landholder receives payments according to her type. The buyer obtains the net benefits from the additional carbon offsets. Each landholder receives a payment equal to the discounted value of her reservation profits.

4 Relational Contracts and REDD

If forest conservation is costly for a third party to verify, formal enforcement of REDD contracts becomes difficult. If the buyer can observe the landholder's conservation at a reasonable cost, then the parties may rely on relational contracting (i.e., informal incentives and good faith) as a private enforcement—i.e., self-enforcement—mechanism. However, the contingent payments are just a promise; therefore, the parties are tempted to deviate from the contract because they do not incur a formal penalty for reneging the original agreement.

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[7]The H-type landholder is closer to the margin, where the returns from non-forest activities are very low. But we assume that an H-type landholder will still deforest absent conservation payments. As a result, contracting with the H-type landholder provides more efficient additionality because her cost of keeping additional land in forest is lower than the L-type's cost of keeping additional forest; i.e., the opportunity cost of the land is lower for the H-type.

If the parties interact just once, the buyer can only make the base payment credible because it is paid regardless of the final outcome. Because this payment does not include additional incentives for any type of landholder to conserve additional forest, keeping additional land from deforestation and degradation cannot occur in a static equilibrium. Consequently, trade does not occur and both parties receive their outside options.

In contrast, the ongoing interaction sustains the equilibrium by allowing the parties to support future terms of trade contingent on the satisfactory performance of present trade. This implies that the buyer observes the area in conservation and makes the contracted payment if the landholder has kept the forest.[8] Suppose that the buyer can distinguish L- and H-type landholders such that he can offer a self-enforcing contract to a landholder according to her type. The parties cooperate if the history of play in all periods has been cooperation. The parties break trade forever if deviation is observed. There is no loss from assuming that deviation causes the parties to break trade forever because this outcome never happens in equilibrium (Levin, 2003). Furthermore, we assume that after deviation the parties do not trade anymore. This assumption reflects the fact that it would take a long time to recuperate the forest if it is deforested. Therefore, the buyer will not trade with a landholder who has deforested because she does not have forest to offer. However, if the buyer deviates, the landholder responds by changing the land use to a non-forest activity. Again, forests are destroyed along with the opportunity of future trade.

Additionally, parties cannot renegotiate the trading decision after forest conservation is observed. The reason for this is that, if a self-enforcing contract is optimal given any history, then the contract is strongly optimal. A strongly optimal contract has the property that parties cannot jointly gain from renegotiating even off the equilibrium path. Because behavior off the equilibrium path implies deviation, if either party deviates, additional forests are

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[8]In practice, the contract defines a *period*, which can be a year or other convenient time unit. The buyer observes the forest conservation with some positive but low cost, such that the net value of conservation is positive.

destroyed and with them the social surplus. Therefore, there is no gain from renegotiation.

Finally, each period is played following a Nash equilibrium, and the parties use a stationary contract in which the buyer always offers the same type-dependent payment scheme, the landholder always takes the same action, and the rents to the relationship are attractive enough for the parties to self-enforce the contract (Baker, Gibbons, and Murphy, 1994; MacLeod, 2006; MacLeod and Malcomson, 1989, 1998). Repetition allows players to maintain a sub-game perfect Nash equilibrium where parties maintain long-term relationships. Last, because the buyer's behavior is perfectly observable, a stationary contract delivers the optimal REDD surplus (Levin, 2003). These assumptions allow for self-enforcing contracts—relational contracts—since they contain a complete plan for the relationship that describes behavior on and off the equilibrium path.

4.1 Self-enforcing Contracts with Symmetric Information

Because third-party enforcement is imperfect but the buyer can distinguish landholders with high and low opportunity costs, he offers an explicit type-dependent contract $y_\theta = \langle p_\theta, b(\ell_\theta^*) \rangle$ through which he provides additional incentives for the landholder to avoid deforestation and forest degradation in some additional land relative to what each landholder would keep in forest in a business-as-usual scenario. The buyer pays p_θ as a base payment regardless of the landholder's performance, and the contingent payment takes the form of a bonus that the buyer promises to pay as long as the landholder does not shirk. Because enforcement is imperfect after the landholder accepts a contract y_θ^*, she decides how to use the land. She can cooperate by choosing $\ell_{t\theta} \geq \ell_\theta^*$ or shirk by choosing $\ell_{t\theta} = \theta$. The buyer, after perfectly observing the conserved area in forest, may cooperate by paying $P_{t\theta}(\ell_{t\theta}) = p_{t\theta} + b_{t\theta}(\ell_{t\theta})$ or renege by choosing the most profitable deviation, not paying the bonus, $b(\ell_\theta) = 0$.

