SOCIALLY OPTIMAL ROYALTY DESIGN AND ILLEGAL LOGGING UNDER ALTERNATIVE PENALTY SCHEMES

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Abstract

We study the socially optimal design of forest royalty and enforcement instruments in the case where concessions are allocated by a government, illegal logging incentives are present, and the government has available both area-based and value-based royalty instruments. When harvesters are risk neutral, the optimal policy mix depends on the presence of negative externalities and on the type of penalty scheme. For risk-averse harvesters the results differ. When the penalty is assessed on undeclared income, a royalty based subsidy is not optimal, but when penalties are levied on evaded royalty payments, the optimal royalty system may be progressive or regressive depending on the importance of the government's revenue constraint. Auditing is optimal regardless of the penalty scheme or presence of externalities, although its level differs. Accounting for negative externalities in the social welfare function implies a higher optimal royalty rate, but lower progression in the rate, and increased auditing.

Keywords: illegal logging, royalty design, penalty schemes.

JEL Classification: D81, H26, Q21, Q23.

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1. Introduction

In most of the countries with tropical forests, concessions are the primary means by which government-owned native forests are harvested (Walker and Smith 1993, Gray 2000). Policy makers sometimes view concessions as a means for providing stable wood flows to domestic forest industry (Verissimo et al. 2002). Royalties, or fees, charged for harvesting concessions provide large sources of funds to many developing country governments (Gray 2000, Amacher et al. 2001). Witness Brazil, which is about to open up over 70 million hectares of public Amazon forests for concessions, with a cited purpose being the generation of government revenues through fees attached to the concessions and sustainable forest harvesting for timber concerns (MMA 2001).

Despite the importance of royalty systems, the principles of socially optimal instrument design have not been considered. This is an important omission given the problems that are known to exist with these systems. For example, countries with distant forest concessions and inefficient centrally-located governments have difficulty containing illegal logging (a main component of tropical deforestation). There is also an inability, and sometimes unwillingness, of governments to enforce and penalize such acts even when detected (e.g., see Clarke et al 1993 for a discussion of lack of monitoring of harvest activities in developing countries, and Palmer 2000). As a result concession harvesting is usually inconsistent with parameters specified in contracts made between a government and harvesters. Illegal logging and underreporting of harvest income undermine a government's ability to implement royalty systems. Both may also increase negative externalities from deforestation and unnecessarily increase net rents to harvesters (ITTO 2002, Repetto and Gillis 1988). It has also been argued that current royalty rates in developing countries are far too low, providing little incentive to curb excessive harvesting (Gray 2000, Vincent 1990, Merry et al. 1998). Moreover, poorly-designed royalty systems have been linked to incentives for illegal logging (Palmer 2000).[1]

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[1] Royalties and logging behavior have been studied recently. Vincent and Boscolo (2000) analyze the impact of royalties on use of improved logging practices, such as reduced impact logging and diameter limits. Their results are simulation-based and royalty/auditing choice and the possibility of illegal

In this paper we develop benchmark results for the socially optimal design of forest royalty and enforcement instruments. We assume that concessions are allocated by a government, and that harvesters have incentives to illegally log within the concession. Illegal logging is introduced as either excessive volume removal or logging beyond the concession boundary. Illegal logging is not detectable by the government unless costly enforcement is employed, and even with enforcement the government can detect illegal logging with a probability less than one. Detection occurs through auditing, and the cost of auditing represents the enforcement efficiency of the government. Should the government detect illegal logging, we allow for one of two penalty schemes, both of which mimic penalties currently used in practice: a fine collected on undeclared (unreported) harvest income, or a fine collected on evaded (non-paid) royalty payments.[2] We consider two types of royalties common in practice and the literature, concession area-based royalties and harvest value- or volume-based royalties. We allow these to also be used in combinations, making the royalty system progressive or regressive in the sense that the average tax rates are either increasing or decreasing in the taxable base.

While there are several political economy discussions of concessions each based on its own empirical peculiarities, no one to our knowledge has stepped back and evaluated the benchmark theory behind a benevolent dictator that chooses these instruments to maximize social welfare and generate rents and revenues. Obviously, we need this benchmark before we evaluate specific cases from a political economy point of view. To this end we evaluate two questions of optimal policy design, first, how do incentives for harvesters to illegally log depend on auditing effort and royalty choices, among other parameters?, and, second, how should a policy maker choose royalties and audit frequencies to provide the efficient level of rents to harvesters and amenities provided by native forests? We find that illegal logging, negative externalites

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logging and penalties are not considered (they do acknowledge the potential difficulties of monitoring logging, however). Clarke et al (1993) examine the role of penalty schemes and optimal dynamic enforcement expenditures for an open access forest situation by considering a Nash game between authorities and forest poachers, where detection of illegal logging leads to prosecution. Walker and Smith (1993) model noncompliance of loggers facing a given concessions contract, and they formulate a type of auditing procedure that can limit noncompliance. But the choices of royalty and auditing policies from the perspective of a government, under revenue constraints and illegal logging incentives for harvesters, are not examined in this collection of work.

[2] This idea is related to literature on tax evasion, see e.g. Cowell (1987) and Myles (1995) for surveys.

from a social welfare point of view, penalty schemes, and risk preferences of harvester, factor importantly in instrument design, serving to make the choice of royalties much more complicated than what is usually assumed. Solutions to deforestation are not as simple as raising all royalty fees or shifting more resources toward enforcement of concessions contracts. Rather, royalties and auditing must be designed as a system and not considered, as they often are, as separate instruments. In some rare cases, a social welfare maximizing government may never find it optimal to either eliminate illegal logging or enforce penalties under some conditions. In other cases the optimal royalty system may be progressive or even regressive, as a combination of area-based and value- or volume-based royalties. The appropriateness of progressivity has not been part of the policy debate, but our results suggest it should be.

The rest of the paper is organized as follows. In section 2 we present a simple model how illegal logging depends on penalty schemes, audit strategies and royalties, and risk attitudes of the harvester. In section 3 we study socially optimal royalty and auditing design for a risk neutral harvester when negative externalities are either present or absent. We extend this analysis in section 4 for the case of risk-averse harvesters. The last section contains our conclusions.

2. A Basic Model of Illegal Logging

Consider a concessionaire (i.e., harvester) who receives a permit to harvest a concession. Suppose that the harvester receives a right to harvest some amount $Q = \overline{Q}$. We will interpret this as volume throughout the paper. Governments normally impose royalties, or fees, for these harvest rights. We consider two common forms of royalties, a harvested volume- or value-based fee denoted by *t*, and an area-based royalty subsidy or fee denoted by *I*. The royalty rate *t* is often assessed against the value permitted for harvesting, $tq\overline{Q}$, where *q* is the timber price. This value-based interpretation is the one we will use for *t*. We allow the area-based royalty to be either a net fee or a net subsidy – we show later how this distinction is important to instrument design. Combinations of royalties are common. Usually, with either area- or value-based royalties, some quantity of harvest volume or benefit is exempted from the fee paid by the harvester.

