Illegal Extractions of Renewable Resources and Trade*

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Abstract

Illegal extractions of renewable resources threaten sustainable use of those resources. The world community has recently paid increasing attention to the issue of illegal logging. This paper tries to explain why it is important to exclude illegally logged timber from the international market by using a stylized model in the literature of trade and renewable resources. It is shown that a fall in the price of timber may cause a switch of management regime from enforced property rights to open-access, expanding the supply of timber and reducing forest stock. When several countries export timber, an expansion of illegal logging in one country due to a regime switch may also increase illegal logging in other countries. A bilateral agreement between one exporting country and importing countries to exclude illegally logged timber from trade may effectively reduce illegal logging in other countries.

Keywords: renewable resources; illegal logging; property rights; open access; enforcement; process and production methods (PPMs).

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1 Introduction

Illegal extractions of renewable resources are a dangerous threat to the sustainability of these resources. For example, in the case of forests, illegal logging is a major cause of deforestation. The average annual change in forest area during 1990–2000 was −9.4 million hectares in the worldwide and −2.27 million hectares in Southeast Asia. Indonesia alone recorded an average annual deforestation of 1.31 million hectares during the period (FAO, 2005). On the other hand, Seneca Creek Associates and Wood Resources International (2004) report that about 8% (131.0 million m^3) of the world's roundwood production, 6% (25.9 million m^3) of lumber production, and 17% (10.0 million m^3) of plywood production are from suspicious sources and likely illegal. Moreover, based on various reports from NGOs, 70%–80% of timber production in Indonesia, 20%–50% in Russia, and 20–90% in Brazil is suspected of being illegal.

Illegal extractions of resources are a serious problem not only because they are "illegal" but also, and more importantly, because they cause overexploitation of resources. Those who illegally extract renewable resources are typically myopic and would not consider the sustainable use of the resources. Therefore, they try to maximize the current period profits without taking the resource dynamics into account. Consequently, if the owner of the resource does not enforce the property rights at all, illegal extractors will harvest the resource, which will result in the well-known "open-access" situation.

From the perspective of sustainable use of renewable resources, the issue of illegal harvests is addressed for various resources. For example, the world community has recently paid increasing attention to illegal logging. This issue began to attract international attention when the G8 Action Program on Forests was initiated in 1998. The leaders of G8 countries also discussed this issue at the Kyushu-Okinawa Summit in July 2000, which triggered international attention. At the World Summit on Sustainable Development in Johannesburg in September 2002, Japan launched the Asia Forest Partnership (AFP) in cooperation with Indonesia, intergovernmental organizations, and NGOs, for promoting sustainable forest management in Asia through controlling illegal logging as well as controlling forest fires and reforesting degraded lands.[1]

Measures that have been implemented or considered to control illegal logging include (i) restrictions

[1] The AFP held six meetings as of September 2006. For details, see the AFP's website (http://www.asiaforests.org/).

on public procurement of wood and wood products by the domestic public procurement policy and (ii) restrictions on trade of wood and wood products by bilateral agreements between importing and exporting countries of these products. For example, the European Union (EU) requires environmental considerations in the public procurement procedure.[2] The Commission of the European Communities (2004) explains how environmental aspects can be incorporated in the public procurement procedure. Moreover, the United Kingdom (UK) announced the "UK Government Timber Procurement Policy: Timber Procurement Advice Note" in January 2004 (DEFRA, 2004), which provides new guidelines on the way of procuring wood and wood products by the public sector in the UK. Japan also restricts public procurement to legal and sustainable wood and wood products. At the G8 Gleneagles Summit in July 2005, Japan announced that it would restrict public procurement of wood and wood products only to those verifying legality and sustainability by utilizing the Law on Promoting Green Purchasing.[3] New guidelines are published in February 2006 (Forestry Agency of Japan, 2006), which require certification of legality and sustainability to suppliers of wood and wood products to the public sector in Japan.

With regard to the restrictions on trade of wood and wood products by bilateral agreements, the EU's Forest Law Enforcement, Governance and Trade (FLEGT), which requires certification of legality for imports of timber on the basis of voluntary bilateral agreements with exporting countries, is under preparation (Commission of the European Communities, 2003). This action plan includes support from the EU to timber-producing countries for development of verification systems, capacity building, and policy reform. Under the FLEGT trade between the signatories of the bilateral agreements is restricted to legally and sustainably harvested timber in exchange for this support.