The buyer participates in REDD if the benefits from the contract with either type are

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greater than his alternative source of carbon reduction. This is given by his IRC:

$$(8) \qquad\qquad V(\ell_\theta) - p_\theta - b(\ell_\theta) \geq \quad \overline{\pi}.$$

In addition, the buyer's offer has to meet the landholder's IRC, equality (3); i.e., the offer has to provide a credible incentive to perform in each period. Because of the imperfect enforcement a dynamic incentive compatibility constraint (DICC) for each party has to be fulfilled such that the parties to prefer to fulfill the terms of the contract instead of reneging. The landholder's and the buyer's DICCs are given by (9) and (10) respectively. A landholder of type θ cooperates if and only if

$$(9) \qquad\qquad \frac{p_\theta + b(\ell_\theta) - c(\ell_\theta, \theta)}{1 - \delta} \quad \geq \quad p_\theta - c(\theta, \theta) + \frac{\overline{u}}{1 - \delta}.$$

The left-hand side is the discounted payoff of the landholder for cooperating and maintaining additional land in forest $\ell_{t\theta} \geq \ell_\theta^*$ at the end of each date t. It represents the discounted gains from the relationship for a landholder of type θ. She receives p_θ during period t and the contingent payment $b(\ell_\theta)$ after conserving the forest for period t. The right-hand side represents the payoff if she shirks. Note that the most profitable deviation for the landholder is to change the land use to what she would choose absent payments for forest conservation, θ. In this case, she does not incur opportunity cost for forest conservation, $c(\theta, \theta) = 0$, which would cause the buyer, after observing the area kept as forest, to not pay the bonus. She then receives p_θ because the base payment is enforceable and independent of performance, collects her reservation profits from the alternative activity starting in period $t = 0$, and therefore receives the present value of the returns from the non-forest activity for all periods.

Additionally, the buyer cooperates if his DICC given by (10) is satisfied for any landholder type. He cooperates if he gets the long-term benefits of the forest conservation net of the payments he makes. If he deviates he gets the benefits of the additional area in forest

minus what he paid upfront. Then in all future periods he guarantees himself the benefits of the alternative options for carbon credits:

$$(10) \qquad \frac{V(\ell_\theta) - p_\theta - b(\ell_\theta)}{1 - \delta} \geq V(\ell_\theta) - p_\theta + \frac{\delta}{1 - \delta}\overline{\pi}$$

A REDD contract is self-enforceable if the long-term returns from the current relationship are at least as good as the present value of the returns from the alternate uses of land, so that the landholder of type θ remains trading with the same buyer and vice versa. Then, since both parties can deviate from the contract, the contingent payment must be sufficient to ensure a self-enforcing contract. It follows that the compensation scheme is bounded by the future gains of the relationship. The buyer solves for each landholder the following optimization program under imperfect enforcement and symmetric information:

$$(11) \qquad \begin{aligned} &\max_{p_\theta, b(\ell_\theta), \ell_\theta} \left(\frac{V(\ell_\theta) - p_\theta - b(\ell_\theta)}{1 - \delta} \right) \\ &\text{subject to} \qquad p_\theta + b(\ell_\theta) = \overline{u} + c(\ell_\theta, \theta), \\ &\qquad\qquad \frac{p_\theta + b(\ell_\theta) - c(\ell_\theta, \theta)}{1 - \delta} \geq p_\theta - c(\theta, \theta) + \frac{\overline{u}}{1-\delta}, \\ &\qquad\qquad \frac{V(\ell_\theta) - p_\theta - b(\ell_\theta)}{1 - \delta} \geq V(\ell_\theta) - p_\theta + \frac{\delta}{1-\delta}\overline{\pi}, \\ &\text{and} \qquad\qquad \ell_\theta \in [\theta_L, \overline{\ell}]. \end{aligned}$$

As the buyer can observe the landholder's type, he offers just enough incentive for a landholder of type θ to participate; the landholder's IRC can be rearranged as $p_\theta = \overline{u} + c(\ell_\theta, \ell) - b(\ell_\theta)$ and expression (9) can be restated as

$$(12) \qquad p_\theta \geq c(\theta, \theta) + \frac{c(\ell_\theta, \theta) - c(\theta, \theta) + \overline{u} - b(\ell_\theta)}{\delta},$$

which gives the lower bound on the base payment, p_θ, for inducing long-term cooperation

from a θ-type landholder. By substituting the IRC in (12), the optimal total compensation and the structure of the incentive scheme is established. The optimal stationary REDD contract is sustainable for all $\delta \geq \underline{\delta}$, where $\underline{\delta}$ is defined in the next section and Proposition (2) gives the optimal contract.