The way we define area- and value-based royalties mimics most systems found in developing countries with concessions, such as Indonesia, The Philippines, and Latin America, as pointed out in Gray (2000), Amacher et al. (2001), and Vincent (1990).

If the harvester does not engage in illegal activities, then the exact amount permitted in the concession is logged, and the harvester earns rents equal to,

$$\pi = q\overline{Q}(1-t) - c(\overline{Q}), \tag{1}$$

where $c(\overline{Q})$ is a convex cost of harvesting, i.e. $c'(\overline{Q}), c''(\overline{Q}) > 0$.[3] If the harvester's rent is positive at $\overline{Q}$, i.e., if $q(1-t) - c'(\overline{Q}) > 0$, then there is an inherent incentive for illegal logging. Given that forest concessions are not constantly observed by the government, there is a problem of moral hazard present, because detection is imperfect. Denote illegal logging by X and let it be defined as 'excessive' harvesting, expressed by the difference between actual logging Q and permitted logging $\overline{Q}$, i.e., $X \equiv (Q - \overline{Q})$. Given our interpretations above, excessive harvesting could be thought of as harvesting too much area, or as removal of too much volume. Timber trespass is a common form of the former, while high grading is a common form of the latter. With high grading, either too much volume is removed, or too much volume is removed from high valued species groups. We can consider the concession above in terms of species groups if we think of $\overline{Q}$ as a vector of species harvest allowances.

Let $p(\leq 1)$ denote the probability of illegal logging detected by the government. The government is not assumed to audit the harvester one hundred percent of the time, and so the frequency of auditing (i.e., the probability of detecting illegal logging) is a measure of the intensity with which the government monitors and detects illegal activities. We consider two types of *penalties* imposed by the government should cheating be detected. Both are common in government documents pertaining to concessions programs (Gray 2000) and have been analyzed in other literature on tax evasion (e.g. see Yitzhaki 1974 for penalties levied against evaded taxes and Allingham and Sandmo 1972 for penalties levied on undeclared incomes).

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[3] In what follows, derivatives of a function with one argument is denoted with primes, while partial derivatives of functions with more than one argument are denoted by subscripts.

The first penalty is a fine assessed against the concessionaire's undeclared gross harvest revenue from illegal logging not reported to the government. The concessionaire's actual profits in this penalty scheme would now depend on whether illegal logging is detected. If illegal logging is not detected with probability (*1-p*), then actual profits are defined as,

$$Y^u = \left[qQ^u - tq\overline{Q} - c(Q^u) + I\right] \tag{2}$$

and if illegal logging is detected with probability *p*, then actual profits include the penalty,

$$Z^u = \left[Y^u - fqX^u\right], \tag{3}$$

where the '*u*' superscript indicates the case where penalties are assessed on undeclared (evaded) gross harvest revenues, *f* is the fine rate, X^u is illegal harvesting under this penalty, and *I* is the area-based royalty (fee or subsidy).

The second penalty system to consider is one where the penalty rate is levied on actual evaded royalty payments. Evaded royalty payments amount to fees the government would have collected if the concessionaire truthfully reported the harvest level to the government. Now the concessionaire's actual profit is written,

$$Y = \left[qQ - tq\overline{Q} - c(Q) + I\right], \tag{4}$$

if illegal logging is not detected with probability $(1-p)$, and

$$Z = \left[Y - ftqX\right], \tag{5}$$

if illegal logging is detected with probability p.

Given a positive probability of being caught, the precise incentive to illegally log depends on the harvester's risk preference. We allow for both risk neutrality and risk aversion.

2.1. Incentives for Illegal Logging: Risk Neutral Harvesters

The risk-neutral harvester maximizes expected profits, defined under the two penalty schemes, respectively, as,

$$\underset{Q^u}{Max}\ E\pi = qQ^u - c(Q^u) - tq\overline{Q} + I - pqfX^u \text{, and} \quad (6)$$

$$\underset{Q}{Max}\ E\pi = qQ - c(Q) - tq\overline{Q} + I - ptqfX \quad (7)$$

First-order conditions for harvesting under each scheme are,

$$Q^u : q - c'(Q^u) - pqf = 0 \text{, and} \quad (8)$$

$$Q : q - c'(Q) - pqtf = 0 \quad (9)$$

Both conditions show that optimal logging is defined by the equality of marginal revenue (q) and expected marginal cost, which consists of harvest cost plus the expected fine payment $(c'(Q^u) + pqf$ or $c'(Q) + pqtf)$.

It is easy to show that illegal logging depends on exogenous parameters as follows.

$$X^u = X^u(\underbrace{q}_{+}, \underbrace{p}_{-}, \underbrace{f}_{-}, \underbrace{t}_{0}, \underbrace{I}_{0}) \quad \text{and} \quad X = X(\underbrace{q}_{+}, \underbrace{p}_{-}, \underbrace{f}_{-}, \underbrace{t}_{-}, \underbrace{I}_{0}) \quad (10)$$

The effects of q, f, p and I on illegal logging are similar in both penalty cases. A higher timber price increases illegal logging, while a higher probability of detection and penalty reduce it. Changes in the area-based royalty I will have no effect under risk neutrality. Interestingly, the effect of the t on illegal logging depends on the penalty scheme. When the penalty is based on undeclared income, t has no effect on actual logging and is a nondistortionary instrument. However, when the penalty is levied on evaded royalty payments, higher royalty rates decrease illegal logging; t is now a distortionary instrument. This difference arises because increases in t introduce a negative substitution effect on actual logging only with penalties levied on evaded royalty payments.

2.2 Incentives for Illegal Logging: Risk-Averse Harvesters

A risk-averse harvester's behavior will differ from that of a risk-neutral harvester. When the penalty is levied on undeclared income, the concessionaire maximizes the following expected utility function,

$$\underset{Q^u}{Max}\; EU(\pi) = (1-p)u(Y^u) + pu(Z^u), \tag{11}$$

where $Y^u = \left[qQ^u - tq\overline{Q} - c(Q^u) + I\right]$ and $Z^u = \left[Y^u - fqX^u\right]$. The first-order condition for the optimal logging is,

$$EU_{Q^u} = (1-p)u'(Y^u)a + pu'(Z^u)b = 0, \tag{12}$$

where $a = q - c'(Q^u) > 0$ and $b = q - c'(Q^u) - fq < 0$. The second-order condition is,

$$EU_{Q^uQ^u} = (1-p)u'(Y^u)a\left[-A(Y^u)a + A(Z^u)b\right] - c''(Q^u)((1-p)u'(Y^u) + pu'(Z^u)) < 0, \tag{13}$$

where $A(Y^u) = -\dfrac{u''(Y^u)}{u'(Y^u)}$ and $A(Z^u) = -\dfrac{u''(Z^u)}{u'(Z^u)}$ denote the Arrow-Pratt measures of absolute risk-aversion (see Arrow 1974).