These actions to exclude illegally harvested resources from the international market would be effective

[2]Parliament and Council of the European Communities (2004), Directive 2004/17/EC of the European Parliament and of the Council of 31 March 2004, coordinating the procurement procedure of entities operating in the water, energy, transport and postal services sectors. Parliament and Council of the European Communities (2004), Directive 2004/18/EC of the European Parliament and of the Council of 31 March 2004, on the coordination of procedures for the award of public works contracts, public supply contracts and public service contracts.

[3]The formal name is the "Law Concerning the Promotion of Procurement of Eco-Friendly Goods and Services by the State and Other Entities." For details, see http://www.env.go.jp/en/lar/green/index.html (Ministry of the Environment).

in controlling illegal extractions of resources in individual countries. The effects of these actions may well be beyond that. The reason is as follows. Illegal extractions of resources in one country may not just be a threat to the conservation of the resources in that country. They may also be a threat to resources in other countries. The intuition is rather simple. Since a larger amount of the resource good is supplied under illegal extraction than under enforced property rights, the world price of the resource good faces a downward pressure. A lower price of the resource good reduces incentive for the resource owners in other countries to enforce property rights when the enforcement of the property rights is costly, while a lower price also reduces the incentive for illegal extractions. If the former effect dominates the latter, illegal extractions would increase in these countries. Actions to exclude illegally harvested resources from the international market may be effective in preventing this international diffusion of illegal harvests.

However, trade restrictions only on illegally harvested resources (or resources harvested in an unsustainable manner) will not be allowed under the current GATT/WTO rules. A principle of the GATT/WTO rules is non-discrimination for the goods that are judged to be "like products." Traditionally, discriminatory treatments based on *process and production methods* (PPMs) have not been allowed under the GATT/WTO rules.[4] Physical characteristics of illegally harvested resource goods (or

[4] However, in some recent trade dispute cases, the Dispute Settlement Body (DSB) of the WTO has revealed broader interpretations of the PPM issue. In the Asbestos case (*EC – Asbestos*), the Appellate Body, which published a report in March 2001, claimed that "a determination of 'likeness' under Article III:4 is, fundamentally, a determination about the nature and extent of a competitive relationship between and among products" (WTO, 2001a: 37) and that health risks associated with products "may be relevant in assessing the *competitive relationship in the marketplace* between allegedly 'like' products" (WTO, 2001a: 45) through their influence on consumers' behaviour with respect to different products at issue. Since chrysotile asbestos fibres and other fibres not only differ in physical properties but also may have no competitive relationship, the Appellate Body reserved the Panel's finding that chrysotile asbestos fibres and other fibres are "like products". Moreover, in the shrimp-turtle case (*US – Shrimp*), the Appellate Body under Article 21.5 of the *Understanding on Rules and Procedures Governing the Settlement of Disputes* (DSU), which published a report in October 2001, concluded that the US measures of embargo on non-turtle-safe shrimp imports were justified under Article XX of the GATT 1994 as long as some conditions, in particular the ongoing "serious good faith" efforts to reach a multilateral agreement, were satisfied (WTO, 2001b). For detailed discussion on the issue of PPMs and on the treatments of this issue in recent GATT/WTO trade dispute cases, see Isaac and Kerr (2003) and Quick and Lau (2003).

resource goods harvested in an unsustainable manner) are not different from those of legally harvested ones (or the ones harvested in a sustainable manner). Thus, the issue of legality (or sustainability) corresponds to *non-product-related process and production methods* (NPR-PPMs), which implies that trade restrictions only on illegally harvested resources will be judged as violating the GATT/WTO rules. It is said that the EU and some countries try to restrict trade of illegally harvested wood and wood products by bilateral agreements in order to avoid potential challenges from other countries at the WTO.

The main purpose of this paper is to examine the issue of illegal extractions of renewable resources in a formal model. In order to accomplish the task, I use a stylized model in the literature of trade and renewable resources (Brander and Taylor, 1997a, b, 1998). Since the model is highly stylized, the implications from its analysis will be applicable to a wide range of renewable resources, including fish, forests, and wildlife. The model is a Ricardian type of general equilibrium model with renewable resources. A key is that enforcement of property rights over renewable resources is endogenously chosen. A fixed cost of enforcement is assumed, which may make a resource owner choose not to enforce property rights if the cost is high. If property rights are not enforced, the resource is subject to open-access. Since the enforcement cost is fixed, the decision of a resource owner is binary: either to enforce the property rights perfectly or not to enforce the property rights at all. While it would be more realistic to allow variable costs and intermediate levels of enforcement, the assumption of the fixed enforcement cost is very useful to simplify the analysis and to illustrate the results clearly.