Proposition 2. *If contract enforcement is imperfect and the buyer can distinguish H-type and L-type landholders, an optimal self-enforcing REDD contract for each type, $\left\langle p^*_{\theta_L}, b^*(\ell^*_{\theta_L}) \right\rangle$ and $\left\langle p^*_{\theta_H}, b^*(\ell^*_{\theta_H}) \right\rangle$, implements additional and permanent forest conservation, ℓ^*_L and ℓ^*_H, for $\delta \geq \underline{\delta}$. The compensation schemes are characterized by:*

$$(13) \qquad p_{\theta_L} = c(\theta_L, \theta_L) \quad and \quad p_{\theta_H} = c(\theta_H, \theta_H),$$

$$(14) \quad b(\ell^*_{\theta_L}) \geq c(\ell^*_L, \theta_L) - c(\theta_L, \theta_L) + \overline{u} \quad and \quad b(\ell^*_{\theta_H}) \geq c(\ell^*_H, \theta_H) - c(\theta_H, \theta_H) + \overline{u}, \; and$$

$$(15) \qquad P(\ell^*_{\theta_L}) = \overline{u} + c(\ell^*_L, \theta_L) \quad and \quad P(\ell^*_{\theta_H}) = \overline{u} + c(\ell^*_H, \theta_H).$$

Equalities (15) identify the total compensation that the buyer offers an L-type landholder and an H-type landholder in each contract. The contract compensates the landholder for the opportunity cost of the additional land placed in forest and the reservation profits she makes when she takes other production alternatives. Equalities (13) give the base payments each landholder receives during date t, and equalities (14) give the size of the bonus that the buyer promises to pay at the end of the period to induce each type of landholder to keep additional land in forest.

Note that $p_{\theta_L} = p_{\theta_H}$ because by assumption $c(\theta_L, \theta_L) = c(\theta_H, \theta_H) = 0$. This means that under the optimal relational contract a landholder does not get paid until the end of the period regardless of her type. The contingent payment includes the opportunity cost of providing optimal forest conservation and the landholder's reservation profits. The contract structure reflects the nature of the problem. If the buyer offers a contract with a positive base payment, the landholder can deviate by placing only θ fraction of land in forest and still

collect the base payment. The buyer is only able to withhold the bonus, and he incurs a loss because $V(\theta) = 0$. Because an ex ante base payment is not conditioned on performance, it does not give the landholder incentive to remain in the relationship, and so the buyer needs to provide the landholder additional incentives to perform under imperfect verifiability of forest conservation. Moreover, because the contingent payments are limited by the future gains from the relationship, all compensation is shifted to the contingent payment so that the landholder has enough incentive to perform. The result is highlighted in the following corollary.

Corollary 4.1. *When formal enforcement is too costly, all compensation is paid as a performance payment at the end of the period upon observed forest conservation regardless of the landholder's alternative use of land.*

Total compensation is weakly increasing because the contingent payment is limited by the gains from the relationship. If the opportunity cost of the land or the landholder's reservation profits are too high, then the future gains from the relationship may not be enough for the parties to perform and self-enforce the contract.

4.2 Sustainability of Self-enforcing Contracts under Symmetric Information

Self-enforcing contracts are sustainable if the parties find the optimal strategy is to cooperate in every period. The cooperation decision depends on each party's discounted payoff stream from the contract (i.e., the relationship's productivity) and on how much each party values the future relative to the present (discount factor). If the parties hold a very low discount factor—δ near zero—the value of the relationship shrinks and contract compliance becomes less attractive. Therefore, it is more difficult to enforce contracts privately. As a consequence, social efficiency is potentially offset by the lack of formal enforcement.

In the case of the optimal REDD contract described in Proposition 2, the parties find cooperation (self-enforcement) to be the best strategy if they value the future relationship enough (given by each party's DICC). Combining the dynamic constraints for both parties given by (9) and (10) yields the self-enforcement constraint and the discount factor necessary to achieve cooperation under the optimal REDD contract.

Proposition 3. *Let $\underline{\delta} > 0$. Cooperation under the optimal REDD contract is achievable $\forall\ \delta \in [\underline{\delta}, 1)$, where $\underline{\delta} = \frac{c(\ell_\theta, \theta) + \overline{u}}{V(\ell_\theta) - \overline{\pi}}$. Long-term contracts are sustainable if the gains from the relationship are greater than the contingent payments needed to induce forest conservation:*

$$(16) \qquad \frac{\delta}{1-\delta}(S(\ell, \theta) - \overline{s}) \geq c(\ell_\theta, \theta) + \overline{u}.$$

Proposition 3 reports the self-enforcement dynamic constraint and the range of discount factors that can support a cooperative equilibrium under the optimal REDD contract. If the relationship is productive enough to cover the necessary incentives to perform, then self-enforcement can implement first-best conservation. The model predicts that parties that have a discount factor greater than or equal to $\underline{\delta}$ find it attractive to cooperate in the REDD context given the landholder's type.