An interior solution requires that $EU_{Q^u}\,_{|Q^u=\overline{Q}} > 0 \Leftrightarrow q - \left[c'(Q^u) + pfq\right] > 0$. Thus for a risk-averse harvester to engage in illegal logging, the timber price must exceed the expected marginal cost of logging, which now includes the marginal cost of harvesting plus the expected fine payment.

The comparative statics of harvesting and illegal logging for this case are reported in Appendix 1. We can express the effects of changes in exogenous variables as follows,

$$X_f^u < 0 \text{ and } X_p^u < 0 \tag{14a}$$

$$X_I^u \geq 0 \text{ and } X_t^u = -q\overline{Q}X_I^u \leq 0 \tag{14b}$$

A higher penalty rate and higher probability of detection both decrease illegal logging. Higher area-based royalty subsidies increase illegal logging under decreasing absolute risk aversion (DARA), but it has no effect under constant risk-aversion (CARA). This follows from the fact that greater rents for the harvester increase the incentive to capture rents illegally and risk a penalty, as long as risk aversion is decreasing in wealth. Naturally, for an area-based royalty fee, the sign is reversed under DARA, i.e. $X_I^u < 0$. As for a higher value-based royalty rate, we find only an income effect but no substitution effect under DARA. Thus, harvesting and illegal logging are inversely related to the royalty rate *t* under DARA.

Turning now to the penalty levied on evaded royalty payments, the concessionaire's expected utility maximization problem becomes,

$$\underset{Q}{Max}\ EU(\pi) = (1-p)u(Y) + pu(Z), \tag{15}$$

where *Y* and *Z* are as defined earlier. The first- order condition is,

$$EU_Q = (1-p)u'(Y)\hat{a} + pu'(Z)\hat{b} = 0, \tag{16}$$

where $\hat{a} = q - c'(Q) > 0$ and $\hat{b} = q - c'(Q) - tfq < 0$, and the second-order condition is,

$$EU_{QQ} = (1-p)u'(Y)\hat{a}\left[-A(Y)\hat{a} + A(Z)\hat{b}\right] - c''(Q)\left[(1-p)u'(Y) + pu'(Z)\right] < 0. \tag{17}$$

The first order condition (16) shows that the harvester's choice of logging equates expected marginal benefits from harvesting to expected marginal costs. An interior solution for illegal logging implies $EU_{Q|Q=\overline{Q}} > 0 \Leftrightarrow q - \left[c'(Q) + ptfq\right] > 0$, with the interpretation being similar to the earlier case.

The comparative statics of illegal logging with respect to the fine, detection probability, and timber price parameters are qualitatively the same as when the penalty is assessed on undeclared income. There is again an important difference between penalty schemes concerning the effect of the value-based royalty *t* on harvesting and illegal logging. When penalties are levied against evaded royalties, *t* is a distortionary instrument. That is, in addition to having an income effect, it also induces a substitution effect on harvesting. In Appendix 2, we demonstrate that an increase in *t* reduces illegal logging, i.e., $X_t < 0$ under DARA, when the penalty is levied on undeclared income, and even under CARA when the penalty is levied on evaded royalty payments. We summarize our comparative statics results in the following,

Result 1. Illegal logging under risk-aversion and alternative penalty schemes. *Illegal logging is inversely related to the fine rate and the probability of detection for both penalty schemes irrespective of risk aversion behavior. It is inversely related to the value-based royalty rate through an income effect under decreasing absolute risk aversion when the penalty is levied against undeclared income, but through income and substitution effects when the penalty is levied against evaded royalty payments, due to the substitution effect and the inverse relationship between illegal logging and royalty rates. The latter also holds under constant absolute risk aversion.*

3. Optimal design of royalties and auditing – Risk neutrality

We now turn to our main objective, the socially optimal design of royalties and auditing. Because the socially optimal design of instruments presupposes a benevolent dictator interpretation for the policy maker, we conventionally assume that the government maximizes a net social welfare function, which includes the profits of the concessionaire and negative externalities caused by illegal logging. In practical terms, these externalities are associated with deforestation of expanding forest frontier boundaries, or with high grading of existing forest stocks, or both. We capture them by writing a function that depends on illegal logging, $v(X)$, with $v'(X) < 0$. The derivative of this function measures the negative externalities associated with deforestation through illegal logging. The social welfare function can now be written,

$$SW = E\pi + v(X)\,, \tag{18}$$

The government must expend some type of auditing effort. The cost of auditing incurred by the government is an increasing and convex function of the probability of detection, $c(p)$, such that $c'(p) > 0$, $c''(p) > 0$, and $c'(0) = 0$.[4] Finally, we assume that the government faces a constraint in terms of expected revenue collections. Expected government revenues depend on any royalty payments collected, fines collected, and the cost of auditing. When penalties for illegal logging are levied on undeclared income or evaded royalty payments, government revenues are specified respectively as,

$$R^u = tq\overline{Q} + pfqX^u - c(p) - I \text{, and} \tag{19}$$

$$R = tq\overline{Q} + ptfqX - c(p) - I\,. \tag{20}$$

3.1 Penalty charged on undeclared income

We first examine policy design under the assumption that negative externalities are not important or are ignored by the government. Under this payment scheme and risk neutrality, it turns out that the area-based royalty is equivalent to the value-based royalty, and so we restrict attention to only the value-based royalty *t* in deriving results. We return to both area- and value-based royalties when the distinction matters.

From (18) the government would choose *t* and the audit probability *p* to maximize the expected indirect profit function $E\pi^*$ subject to $R^u = tq\overline{Q} + pfqX^u - I - c(p) \geq \overline{R}$. Writing the Lagrangian function for this problem as $\Omega^u = E\pi^* + \lambda(R^u - \overline{R})$, and

[4] The high cost of auditing and enforcement of concessions activities has been cited as one reason why illegal logging is a problem in tropical countries with concessions. Because we define the cost of auditing as a function of the audit probability, it could in principle capture several features of this cost in practice, such as the inefficiency of the government in undertaking these actions.

accounting for the harvester's response, we have the following necessary conditions for the choice of t and p:

$$\Omega_t^u = -q\overline{Q} + \lambda q\overline{Q} = 0 \text{, and} \tag{21}$$

$$\Omega_p^u = -fqX^u + \lambda\left[fqX^u + pfqQ_p^u - c'(p)\right] = 0. \tag{22}$$

The government chooses the royalty rate to equate marginal revenue collections, $\lambda q\overline{Q}$, to marginal costs, $q\overline{Q}$, defined in terms of the effects they have on welfare of the concessionaire. The multiplier of the government's revenue constraint is the marginal effect on social welfare of a change in the royalty rate, i.e. it is the marginal cost of public funds.[5] From (21), we see that λ = 1 at the optimal royalty choice – this means all required revenues should be collected using the value-based royalty instrument *t*, which is nondistortionary. Moreover, it is not optimal to allocate any of the government's resources to auditing activities, because expected marginal returns are smaller than the marginal cost of auditing. This can be seen by substituting $\lambda = 1$ in $\Omega_p^u = 0$, which gives $\Omega_p^u\big|_{\lambda=1} < 0$, implying $p = 0$ at the optimum.