Illegal extractions introduce two types of distortion into the economy. The first is a static or *intra-temporal* distortion, namely, rent dissipation due to excess entry to the resource sector. This corresponds to the well-known phenomenon of the "tragedy of the commons." The second distortion is a dynamic or *inter-temporal* one, which is a resource stock reduction due to myopic actions by illegal harvesters.

The cases of small open economy and large countries exporting the resource good are both examined. The starting point of the analysis is at a free-trade steady-state equilibrium in which property rights are enforced. Then, I analyze how this initial steady state would be disturbed by an exogenous shock, such as a fall in the international price of the resource good. I also examine the effects of trade restrictions.

The main results are as follows. First, in the case of a small open economy, a *reduction* in the price of the resource good may lead its *higher* output with *lower* resource stock in a steady state. This counterintuitive result owes to the regime switch from enforced property rights to open-access. Since the long-run supply curve of the resource good is typically backward bending under open-access (Copes, 1970; Clark, 1990), a similar result could be obtained without regime switch. However, without regime switch a larger supply due to a fall in price must be accompanied by an *increase* in the resource stock. The result of a larger supply with lower resource stock caused by a fall in price is hence specific to the case of regime switch. Note that a fall in the price of the resource good also reduces the incentive for illegal harvests. Thus, in order to obtain the result that a fall in the price is followed by an increase in the output and a decrease in the stock, the effect of the regulatory regime switch must dominate the effect of the lower incentive for illegal harvests. Second, in the case of several large countries exporting the resource good, an increase in the enforcement cost of property rights in one country may not only cause a regime switch from enforced property rights to open-access in that country but also cause a regime switch in some other countries. This can be viewed as the international diffusion of illegal harvests. Third, when an import restriction is imposed on imports of the resource good in general, international diffusion of illegal harvests may be reinforced. This is because an inward shift in the world demand for the resource good will further decrease the good's world price. By contrast, a bilateral agreement between one exporting country of the resource good and importing countries to exclude illegally harvested resource good from the bilateral trade may facilitate a regime switch from open-access to enforced property rights in some other countries. This is because the agreement reduces the world supply of the resource good and hence raises the equilibrium price of the resource good.

The analysis in this paper is in line with the studies in the field of trade and renewable resources. The basic model in this paper is based on the one developed by Brander and Taylor (1997a, b, 1998). In their papers, the regime of resource management (private property rights or open-access) is given exogenously. The resource management regime is also exogenous in Chichilnisky (1993, 1994) and Jinji (2007). Francis (2005) endogenizes the enforcement of property rights in the Brander and Taylor model, as this paper does. Like this paper, he considers a fixed cost of enforcing property rights. However, his focus is on the welfare effects of the possible regime switch and does not analyze the possibility of the international diffusion of illegal harvests. Hotte, Long, and Tian (2000) also endogenize the enforcement of property rights. In their model, the cost of enforcing property rights is increasing in the level of enforcement and the level of enforcement can change continuously from perfect enforcement to perfect open-access. They show that for any positive level of enforcement, the owner of the resource always chooses the entry-deterrence level of legal harvests. This implies that even if the possibility of intermediate level of property rights enforcement is allowed, the legally harvested resource good and the illegally harvested one are not supplied at the same time as long as the sites of the resources are symmetric.

Moreover, Jinji (2006) extends the Brander and Taylor model by endogenizing the carrying capacity of the resource. He explicitly models the dependence of the carrying capacity on the "base resource" such as land. Unlike the original Brander and Taylor model, under open-access a fall in the price of the resource good may result in a lower level of the resource stock in Jinji (2006) because a lower price of the resource good takes away not only labour inputs but also inputs of land from the resource sector. One may think that this result seems to be similar to that in this paper. However, a lower stock level due to a fall in the price is not followed by a higher harvest, which differs from the result in this paper.

Although the open-access regime is assumed, Copeland and Taylor (2006) demonstrate the possibility of sequential resource depletion in exporting countries of the resource good, which is similar to the international diffusion of illegal harvests in this paper. The main difference is that in their paper the "domino effect" of the resource depletion is driven by a high demand for the resource good and that the price of the resource good *rises* in the process of the sequential resource depletion.