The term in the numerator includes the total payment the buyer has to make to a landholder of type θ to keep additional land in forest. The payment represents the social cost of forest conservation under a REDD contract. The denominator represents the social net value of the additional forest conserved from contracting with a θ-type landholder (value of additional forest land net of the carbon offsets from an alternative source).

The higher the total payment is relative to the net value of the additional forest procured by the contract, the higher the discount factor needed to maintain cooperation is. As a consequence, only parties who value the future a lot find cooperation to be the optimal strategy. A high discount-factor threshold emerges when the landholder's opportunity cost

or reservation profits are too high. The higher the opportunity cost of the land, the less efficient the landholder is in providing carbon sequestration by maintaining additional land in forest.

For any given REDD payment made to a θ-type landholder when the benefit that the buyer accrues from the contracted land in forest is similar to the benefits of getting carbon credits from other alternative sources, the discount factor needed for cooperation is also very high and cooperation is harder to sustain. Accordingly, contract sustainability requires sufficiently high discount factors and a relationship productive enough to prevent any party from shirking on contract obligations and continue cooperation.

In contrast, the lower the cost of forest conservation is relative to the net benefits from keeping additional land in forest under the contract, the smaller the discount factor needed to self-enforce the contract. In these situations, REDD contracts are more likely to achieve their objective. We end by summarizing these insights in Corollary 4.2.

Corollary 4.2. *Cooperation under the optimal REDD contract is more likely to occur when the opportunity cost of maintaining forest land is low, the reservation options for buyer and a θ-type landholder are low, and the buyer's value of additional forest land is high.*

4.3   Self-enforcing Contracts with Asymmetric Information

Suppose that the landholder's type is private information.[9] However, the buyer knows that a landholder is of H-type with a probability of α. The buyer offers a menu of contracts, $\{(p_{\theta_L}, b(\ell_L)); (p_{\theta_H}, b(\ell_H)\}$, that are self-enforcing and that induce each type θ to keep the designated land in forest ℓ_θ instead of mimicking the other type.

A landholder selects the land she keeps in forest ℓ_θ by maximizing $U_\theta = P(\ell_\theta) - c(\ell_\theta, \theta)$. Let U_L and U_H be the per-period profits each landholder gets from the REDD contract. The

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[9]We assume that a landholder's type is invariant over time. If there are stochastic events such as a family illness or forest fire that may drive a change in landholder's type, this model would need to be modified to account for that.

contract must satisfy the following incentive compatibility constraints (ICC):

$$(17) \qquad\qquad U_L \geq P(\ell_H) - c(\ell_H, \theta_L) \quad \text{and}$$

$$(18) \qquad\qquad U_H \geq P(\ell_L) - c(\ell_L, \theta_H).$$

The individual rationality, self-enforcement, and incentive compatibility constraints characterize the set of feasible additional forest conservation achievable through a menu of contracts when formal enforcement is incomplete and there is hidden information. In addition, regardless of the payment, the per-period payoff for a θ-type landholder, U_θ, is increasing in θ (by the Envelope Theorem). The need for the ICCs reduces the set of feasible contracts, and the contracts are implementable only if they satisfy a monotonicity constraint. The addition of the ICCs yields to the following monotonicity constraint:

$$(19) \qquad\qquad c(\ell_H, \theta_L) - c(\ell_H, \theta_H) \geq c(\ell_L, \theta_L) - c(\ell_L, \theta_H).$$

Because $\theta_H > \theta_L$, $dc/d\ell > 0$, $dc/d\theta < 0$, and $d^2 c/d\ell d\theta < 0$, the contracts are incentive compatible (IC) if and only if ℓ_θ is nondecreasing. Then incentive compatibility implies that the fraction of land requested to be kept as forest from a L-type landholder cannot be higher than that requested from an H-type landholder regardless of the buyer's preferences.