Our result explains an observation made in the literature. Some have argued that many developing country governments who employ royalties do not enforce illegal logging enough or at all (Johnson 2002). We have provided a benchmark case showing that this strategy may indeed be optimal for the policy maker, but under very specific conditions.

When the government responds to externalities the basic result above is modified. The social welfare function is now written as, $SW = E\pi^* + v(X^u)$, and $v'(X^u) < 0$ measures social costs associated with illegal logging. We now have the following first order conditions for the Lagrangian function: $\Omega^u = E\pi^* + v(X^u) + \lambda(R^u - \overline{R})$,

[5] For a formal discussion of λ and its implications for optimal tax instrument design in general, see Atkinson and Stiglitz (1980), or Myles (1995).

$$\Omega_t^u = -q\overline{Q} + \lambda q\overline{Q} = 0 \text{, and} \tag{23}$$

$$\Omega_p^u = -fqX^u + v'(X^u)Q_p^u + \lambda\left[fqX^u + pfqQ_p^u - c'(p)\right] = 0\,. \tag{24}$$

From (23) we continue to find that $\lambda = 1$ at the optimal policy mix, so that required revenue should still be collected using the value-based royalty instrument. However, there is an additional welfare effect of auditing given by the second term in (24). This represents a reduction in the negative externality because of decreased illegal logging. It is now optimal for the government to allocate some royalty revenue collections to auditing activities. To see this, assume that the value-based royalty rate is set at its optimal level, $t = t^*$, and then use (23) to rewrite (24) as,

$$\Omega_p^u\Big|_{t=t^*} = pfqQ_p^u - c'(p) + v'(X^u)Q_p^u\,. \tag{25}$$

Writing this condition at corner solutions of no auditing p = 0 and perfect auditing p = 1, we have $\Omega_p^u\Big|_{\substack{t=t^* \\ p=0}} = v'(X^u)Q_p^u > 0$, and $\Omega_p^u\Big|_{\substack{t=t^* \\ p=1}} = fqQ_p^u - c'(1) + v'(X^u)Q_p^u < 0$, respectively. Comparing these suggests it is optimal to devote a share of the government's royalty revenues to auditing efforts.

In order to facilitate interpretation, we re-express (25) as follows,

$$c'(p) = \frac{p}{Q^u}(fq + \frac{1}{p}v'(X^u))\varepsilon_p^u\,, \tag{26}$$

where $\varepsilon_p^u = \dfrac{Q_p^u p}{Q^u} < 0$ and $pfq + v'(X^u) < 0$. Auditing is chosen so that the marginal cost of auditing (LHS) is equal to the marginal benefit (RHS). The marginal benefit includes the marginal expected fine revenue (first term) plus the marginal benefit of additional externalities that follow from reductions in illegal logging (second term). Hence, the amount of resources the government should devote to its auditing strategy depends on the difference between revenue collection changes and externality reductions that follow from policy-induced reductions in logging.

3.2 Penalty charged on evaded royalty payment

Under this penalty scheme, the value-based royalty rate t enters the harvester's penalty payment explicitly, and there is an important distinction between it and the area-based royalty, so we explicitly examine both instruments. Assuming first that the government omits or ignores negative externalities from deforestation, we have the following maximization problem: $Max\ SW = E\pi^*$ subject to $R = tq\overline{Q} + ptfqX - I - c(p) \geq \overline{R}$. The choice of area-based royalty fee is given by $\Omega_I = -1 + \lambda = 0$, and the necessary conditions for the Lagrangian, $\Omega = E\pi^* + \lambda(R - \overline{R})$, in terms of the government's choices of t and p are:

$$\Omega_t = -(q\overline{Q} + pqfX) + \lambda\left[q\overline{Q} + pqfX + pqftQ_t\right] = 0 \text{, and} \tag{27}$$

$$\Omega_p = -fqtX + \lambda\left[fqtX + pfqtQ_p - c'(p)\right] = 0 \tag{28}$$

$\lambda = 1$ implies that the government should use only the area-based royalty fee and set $t = 0$. This is because the value-based royalty t is a distortionary instrument and induces a negative substitution effect on logging, while I is a lump sum instrument here. Moreover, it is not optimal to allocate any of the government's resources to auditing activities, because expected marginal returns are smaller than the marginal cost of auditing. This can be seen by substituting $\lambda = 1$ in $\Omega_p^u = 0$, which gives $\Omega_p^u\big|_{\lambda=1} < 0$, implying $p = 0$ at the optimum.

When the government accounts for negative externalities arising from deforestation, the optimal policy design is now different. The choice of area-based royalty fee is given by $\Omega_I = -1 + \lambda = 0$, and the choice of the optimal value-based royalty and the auditing probability are now defined by,

$$\Omega_t = -(q\overline{Q} + pqfX) + v'(X)Q_t + \lambda\left[q\overline{Q} + pqfX + pqftQ_t\right] = 0 \text{, and} \tag{29}$$

$$\Omega_p = -fqtX + v'(X)Q_p + \lambda\left[fqtX + pfqtQ_p - c'(p)\right] = 0. \tag{30}$$

Under $\lambda = 1$ (29) and (30) can be written as

$$\Omega_t = 0 \Leftrightarrow v'(X) + pqft = 0 \text{, and} \tag{29'}$$

$$\Omega_p = v'(X)Q_p + pfqtQ_p - c'(p) = 0 . \tag{30'}$$

According to (29') it is optimal to introduce a positive value-based royalty along with an area-based royalty fee. Proceeding as before, we can evaluate (30') assuming $t = t^*$ at the corner solutions for auditing probabilities to obtain, $\Omega_p \big|_{\substack{t=t^* \\ p=0}} = v'(X)Q_p > 0$, and $\Omega_p \big|_{\substack{t=t^* \\ p=1}} = -c'(1) < 0$, where we have used (29') with $p = 1$. These conditions indicate that it is also optimal to devote resources to auditing as long as externalities arise from deforestation. We can collect our policy design findings in,

Result 2. Policy design under risk neutrality.