The rest of the paper is organized in the following way. Section 2 sets up the basic framework of the model. Section 3 analyzes the case of a small open economy. Section 4 extends the analysis to the case of large exporting countries of resource goods. Section 5 provides some concluding remarks.

2 The Basic Setup

2.1 Supply and demand

The model is a Ricardian type of general equilibrium model with renewable resources developed by Brander and Taylor (1997a, b, 1998). Let $S(t)$ denote the size of the renewable resource stock at time t and $S(0) = S_0$ be the initial stock size.

The net change in the resource stock at time t is given by

$$dS/dt = G(S(t)) - H(t), \tag{1}$$

where $G(S(t))$ denotes the natural growth rate and $H(t)$ is the harvest rate. I omit the time argument hereafter. As is usual in the previous studies, I use a specific functional form for $G(S)$, which is given by

$$G(S) = rS(1 - S/K), \tag{2}$$

where r is the intrinsic growth rate and K is the "carrying capacity." A typical resource dynamics is depicted in Figure 1. The resource stock size is measured along the horizontal axis and the growth rate and the harvest rate are measured along the vertical axis. The inverted U shaped curve represents the growth function $G(S)$. Since the growth rate is positive for $S < K$ and negative for $S > K$, $S = K$ is a unique stable steady state without human harvests. The highest harvest is obtained in steady states when $S = K/2$, which is called the "maximum sustainable yield." For concreteness, I refer to the renewable resource as "forest" and the resource extraction activity as "logging." However, the implications of the analysis are applicable to a wide range of renewable resources not merely specific to forests.

There are two goods: the harvest of the renewable resource or "timber", H, and some other good or "manufactures", M. Good M is treated as a numeraire. Labour, L, is the only primary factor of production, besides the resource stock. Good M is produced with constant returns to scale technology using only labour. By choice of units, one unit of good M is simply produced by one unit of labour:

$$M = L_M, \tag{3}$$

where L_M denotes the amount of labour employed in manufacturing. The harvest of timber is, on the other hand, carried out by the Schaefer production function:

$$H = \alpha S L_H, \tag{4}$$

where α is a positive constant and L_H is amount of labour used in the forestry sector, which may be legitimately employed labour or illegal extractors. Let L_E be legitimately employed labour and L_P be illegal extractors or "poachers". Then, $L_H = L_E + L_P$ holds. In Figure 1, the harvest function is depicted as an upward-sloping line. The full employment condition is given by

$$L = L_E + L_P + L_M + L_R, \tag{5}$$

where L_R is labour used for the enforcement of property rights as is defined in section 2.2. Substitute (3) and (4) into (5) to yield the Ricardian production possibility frontier:

$$H = \alpha S(L - L_R - M). \tag{6}$$

A steady state emerges when $dS/dt = 0$, or $G(S) = H$. Equate $G(S)$ with H as given by (4) and solve for S to yield $S = 0$ or $S_{ss} = K(1 - \alpha L_H / r)$. The harvest of good H in a steady state with positive resource stock is given by substituting S_{ss} into (4), yielding

$$H_{ss} = r S_{ss}(1 - S_{ss}/K). \tag{7}$$

Substitute (7) and S_{ss} into (6) to obtain production of manufactures in a steady state:

$$M_{ss} = L - L_R - (r/\alpha)(1 - S_{ss}/K). \tag{8}$$

2.2 Endogenous enforcement of property rights

A representative forest owner maximizes the steady-state rents from forestry, given the price of timber and wages.[5] He/She decides whether or not to enforce property rights. The enforcement of property

[5]This assumption would be more relevant in the forestry sector, because forest owners make decisions on planting and cutting trees by taking into account future profits several decades later.