Let $\Delta_L = c(\ell_L, \theta_L) - c(\ell_L, \theta_H)$ and $\Delta_H = c(\ell_H, \theta_L) - c(\ell_H, \theta_H)$ be the difference in the opportunity cost of keeping additional land in forest, ℓ_L and ℓ_H. An H-type landholder's ICC is relevant because she could mimic a L-type landholder and get profits equal to $P(\ell_L) - c(\ell_L, \theta_H) = P(\ell_L) - c(\ell_L, \theta_L) + c(\ell_L, \theta_L) - c(\ell_L, \theta_H) = U_L + \Delta_L$. Even if the L-type landholder's profit level is set to the lowest possible level fixed at $\bar{u}$ from the IRC, the H-type landholder benefits from an information rent Δ_L.[10] In contrast, the L-type does not benefit by imitating

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[10] Δ_L can be thought of as the buyer's expected additional per-period cost due to asymmetric information. Hence, it sets the upper limit on per-period expenditures the buyer would make on eliminating information asymmetries.

the H-type. If the L-type does, she gets $P(\ell_H) - c(\ell_H, \theta_L) = U_H - \Delta_H$. If $U_H = \bar{u}$, the L-type landholder gets a lower profit than her reservation profits. Then from the ICC we have

$$(20) \qquad\qquad U_H = \quad P(\ell_H) - c(\ell_H, \theta_H) = U_L + \Delta_L \quad \text{and}$$

$$(21) \qquad\qquad U_L = \qquad P(\ell_L) - c(\ell_L, \theta_L) = \bar{u}.$$

Assume that ℓ_H and $P(\ell_H)$ satisfy IC. This means that $\ell_H \geq \ell_L$ and inequality (20) can be rewritten as

$$(22) \qquad\qquad P(\ell_H) = c(\ell_H, \theta_H) + U_L + \Delta_L.$$

In addition, the contract for each type must satisfy $U_\theta = P(\ell_\theta) - c(\ell_\theta, \theta) \geq P(\hat{\ell}) - c(\hat{\ell}, \theta)$, where $\hat{\ell} \notin \mathcal{L} = [\theta_L, \bar{\ell}]$; neither type of landholder prefers an $\hat{\ell}$ that is not ℓ_L or ℓ_H. This implies that, since either type can deviate to $\ell = \theta$ and $c(\theta, \theta) = 0$, then $U_L = P(\ell_L) - c(\ell_L, \theta_L) \geq P(\theta_L) + \bar{u}$. Combining this with equality (22) results in

$$(23) \qquad\qquad P(\ell_H) - P(\theta_L) \geq c(\ell_H, \theta_H) + \Delta_L + \bar{u}.$$

Note that $P(\ell_H)$ is the maximum payment that the buyer gives to a landholder and $P(\theta_L)$ is the minimum, which equals zero because the buyer does not pay for a θ_L amount of land in forest. Without knowing the landholder's type, the buyer knows that any landholder would maintain at least θ_L land in forest because in the absence of payments landholders maintain some land in forest such that $\theta_H \geq \theta_L$. Long-term self-enforcement implies that the difference between the highest and lowest payment the buyer pays, $P(\ell_H) - P(\theta_L)$, must be less than or equal to the future gains from the relationship, $\frac{\delta}{1-\delta}(S(\ell, \theta) - \bar{s}) \geq P(\ell_H) - P(\theta_L)$. This relationship results in the next proposition.

Proposition 4. *When the buyer does not know the landholder's type, a REDD contract can*

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implement the conservation of additional land in forest, ℓ_θ, that generates a surplus $S(\ell_\theta, \theta)$ if and only if ℓ_θ is nondecreasing and

$$(24) \qquad \frac{\delta}{1-\delta}(S(\ell_\theta, \theta) - \bar{s}) \geq c(\ell_H, \theta_H) + \Delta_L + \bar{u}.$$

Inequality (24) combines the self-enforcing constraint with the standard IC constraint. The gains from the relationship should be at least as great as the cost of providing the highest fraction of land in forest, the value of the reservation profits, and the information rent to induce self-selection. Furthermore, the optimal payment depends on how restrictive the self-enforcement constraint is. Note that because ℓ_θ is nondecreasing, the right-hand side of (24) is nondecreasing in θ; therefore, the self-enforcing ICC is tightest for $\theta = \theta_H$. The optimal contract is now given by

$$(25) \qquad \begin{aligned} &\max_{\ell_\theta} \left(\frac{V(\ell_\theta) - c(\ell_\theta, \theta)}{1 - \delta} \right) \\ &\text{subject to} \quad \frac{\delta}{1-\delta}(S(\ell_\theta, \theta) - \bar{s}) \geq c(\ell_H, \theta_H) + \Delta_L + \bar{u} \quad \text{and} \\ &\qquad \ell_\theta \qquad\qquad\qquad \text{is nondecreasing.} \end{aligned}$$

Because of the hidden information, the buyer has to provide information rents to an H-type landholder such that she reveals her type. The information rents depend only on the quantity of land that the buyer requests from the L-type to keep in forest and not on the quantity requested from the H-type. As a consequence, incentive compatibility allows the buyer to request from the H-type the first-best forest conservation. But the more forested land that is requested from the L-type, the higher the cost for the buyer to induce the H-type is to deliver ℓ_H because he needs to pay higher information rents.