When the penalty is assessed on undeclared income, revenue should always be collected with a positive value-based royalty rate, which is non-distortionary. When the penalty is assessed on evaded royalty payments, revenues should be collected using an area-based royalty fee in the absence of negative externalities, and using a combination of area-based and value-based royalties in the presence of externalities. Auditing is optimal to enforce illegal logging under both penalty schemes when externalities are present.

4 Optimal design of royalties and auditing – Risk aversion

Because risk aversion is sensitive to income changes, it now makes sense to examine its implication to optimal design or royalty and auditing instruments. Therefore, we allow for the possibility that the royalty system is progressive or regressive, in the sense that the royalty system includes an area-based royalty subsidy or fee. In the taxation literature, progressivity (regressivity) means that the average tax rate is increasing (decreasing) in the tax base, i.e., in the value of the concession (Musgrave and Thin 1948).

In the presence of progression, the concessionaire's revenues are defined as $Y = \left[qQ - (tq\overline{Q} - I) - c(Q)\right]$ and $Z = \left[Y - fqX\right]$ when a penalty is assessed against evaded royalty payments, and $Y^u = \left[qQ^u - (tq\overline{Q} - I) - c(Q^u)\right]$ and $Z^u = \left[Y^u - fqX\right]$ when the penalty is assessed against unreported income. Using these definitions, expected government royalty collections become $R = (tq\overline{Q} - I) + ptfqX - c(p)$ and $R^u = (tq\overline{Q} - I) + pfqX^u - c(p)$ respectively under the two penalty schemes.

Finally, with risk aversion the social welfare function is now given by expected indirect utility of the harvester plus externalities foregone by protecting forests, i.e. $SW = EU(\pi)^* + v(X)$.

4.1 Penalty charged on undeclared income

The government now chooses value-based and area-based royalty rates, and the audit probability to solve the following problem,

$$\underset{t,I,p}{Max}\ SW = EU(\pi)^* + v(X^u) \text{ s.t. } R^u = (tq\overline{Q} - I) + pfqX^u - c(p) \geq \overline{R}\,. \tag{31}$$

Like in the previous section, we first study the case where either there is no externality associated with deforestation or the government ignores it, and then we consider the case where externalities are important.

A. Externalities ignored

With the externality term $v(X^u)$ set equal to zero, the first order conditions for the problem in (31) for the value-based royalty rate, area-based royalty, and auditing are written,

$$\Omega_t^u = -\left[(1-p)u'(Y^u) + pu'(Z^u)\right]q\overline{Q} + \lambda\left[q\overline{Q} + pfqQ_t^u\right] = 0\,, \tag{32}$$

$$\Omega_I^u = \left[(1-p)u'(Y^u) + pu'(Z^u)\right] - \lambda\left[1 - pfqQ_I^u\right] = 0\,, \text{ and} \tag{33}$$

$$\Omega_p^u = -\left[u(Y^u) + u(Z^u)\right] + \lambda\left[fqX^u + pfqQ_p^u - c'(p)\right] = 0\,. \tag{34}$$

According to (32) the government chooses the royalty t to equate marginal revenue collections (RHS) with the marginal effect of the royalty on welfare, measured in expected utility terms (LHS). Using the fact that $Q_t^u = -q\overline{Q}Q_I^u$ from (32) and (33), we can re-express the optimality condition for I in a form identical to the optimal value-based royalty condition. Doing so shows that use of I is not needed when t is set at its optimal level – progression is not optimal. We show later that this result changes when the penalty is charged on evaded royalty payments.

We can express the optimal value-based royalty rate in closed form, and investigate how it depends on parameters of the problem. From the first-order conditions we have,

$\Omega_t^u = 0 \Leftrightarrow pu'(Z^u)\dfrac{fq}{q-c'(Q^u)} = \lambda\left[1+\dfrac{pfQ^u}{\overline{Q}}\varepsilon_t\right]$, where $\varepsilon_t = \dfrac{Q_t^u t}{Q^u} \leq 0$ as $A' \leq 0$. Solving for Z^u gives $Z^u = u'^{-1}(\Delta)$, with $\Delta = (1+\dfrac{pfQ^u}{\overline{Q}}\varepsilon_t)$. Using next the definition of Z^u we have the following optimal royalty rate expression:

$$t^* = \frac{qQ^u - c(Q^u) - fqX^u}{q\overline{Q}} - \frac{u'^{-1}(\Delta)}{q\overline{Q}}. \tag{35}$$

Notice first that the derivative of the optimal royalty rate with respect to Δ is $t_\Delta^* = -\dfrac{u''^{-1}(\Delta)}{q\overline{Q}} > 0$. Thus, we can examine how the size of the optimal royalty rate depends on the other parameters of the model. t* has the following properties: $t_{\varepsilon_t}^* < 0$, $t_p^* < 0$, and $t_f^* < 0$.

There are three interpretations that follow from (35). First, the optimal value-based rate decreases as the elasticity of harvesting with respect to the royalty rate increases. When harvests are very elastic in terms the royalty rate, this means that large royalty rates will reduce welfare more and increase the inability of the government to collect revenues as harvesting declines. The opposite is true if harvesting elasticity is low. Second, the audit probability and the penalty rate are substitute instruments for the royalty. If the probability of detection is low, as it is in most developing countries, then higher royalty rates are needed for the government to satisfy its revenue constraint, ceteris paribus; this is because illegal logging, which reduces revenues the government captures, increases as the detection probability decreases. Third, the optimal royalty rate is lower when the fine imposed for illegal logging is higher. These three results collectively show that the design of royalty instruments and of auditing and fines cannot be considered separately, as they are often discussed in the literature on concessions and illegal logging.

We can also show how resources should be allocated for detection of illegal logging. From (34) we develop the following modified condition,

$$c'(p) = \frac{u(Z^u) - u(Y^u)}{\lambda} + fqX^u(1 + \frac{Q^u}{X^u}\varepsilon_p). \tag{36}$$

From (36), it is *always* optimal for the government to devote resources to auditing. The allocation of resources to detection activities depends on the direct effect on the expected utility of these efforts, and on the sum of the immediate and indirect effects of higher detection rate on illegal logging as well as on the marginal cost of public funds. We summarize our findings in,

Proposition 1. **Optimal royalty and auditing design under risk aversion when penalty is levied on undeclared income.**

When externalities are not present, the optimal value-based royalty is positive. Introducing an area-based royalty fee or subsidy is not optimal when the value-based royalty is set to its optimal level. The optimal value-based royalty rate is inversely related to the elasticity of harvesting with respect to the royalty rate, the audit probability, and the fine rate. Auditing of illegal logging is always optimal.