rights is costly. Following Francis (2005) and Jinji (2006), I assume that the property rights can be perfectly enforced by hiring a fixed number of workers, L_R, to restrict access to the forest.[6] Rents in the forestry sector, π^H, are given by

$$\pi^H = pH - wL_E - L_R. \tag{9}$$

The steady-state rents, π^H_{ss}, are obtained by substituting steady-state values of price and wage rate, p_{ss} and w_{ss} respectively, into (9). The forest owner maximizes π^H_{ss} subject to (4) and $S_{ss} = K(1 - \alpha L_E/r)$. Assuming an interior solution, the first-order condition yields the optimal employment and the optimal steady-state level of S in the enforced property right regime for a given p_{ss}, respectively, as

$$L^R_E(p_{ss}) = (r/2\alpha)(1 - w_{ss}/\alpha K p_{ss}), \tag{10}$$

$$S^R_{ss}(p_{ss}) = K/2 + w_{ss}/2\alpha p_{ss}, \tag{11}$$

where the superscript R indicates variables under enforced property rights.[7] Eq. (11) implies that under the enforced property rights the resource stock in steady states never goes below $K/2$. Substitute (10) and (11) into (4) to yield the steady-state supply of timber under enforced property rights:

$$H^R_{ss}(p_{ss}) = (r/\alpha p_{ss})(\alpha K p_{ss} + w_{ss})(\alpha K p_{ss} - w_{ss})/4\alpha K p_{ss}. \tag{12}$$

A typical curve of H^R_{ss} is illustrated as H^R_{ss} in Figure 2.

Substituting (10) and (11) into (9) yields the maximized rents in the forestry sector in steady states:[8]

$$\pi^{H*}_{ss} = (r/\alpha)(\alpha K p_{ss} - w_{ss})/4\alpha K p_{ss} - L_R. \tag{13}$$

Note that an interior solution requires $L^R_E < L - L_R$, or

$$(r/2\alpha)(1 - 1/\alpha K p_{ss}) < L - L_R. \tag{14}$$

Throughout the paper, I assume that condition (14) is satisfied so that when the property rights are enforced, an interior solution prevails. Then, under (14) the economy is always diversified whenever the property rights are enforced. This implies that $w = 1$ holds when the property rights are enforced.

[6]Equivalently, the enforcement costs are equal to $M_R = L_R$ units of good M.

[7]They are essentially equivalent to those in the case of the "conservationist country" in Brander and Taylor (1997b).

[8]This is the same as what Francis (2005) shows, while he assumes that the government acts to maximize the rents at the aggregate level.

The following comparative statics results are obtained (proofs of Lemmas and Propositions are presented in the Appendix.):

Lemma 1 *Assuming an interior solution, (i)* $d\pi_{ss}^{H*}/dp_{ss} > 0$*; (ii)* $d\pi_{ss}^{H*}/dL_R < 0$.

For simplicity, I model the forest owner's decision of enforcing property rights as one-time choice.[9] That is, the forest owner decides to enforce property rights if and only if the present value of rents from forestry is non-negative, which is given by

$$V = \int_0^\infty e^{-\delta t}\pi^H(t)\ \mathrm{d}t, \tag{15}$$

where δ is a constant positive discount rate. Since the employment level is fixed at L_E^R (Eq. (10)) and $w = 1$ throughout the transition and in steady states, substitute (10) and $w = 1$ into (15) to yield

$$V^* = \int_0^\infty e^{-\delta t}\left[\left(p(t)\alpha S(t) - 1\right)(r/2\alpha)\left(1 - 1/\alpha K p_{ss}\right) - L_R\right]\ \mathrm{d}t. \tag{16}$$

Then, the forest owner decides to enforce property rights if and only if $V^* \geq 0$.[10]

When the forest owner decides not to enforce the property rights, the forest is subject to illegal logging and hence the usual open-access condition holds. Under the open-access, the harvest of timber is determined by profit maximization under free-entry conditions, which requires current-period profits for the representative harvester to be zero. The necessary condition yields

$$p = w/\alpha S. \tag{17}$$

Thus, the steady-state level of S under open-access for a given p_{ss} is given by

$$S_{ss}^O(p_{ss}) = w_{ss}/\alpha p_{ss}, \tag{18}$$

where the superscript O indicates variables under open-access. Noting that as shown above, the steady-state stock level is given by $S_{ss} = K(1 - \alpha L_H/r)$, the number of illegal extractors in steady states is

[9] This means that if the forest owner decides to enforce property rights, he/she does so throughout the transition and in steady states.

[10] Sinde the employment level is fixed at L_E^R throughout the transition and workers for enforcing property rights, L_R, must be employed in each period, the forest owner may suffer some losses in the transition to steady states.

given by $L_P = (r/\alpha)(1 - S/K)$. Substitute this and (18) into (4) to obtain the steady-state supply of timber under open-access:

$$H_{ss}^O(p_{ss}) = (rw_{ss}/\alpha p_{ss})(1 - w_{ss}/\alpha K p_{ss}). \tag{19}$$

As is well known (Copes, 1970; Clark, 1990), the steady-state supply curve of a renewable resource under open-access is backward bending, as illustrated as H_{ss}^O in Figure 2.