If the relationship is sufficiently productive and the discount factor is sufficiently high, the self-enforcing ICC (inequality 24) is not binding for the H-type landholder at the efficient

fraction in forest for both types, ℓ_L^* and ℓ_H^*. Consequently, the buyer is able to achieve first-best forest conservation for both types of landholders.

Proposition 5. *When the buyer does not know the landholder's type and the relationship is sufficiently productive, REDD contracts can implement first-best additional conservation of carbon offsets such that $\ell_L^* \leq \ell_H^*$. The compensation schemes are characterized by:*

(26) $$p_{\theta_L} = c(\theta_L, \theta_L) \quad and \quad p_{\theta_H} = c(\theta_H, \theta_H);$$

(27) $$b(\ell_{\theta_L}^*) \geq c(\ell_L^*, \theta_L) + \overline{u} \quad and \quad b(\ell_{\theta_H}^*) \geq c(\ell_H^*, \theta_H) + \overline{u} + \Delta_L^*; \ and$$

(28) $$P(\ell_{\theta_L}^*) = \overline{u} + c(\ell_L^*, \theta_L) \quad and \quad P(\ell_{\theta_H}^*) = \overline{u} + c(\ell_H^*, \theta_H) + \Delta_L^*$$

and the discount factor satisfies $\delta > \frac{c(\ell_H^*, \theta_H) + \Delta_L^* + \overline{u}}{V(\ell_H) + \Delta_L^* - \overline{\pi}}$.

Under these circumstances the first-best outcome can be implemented, and it is optimal to do so. As in the symmetric information case, the optimal contracts do not give any landholder regardless of her type an upfront payment, and the full payment is made contingent on the conservation of forest at the end of the period. An L-type landholder receives the same payment she would receive if the buyer could distinguish types. But the H-type also receives the information rents corresponding to the first-best allocation of land in forest for an L-type, Δ_L^*.

If the reservation profits are too high or the discount factor is small, the future gains from the forest-conservation relationship become too small to support any level of forest conservation. In this case, no schedule may satisfy the constraints, and forest conservation is not possible under a relational contract.

However, even if the gains from the relationship are small, relational contracts may still implement conservation, depending on how restrictive the self-enforcement constraint is. In this case, inequality (24) binds with $\theta = \theta_H$ for $\ell_H = \ell_H^*$. If the self-enforcement constraint is very restrictive, it is better to reduce the quantity of land in forest for both types below the

first-best level and request some levels of conservation for both types instead of having only the H-type providing the first-level and the L-type not participating in carbon sequestration. Requesting additional land in forest from the L-type implies an increase in the slope of the H-type payment schedule (due to information rents). Because the total payment is limited by the gains from the relationship, giving additional incentives for the H-type landholder means decreasing incentives for the L-type landholder. This is sub-optimal because a marginal reduction in forest conserved by the H-type reduces the surplus generated but allows for more area in forest from the L-type. As the L-type conservation is substantially below the first-best, ℓ_L^*, increasing ℓ_L raises the overall surplus. As a result, the requested quantity of forest for each type is given by ℓ_{LR} and ℓ_{HR}, for which the marginal gains of inducing ℓ_L equals the marginal cost of reducing ℓ_H.

If the self-enforcement constraint is less restrictive, the landholder with low opportunity cost (H-type) is asked to keep a higher quantity of land in forest (but below first-best) because she is more efficient in providing carbon sequestration. Requiring a given-type landholder to place more land in forest requires an increase in the size of the bonus. As the requested land in forest increases, raising the land maintained in forest by the L-type becomes more expensive relative to the H-type. Therefore, the buyer screens L-type landholders, who provide lower forest conservation, while H-type landholders provide higher amounts of carbon offsets. This is summarized in the next corollary.

Corollary 4.3. *When the discounted value of the forest conservation is small, a relational contract may still implement sub-optimal but strictly positive forest conservation. If self-enforcement is too restrictive, the contract lowers provision of both types to a similar level of forest conservation. If self-enforcement is less restrictive, the L-type landholder provides less forest conservation than the H-type landholder, who provides less forest conservation than first-best levels.*

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5 Conclusions

Among the alternate measures to mitigate global climate change, reducing emissions from deforestation and forest degradation has been identified as a cost-effective option. However, REDD contract implementation is challenging because of technical, financial, and institutional considerations, including the verifiability, additionality, and permanence of the carbon offsets. These elements make contract design and enforceability a key issue for the implementation of a REDD mechanism. Previous research on REDD contracts assumes that there exists some probability of enforcement (Palmer, Ohndorf, and MacKenzie, 2009) or that contracts are fully enforceable (Mason and Plantinga, 2011). However, because of the multiple institutional frameworks in which REDD is potentially embedded, this may not be the case. In this paper, we propose the use of informal incentives and good faith as key elements to enforce contracts and overcome incomplete enforcement. We have derived the optimal REDD contract and shown how the optimal level of incentive provision is characterized when participants have symmetric and asymmetric information about the opportunity cost of the land. We have also derived the parameters under which self-enforcement and cooperation are sustainable.