B. Externalities included

When externalities are present and the government responds to them, the first-order conditions for the government's choice of instruments become,

$$\Omega_t^u = -[(1-p)u'(Y^u) + pu'(Z^u)]q\overline{Q} + v'(X^u)Q_t^u + \lambda[q\overline{Q} + pfqQ_t^u] = 0, \tag{37}$$

$$\Omega_I^u = [(1-p)u'(Y^u) + pu'(Z^u)] + v'(X^u)Q_I^u - \lambda[1 - pfqQ_I^u] = 0, \text{ and} \tag{38}$$

$$\Omega_p^u = -\left[u'(Y^u) - u(Z^u)\right] + v'(X^u)Q_p^u + \lambda\left[fqX^u + pfqQ_p^u - c'(p)\right] = 0\,, \tag{39}$$

As is evident from (37) and (38), our earlier results remain valid. That is, it is never optimal for the government to employ the area-based royalty given it uses the optimal value-based royalty t, as long as the penalty is levied on undeclared income. For the optimal auditing policy, we can after some rearranging arrive at the following condition,

$$c'(p) = \frac{u(Z^u) - u(Y^u)}{\lambda} + \frac{v'(X^u)}{\lambda}\frac{q}{Q^u}\varepsilon_p + fqX^u(1 + \frac{Q^u}{X^u}\varepsilon_p) \tag{40}$$

The LHS is the marginal cost of auditing for a given probability of detection. The RHS measures the welfare cost of the policy on harvesters (first term), the welfare benefit of reductions in deforestation (second term), and marginal revenue collection by the government (third term). Notice that, relative to the case where negative externalities were absent, the RHS of this condition is larger. Thus, given the convex auditing cost function, it is optimal for the society to devote more resources to auditing activities in this case, as the marginal benefits of reductions in illegal logging are greater. This implies, naturally, that under DARA the value-based royalty rate will also be higher than in the previous case.

Corollary 1. Importance of externalities for policy design under risk aversion when penalty is levied on undeclared income

When negative externalities arise from illegal logging, then given the optimal value-based royalty rate, introducing an area-based royalty fee or subsidy is not optimal. The optimal value-based royalty rate is higher under decreasing absolute risk aversion and auditing is higher when externalities are present.

4.2 Penalty charged on evaded royalty payment

When the penalty is charged against evaded royalty payments, the concessionaire's revenues for the alterative outcomes under non-detection and detection of illegal logging are, $Y = \left[qQ - (tq\overline{Q} - I) - c(Q)\right]$ and $Z = \left[Y - tfqX\right]$, respectively. The government's revenue constraint is also modified accordingly, and the policy choice problem becomes,

$$\underset{t,I,p}{Max}\; SW = EU(\pi)^{*} + v(X) \quad \text{s.t. } R = (tq\overline{Q} - I) + ptfqX - c(p) \geq \overline{R} \tag{41}$$

A. Externalities ignored

Neglecting for the moment the externality term, the first order conditions are,

$$\Omega_t = -\left[(1-p)u'(Y)q\overline{Q} + pu'(Z)(q\overline{Q} + qfX)\right] + \lambda\left[(q\overline{Q} + pqfX) + pfqtQ_t\right] = 0\,, \tag{42}$$

$$\Omega_I = \left[(1-p)u'(Y) + pu'(Z)\right] + \lambda\left[-1 + pfqtQ_I\right] = 0\,, \text{ and} \tag{43}$$

$$\Omega_p = -\left[u(Y) - u(Z)\right] + \lambda\left[tfqX + pfqtQ_p - c'(p)\right] = 0\,, \tag{44}$$

where (43) describes the optimal area-based royalty. Using the condition $\Omega_I = 0$, we have $\lambda = \dfrac{(1-p)u'(Y) + pu'(Z)}{1 - pfqtQ_I} \geq 1$, so that $\lambda \geq (1-p)u'(Y) + pu'(Z)$ as $Q_I \geq 0$. Given $I = I^{*}$ the first-order condition (42) can be re-expressed after some rearranging as,

$$t^{*}: \quad \frac{u'(Z) - \lambda}{\lambda} = \frac{t}{X}\left[q\overline{Q}Q_I + Q_t\right]\,, \tag{42'}$$

where $\left[q\overline{Q}Q_I + Q_t\right] = Q_t^c - xq\overline{Q}Q_I < 0$ with $x = \dfrac{fX}{\overline{Q}} > 0$ (see Appendix 2). Since the LHS and bracketed RHS term of (42') are negative, the optimal value-based royalty rate t^{*} must be positive. According to (43), the optimal area-based royalty subsidy should be chosen in a manner that equates marginal welfare gain to the concessionaire, $(1-p)u'(Y) + pu'(Z)$, to marginal cost of public funds due to royalty revenue collections, $\lambda\left[1 - pfqtQ_I\right]$. If the government employs an area-based royalty fee, instead of a subsidy, then we can rewrite (43) simply as: $\Omega_I = -\left[(1-p)u'(Y) + pu'(Z)\right] + \lambda\left[1 + pfqtQ_I\right] = 0$, where $Q_I \leq 0$ as $A'(.) \leq 0$. In this case the Slutsky equation for the value-based royalty rate t is $Q_t = Q_t^c + q\overline{Q}(1-x)Q_I$. Given $I = I^*$ the first-order condition (42) can now be re-expressed to obtain,

$$t^*: \quad \frac{u'(Z)-\lambda}{\lambda} = \frac{t}{X}\left[-q\overline{Q}Q_I + Q_t\right], \tag{45}$$

where $-\left[q\overline{Q}Q_I + Q_t\right] = Q_t^c + xq\overline{Q}Q_I < 0$. Hence, the optimal value-based royalty rate t^* is again positive, so that when penalties are charged against evaded royalty payments, both area-based and value-based royalty instruments should be used – this is similar to the policy mix we found to be optimal under risk neutrality.

These results raise the following question: should the government use an area-based royalty subsidy or fee as a supplement to the value-based royalty? The answer depends on the size of the tax revenue requirement the government seeks to collect. If the value-based royalty applied together with the auditing strategy is not sufficient to meet the revenue requirement, then the government should use an area-based royalty fee, but not the subsidy, when using a value-based royalty. This case is counter to the typical practice of using both a value-based royalty and an area-based subsidy by governments with concessions in tropical countries. In the case we have established, this means the optimal royalty structure is *regressive*.

Finally we turn to the government's auditing strategy. From the corresponding condition for $\Omega_p = 0$ in (44), we can establish that it is *always* optimal to devote resources to auditing for illegal logging. The allocation of resources is defined by the following condition,

$$c'(p) = \frac{u(Z)-u(Y)}{\lambda} + fqX\left(1 + \frac{Q}{X}\varepsilon_p\right) \tag{46}$$

Thus, the allocation of auditing resources depends on its negative direct effect on the expected utility of the concessionaire, as well as the positive sum of immediate and indirect effects of higher detection rates on illegal logging and, thus, government revenue collections. The following proposition summarizes the above results,

Proposition 2. Optimal royalty and auditing design under risk aversion when penalty is levied on evaded royalty payments

When externalities are not present, the optimal value-based royalty rate is positive. It is optimal to introduce an area-based royalty, and the royalty system may be progressive or regressive. The higher the government tax revenue requirement, the more likely the system should be regressive. Auditing of illegal logging is always optimal.

B. Externalities included

Finally, we consider briefly how externalities modify policy choices under this penalty scheme. Consider the first-order conditions governing the choice of instruments,

$$\Omega_t = -\left[(1-p)u'(Y)q\overline{Q} + pu'(Z)(q\overline{Q} + qfX)\right] + v'(X)Q_t + \lambda\left[(q\overline{Q} + pqfX) + pfqtQ_t\right] = 0 \tag{47}$$

$$\Omega_I = \left[(1-p)u'(Y) + pu'(Z)\right] + v'(X)Q_I - \lambda\left[1 - pfqtQ_I\right] = 0 \text{, and} \tag{48}$$

$$\Omega_p = -\left[u(Y) - u(Z)\right] + v'(X)Q_p + \lambda\left[fqtX + pfqtQ_p - c'(p)\right] = 0. \tag{49}$$

As is evident from the conditions $\Omega_t = 0$ and $\Omega_I = 0$, our previous results continue to hold if the expected revenue loss from a higher value-based royalty rate ($\lambda pqfQ_t$) is greater than the positive welfare effect due to resulting lower illegal logging ($v'(X)Q_t$). Looking at the second RHS terms in (47-49) we can see that under this condition the value-based royalty rate is higher and the area-based royalty subsidy is lower than in the absence of externalities. This implies that allowing for externalities will increase the likelihood of a regressive royalty system being optimal, because higher royalty rates decrease illegal logging.

For the optimal probability of detection we have,

$$c'(p) = \frac{u(Z) - u(Y)}{\lambda} + \frac{v'(X)}{\lambda}\frac{q}{Q}\varepsilon_p + fqX(1 + \frac{Q}{X}\varepsilon_p), \tag{50}$$

Thus, the RHS of (50) is higher than the RHS of (46), and so the government should devote more resources to auditing when externalities are present given that enforcement costs are convex. This finding clearly indicates that it is optimal for the society to devote more resources to auditing activities in order to prevent illegal logging and deforestation. We summarize these findings as,

Corollary 2. **Importance of externalities to policy design under risk aversion when penalty is levied on evaded royalty payments.**

When negative externalities arise from illegal logging, the optimal value-based royalty rate is positive and auditing effort continues to be optimal, but more resources should be devoted to auditing compared to the case where externalities are absent. The optimal area-based royalty subsidy is lower, or equivalently the optimal area-based royalty fee is higher.

5. Conclusions

We address the socially optimal design of instruments in economies with concessions, arriving at several benchmark results. We consider both area-based and value-based royalty instruments, as well as auditing choices, in a context where illegal logging can occur. We also examine the common case where combinations of royalty fees and subsidies are used, that is, we examine the optimality of progressivity or regressivity in the instrument system. Two Important distinctions we also consider in the choice of instruments are how the penalty scheme is structured for punishment of illegal logging, and whether externalities are present that are reduced by illegal logging.

The form of illegal logging we consider is the most common, i.e., one in which the concessionaire harvests more than is contracted for in the concession. Illegal logging activity is not detectable by the government unless costly auditing is employed. Auditing ensures that detection occurs with some positive probability. Should the government detect illegal logging, two possible penalty schemes are modeled: a fine assessed on undeclared harvest income, and a fine assessed on evaded royalty payments. Increasing auditing probabilities is consistent with use of greater government resources to detect illegal logging.

Within this framework we evaluate two questions: First, how do incentives for harvesters to illegally log depend on government auditing effort and royalty choices, and second, how should a benevolent policy maker employ instruments to achieve the social optimum while facing revenue constraints on their choices. When forest harvesters are risk neutral, policy choices depend on the presence of externalities (or the government's preference to provide them) and on the penalty scheme.

When the penalty is assessed on undeclared income, the value-based or area-based royalties are equivalent, so that a positive value-based optimal royalty implies the area-based royalty is not needed. But the government will never find it optimal to completely eliminate illegal logging even when forest externalities are lost through such activities. When negative externalities are not present, auditing will not be employed. When penalties are imposed on evaded royalty payments, both the value-based and area-based royalties should be used, and auditing is optimal only if negative externalities are present.

The case where harvesters are risk averse leads to different instrument choice results, some of which are in striking contrast with the way royalty systems are currently employed or discussed. In the absence of externalities and when penalties are assessed on undeclared income, neither an area-based royalty fee or an area-based royalty subsidy are optimal, but a value-based royalty is optimal and should be inversely related to the elasticity of harvesting with respect to the royalty rate, the audit probability, and the fine rate. Auditing of illegal logging is also optimal. When externalities are absent and penalties are levied on evaded royalty payments, we find the counterintuitive result that a royalty system may be either progressive or regressive, so that there is scope for an area-based fee or subsidy; the correct instrument mix depends on the importance of the government's revenue constraint. When externalities are present, the value-based royalty rate should be higher, progression lower, and regression higher. More resources should also be devoted to auditing compared to the case where externalities are absent.

These contrasting results suggest that royalties and enforcement of illegal logging must be balanced in ways that have not even been discussed in the literature, let alone applied in countries with concessions. The benchmark cases here suggest that area-based and value-based royalties have important differences in some cases, and important similarities in others. In all cases, the design of these policies is quite complicated and depends on the risk preferences of harvesters, the way enforcement and fines are structured, and how governments view externalities associated with illegal logging. Whether a combination of instruments is needed, or whether the instruments should be progressive or regressive, all depend critically on specific characteristics of each application. For example, we establish cases where a government would not choose to audit for illegal logging at all, i.e., when harvesters are risk neutral and the government does not respond to externalities associated with deforestation or illegal logging.