When contracts are not enforceable but the buyer knows the landholder's type, the buyer can induce the optimal forest conservation from all types of landholders. Each landholder is paid the opportunity cost of the land and her reservation profits. The total payment includes a single payment contingent on performance that is paid at the end of the period.

When the buyer cannot distinguish landholder types, the model predicts that he can still induce first-best conservation if the gains from the relationship are sufficiently large. The optimal contract includes the same payment structure and value for the landholder with high opportunity cost, while the landholder with low opportunity cost accrues additional information rents, which are also paid at the end of the period.

If the gains from the relationship are smaller, first-best forest conservation is not achievable through self-enforcing contracts. However, a second-best level of conservation is possible depending on how small the gains from the relationship are. Both types of landholders can be induced to maintain the same relative quantity of land in forest, or if the gains are larger, the H-type landholder conserves a higher amount of forest than the L-type landholder. But if the gains from the relationship are too small, self-enforcing contracts are not implementable.

This paper takes a first step to apply the relational contracting framework to a REDD environment when the the owner of the land has private information about her opportunity cost. The results provide insight into the power of informal enforcement mechanisms that support incentives even when REDD-explicit contracts are incomplete. It also highlights the limits of self-enforcement when there is hidden information. From the policy perspective, the results of the paper provide insights on the situations in which self-enforcing contracts can be successfully implemented to achieve additional and permanent carbon offsets.

Appendix

Proof of Proposition 1. Because forest conservation is verifiable—and so there is no asymmetric information between the buyer and sellers—it is included in the contract and the buyer is able to offer a specific contract to each seller according to her type. The buyer solves the following maximization program for each seller:

$$\max_{P_\theta, \ell_\theta} \left(\frac{V(\ell_\theta) - P_\theta}{1 - \delta} \right)$$

(A-1) $\qquad\qquad$ subject to $\quad P_\theta = \overline{u} + c(\ell_\theta, \theta)$ and $\ell_\theta \in [\theta_L, \overline{\ell}].$

Substituting the seller's participation constraint into the buyer's profit option and solving for the first-order Kuhn-Tucker conditions gives

$$V'(\ell_\theta) \begin{cases} < c'(\ell_\theta) & \text{if } \ell_\theta^* = \theta \\ = c'(\ell_\theta) & \text{if } \theta < \ell^* \leq \overline{\ell} \end{cases}$$

Because by assumption the buyer is only going to contract with types for which the benefit of forest conservation exceeds its cost and $\ell_\theta \in [\theta_L, \overline{\ell}]$, forest conservation is optimal when the marginal cost equals its marginal benefit, which is given by the following first order condition for each type: $V'(\ell_\theta^*) = c'(\ell_\theta^*, \theta)$.

Each seller receives a payment that induces her participation, $P_\theta = \overline{u} + c(\ell_\theta, \theta)$, each seller receives a profit of $U_\theta^* = \frac{\overline{u}}{1-\delta}$, and the buyer gets $\pi^* = \frac{V(\ell_\theta^*) - c(\ell_\theta^*, \theta) - \overline{u}}{1-\delta}$ from each relationship. $\qquad\square$

Proof of Proposition 2. First let's prove that each seller's IRC binds. If her IRC binds then $P(\ell_\theta) - c(\ell_\theta) = \overline{u}$. Substituting her IRC into her $DICC$ (inequaliy 9) yields $\frac{\overline{u}}{1-\delta} \geq \frac{\overline{u}}{1-\delta}$, which is true. Then her IRC binds. If her $DICC$ binds we have $\frac{p + b(\ell_\theta) - c(\ell_\theta)}{1-\delta} = p_\theta - c(\theta, \theta) + \frac{\overline{u}}{1-\delta}$. Rearranging we get $b(\ell_\theta) = c(\ell_\theta) - \delta p_\theta + \overline{u}$, and substituting into the seller's

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IRC we get $p_\theta > 0$, which is not true because by assumption the fixed payment can be zero. Now let y^* be the equilibrium contract that a buyer offers to a θ-type seller, where $P(\ell_\theta) = p_\theta + b(\ell_\theta)$. The buyer maximizes his profit holding the seller's *IRC* with equality, $P(\ell_\theta) = \overline{u} + c(\ell_\theta)$, and solving for p_θ in both her *IRC* $(p_\theta = \overline{u} + c(\ell_\theta)) - b(\ell_\theta))$ and *DICC* $(p_\theta \geq c(\theta, \theta) + \frac{c(\ell_\theta) - c(\theta,\theta) + \overline{u} - b(\ell_\theta)}{\delta})$. Substituting her *IRC* into her *DICC* and rearranging we get $b(\ell_\theta) \geq c(\ell_\theta) - c(\theta, \theta) + \overline{u}$, which holds with equality because the buyer is maximizing his utility subject to the participation of a θ-type seller. He will only offer a $b(\ell_\theta)$ large enough to induce conservation and participation. Substituting back into the *IRC* and rearranging leads to $p_\theta = c(\theta, \theta)$, which is zero because by assumption $c(\theta, \theta) = 0$ for each type. Combining p_θ and $b(\ell_\theta)$ the total payment is $P(\ell_\theta) = \overline{u} + c(\ell_\theta)$.

Substituting $P(\ell_\theta)$ into the buyer's objective function, we obtain the same first-order Kuhn-Tucker conditions as in proof one. Then the buyer requests ℓ^* such that it maximizes the surplus. $P(\ell^*) = p + b(\ell^*) = c(\ell^*) + \overline{u}$. Let's check the participation constraint of the buyer. Substituting $P(\ell^*)$ we get $V(\ell^*) - c(\ell^*) - \overline{u} \geq \overline{\pi}$, which ends up being $S(\ell^*) - \overline{s} \geq 0$, which is true since the net surplus from conservation exceeds zero. $\qquad\square$

Proof of Proposition 3. For cooperation to be achievable, the DICC for the buyer and for the θ-type seller must hold. Then combining equations (9) and (10) we get the self-enforcing constraint: $\frac{\delta}{1-\delta}(S(\ell, \theta) - \overline{s}) \geq c(\ell_\theta, \theta) + \overline{u}$. Solving for the discount factor we get $\underline{\delta} \geq \frac{c(\ell) - c(\theta,\theta) + \overline{u}}{V(\ell) - c(\theta,\theta) - \overline{\pi}}$. Hence, cooperation takes place for all values of δ that satisfy $\underline{\delta}$. $\qquad\square$

Proof of Proposition 4. From the ICC for each seller type we get equation (23): $P(\ell_H) - P(\theta_L) \geq c(\ell_H, \theta_H) + \Delta_L + \overline{u}$. A buyer makes the highest payment to the H-type seller and the lowest payment to the L-type seller. Self-enforcement dictates that the difference between the highest possible payment and the lowest payment should be lower or equal to the gains from the relationship: $\frac{\delta}{1-\delta}(S(\ell, \theta) - \overline{s}) \geq P(\ell_H) - P(\theta_L)$. Combining this with equation (23) we get $\frac{\delta}{1-\delta}(S(\ell_\theta, \theta) - \overline{s}) \geq c(\ell_H, \theta_H) + \Delta_L + \overline{u}$. $\qquad\square$

Proof of Proposition 5. First let's prove that the L-type seller's IRC binds. In the proof of proposition 2, we proved that the IRC is binding and that the DICC is not for all types. Because of the asymmetric information about the seller's type, an incentive compatibility constraint (ICC) for each must be added to have each seller to reveal her true type. Given the ICCs (equations (17) and (18)), the L-type seller does not benefit by mimicking the H-type seller because she gets $P(\ell_H) - c(\ell_H, \theta_L) = U_H - \Delta_H$. If $U_H = \overline{u}$, the L-type seller gets less than her reservation profit. Then the L-type seller's binds. In contrast, if the H-type seller mimics an L-type seller, she gets profits equal to $P(\ell_L) - c(\ell_L, \theta_H) = P(\ell_L) - c(\ell_L, \theta_L) + c(\ell_L, \theta_L) - c(\ell_L, \theta_H) = U_L + \Delta_L$. Even if the L-type seller's profit is $\overline{u}$ from the participation constraint, the H-type seller benefits from an information rent Δ_L. Therefore, the H-type IRC does not bind while the ICC binds. By substituting the IRC into the self-enforcing constraint for the L-type, we get the payment structure given in proposition 5. To get the payment structure for the H-type, the ICC and DICC are combined. Finally, the discount factor is derived by solving for δ in $\frac{\delta}{1-\delta}(S(\ell_\theta, \theta) - \overline{s}) \geq c(\ell_H, \theta_H) + \Delta_L + \overline{u}$.

$\square$

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