Appendix 1. Comparative Statics of Instruments under Risk-Aversion

Penalty fine rate, and detection probability:

$$Q_f^u = -\frac{EU_{Q^u f}}{EU_{Q^u Q^u}} < 0 \text{, where } EU_{Q^u f} = -\left[qX^u u''(Z^u)b + qu'(Z^u)\right] < 0 \qquad \text{A1.1}$$

$$Q_p^u = -\frac{EU_{Q^u p}}{EU_{Q^u Q^u}} < 0 \text{, where } EU_{Q^u p} = -u'(Y^u)a + u'(Z^u)b < 0. \qquad \text{A1.2}$$

Exogenous income and royalty rate:

$$Q_I^u = -\frac{EU_{Q^u I}}{EU_{Q^u Q^u}} \leq 0, \text{ when } A'(.) \leq 0, \qquad \text{A1.3}$$

where $EU_{Q^u I} = -a(1-p)u'(Y^u)\left[A(Y^u) - A(Z^u)\right] \geq 0$, and

$$Q_t^u = -\frac{EU_{Q^u t}}{EU_{Q^u Q^u}} \leq 0, \quad \text{when } A'(.) \leq 0, \qquad \text{A1.4}$$

where $EU_{Q_t^u} = q\overline{Q}a(1-p)u'(Y^u)\left[A(Y^u) - A(Z^u)\right] \leq 0$. A1.4 can be decomposed into the income and substitution effects (see Appendix 2)

$$Q_t^u = Q_t^c - q\overline{Q}Q_I^u, \quad \text{where} \quad Q_t^c = Q_t^u + g\overline{Q}Q_I^u = 0 \qquad \text{A1.5}$$

so that the substitution effect of the royalty rate is zero.

Appendix 2. Slutsky Decompositions for the Royalty Rate

We develop Slutsky decompositions for the total effect of the royalty rate t on logging under the alternative penalty schemes.

A. Penalty on undeclared income

The concessionaire's expected utility is,

$$EU(\pi) = (1-p)u(Y^u) + pu(Z^u) \qquad \text{A2.1}$$

where $Y^u = qQ^u - c(Q^u) - tq\overline{Q} + I$, $Z^u = Y^u - fq(Q^u - \overline{Q})$ and I is the area-based royalty. The first-order condition for the optimal logging $EU_Q{}^u = 0$ implicitly defines Q^u as $Q^u \equiv Q^u(t, I)$. Substituting $Q^u(t, I)$ for Q in A.2.1 gives expected indirect utility $EU^*(t, I) = U^o$, with the following properties holding due to the envelope theorem,

$$EU_I^* = (1-p)u'(Y^u) + pu'(Z^u) > 0 \text{ , and} \qquad \text{A2.2a}$$

$$EU_t^* = -q\overline{Q}EU_I^* < 0 \text{ .} \qquad \text{A2.2b}$$

Inverting EU^* for I to obtain $I = h(t, U^o)$ and substituting this for I in EU^* we obtain the compensated expected indirect utility function (see Diamond-Yaari (1972))

$$EU^*(t, h(t, U^o)) = U^o \qquad \text{A2.3}$$

Differentiating A2.3 with respect to the royalty tax rate yields: $EU_t^* + EU_I^* h_I = 0$, and holding the expected utility constant gives,

$$h_I = -\frac{EU_t^*}{EU_I^*} = q\overline{Q} > 0 \qquad \text{A2.4}$$

From the duality theorem (see e.g. Varian 1992, pp. 81-93), the relationship between uncompensated logging, Q^u, and compensated logging, Q^c, is,

$$Q^u(t, h(t, U^o)) = Q^c(t, U^o) \qquad \text{A2.5}$$

Differentiating A2.5 with respect to the royalty rate yields $Q_t + Q_I h_t = Q_t^c$, and using A2.4 we obtain,

$$Q_t^u = Q_t^c \; - q\overline{Q}Q_I^u \text{ ,} \qquad \text{A2.6}$$

where the total effect is decomposed into the substitution effect (Q_t^c) and the income effect $(-q\overline{Q}Q_I^u)$.

The total effect of the royalty rate is given by the expression,

$$Q_t^u = -\frac{EU_{Q^u t}}{EU_{Q^u Q^u}} 0 \text{ , where } EU_{Q^u t} = q\overline{Q}(q - c'(Q^u))(1-p)u'(Y^u)\left[A(Y^u) - A(Z^u)\right]$$

The effect of non-logging income can be expressed similarly as,

$$Q_I^u = -\frac{EU_{Q^u I}}{EU_{Q^u Q^u}} \text{ , where } EU_{Q^u I} = -(q - c'(Q^u))(1-p)u'(Y^u)\left[A(Y^u) - A(Z^u)\right]$$

Thus in the case of the penalty assessed on undeclared income we have,

$$Q_t^c = Q_t^u + q\overline{Q}Q_I^u = 0 \text{ .} \qquad \text{A2.7}$$

B. Penalty on evaded royalty payment

When the penalty is assessed on evaded royalty payments, the concessionaire's expected utility income terms in A.1 are written $Y = qQ - c(Q) - tq\overline{Q} + I$ and , so that first order conditions become,

$$EU_I^* = (1-p)u'(Y) + pu'(Z) > 0 \qquad \text{A2.8a}$$
$$EU_t^* = -q\overline{Q}(1+x)EU_I^* > 0 \qquad \text{A2.8b}$$

where $x = \dfrac{fX}{\overline{Q}} > 0$. We can use A2.8a to invert the expected indirect utility function and obtain the corresponding compensated utility function

$$h_I = -\frac{EU_t^*}{EU_I^*} = q\overline{Q}(1+x) > 0 \qquad \text{A2.9}$$

Using the relationship between uncompensated and compensated logging behavior, like in A2.5, and equation A2.9, we can derive the following Slutsky equation for the effect of the royalty rate on logging,

$$Q_t = Q_t^c \ - q\overline{Q}(1+x)Q_I \,. \qquad \text{A2.10}$$

We know that the total effect of the royalty rate is given by,

$$Q_t = -\frac{EU_{Qt}}{EU_{QQ}} < 0 \qquad \text{A2.11}$$

where $EU_{Qt} = q\overline{Q}(1+x)(q - c'(Q)(1-p)u'(Y)\left[A(Y) - A(Z)\right] - pu'(Z)fq < 0$ under non-increasing absolute risk aversion. Moreover, we have previously shown,

$$Q_I = -\frac{EU_{QI}}{EU_{QQ}} \text{ where } EU_{QI} = -(q - c'(Q))(1-p)u'(Y)\left[A(Y) - A(Z)\right] \geq 0 \text{ as } A'(.) \leq 0 \qquad \text{A2.12}$$

Using A2.11 and A2.12 yields negative substitution effects,

$$Q_t^c = Q_t + q\overline{Q}(1+x)Q_I = (-EU_{QQ})^{-1}\left\{-fqpu'(Z)\right\} < 0\,, \qquad \text{A2.13}$$

.

In the case of $I < 0$, the following Slutsky equations are obtained,

$$Q_t = Q_t^c \ + q\overline{Q}(1+x)Q_I \,. \qquad \text{A2.10'}$$

where $Q_t < 0$ and $Q_I \leq 0$ as $A'(.) \leq 0$. Now we end up with $Q_t^c = Q_t - q\overline{Q}(1+x)Q_I = (-EU_{QQ})^{-1}\left\{-fqpu'(Z)\right\} < 0\,.$ A2.13'

* * * * *

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