Since the enforcement of the property rights is costly, the forest owner may optimally choose not to enforce the property rights. Even when the forest owner decides not to enforce the property rights, he may possibly employ workers to harvest timber legally. This means that under open-access legally and illegally logged timber may be both supplied at the same time. However, I rule out this possibility so that only illegally logged timber is supplied under open-access.

Throughout the paper I assume that $L > r/\alpha$ holds so that the economy cannot specialize in good H in steady states.

Define p^x implicitly by $H_{ss}^R(p^x) = H_{ss}^O(p^x)$ with $p^x > 1/\alpha K$, as depicted in Figure 2. H_{ss}^R and H_{ss}^O are given by (12) and (19), respectively. Thus, equating (12) and (19) yields $p^x = (2w_{ss}+1)/\alpha K$. When the economy is diversified under open-access in steady states, $w_{ss} = 1$ and hence $p^x = 3/\alpha K$.

Define also $\bar{p}_{ss}$ implicitly by $V^*(\bar{p}_{ss}) = 0$, i.e., the steady-state price at which the forest owner is indifferent between enforcing property rights and not doing so. Then, Lemma 1 (i) implies that for $p_{ss} \geq \bar{p}_{ss}$ the resource owner enforces property rights and that for $p_{ss} < \bar{p}_{ss}$ he/she does not. I call the case in which $\bar{p}_{ss} < p^x$ the "low enforcement cost" case and the case in which $\bar{p}_{ss} > p^x$ the "high enforcement cost" case.

Taking the endogenous enforcement of property rights into account, typical examples of the steady-state supply curve of timber in the low enforcement cost and high enforcement cost cases are illustrated in Figure 3 (a) and (b), respectively. As seen in Figure 3, the main difference between the two cases is that at the threshold price there is a downward jump in the supply in the low-enforcement cost case, while there is an upward jump in the high-enforcement cost case.

3 A Small Open Economy

In this section, I examine the case of a small open economy that exports timber. I consider two different world prices: at one price the property rights are enforced in the small open economy and at another price they are not. Then, I analyze how a change in the world price will affect the supply of timber and the forest stock.

Let p^w be an (exogenous) world price of timber at which the property rights are enforced in the small open economy, i.e., $p^w > \bar{p}_{ss}$ holds.[11] Then, there exists a price p^c such that $H^R_{ss}(p^w) = H^O_{ss}(p^c)$ with $S^O_{ss}(p^c) > K/2$. In words, p^c is the price at which the steady-state timber harvest and the steady-state stock level under open-access are the same as those under enforced property rights at p^w, respectively. It yields that

$$p^c = 2p^w/(\alpha K p^w + 1). \tag{20}$$

A change in p affects both an incentive for the forest owner to enforce the property rights and the incentive for workers to engage in illegal logging. When the world price decreases from p^w to p^c, the incentive for the forest owner to enforce the property rights is reduced so that the decision of the forest owner is now no enforcement. However, the number of workers who engage in illegal logging is also reduced due to the fall in p. When the price changes from p^w to p^c, the effects due to the reductions in the incentives for enforcement and illegal logging just offset each other, so that the harvest and the forest stock in steady states remain the same before and after the change. For price $p < p^c$, the latter effect dominates the former effect and hence a lower steady-state harvest and a higher steady-state stock are obtained. For price $p \in (p^c, \bar{p})$, the former incentive dominates the latter effect and hence a lower steady-state stock follows. The effect on the steady-state harvest depends on the case. In the low enforcement cost case, a higher steady-state harvest must follow for price $p \in (p^c, \bar{p})$. In the high enforcement cost case, a higher steady-state harvest follows only for price $p \in (p^c, p^d)$, where p^d is defined below.

When $p^w > p^x$ holds, there may exist a price p^d such that $H^R_{ss}(p^w) = H^O_{ss}(p^d)$ with $S^O_{ss}(p^d) < K/2$,

[11] For simplicity, I assume that the world price is constant all the time. Then, $\bar{p}_{ss}$ is determined under the assumption of constant p.

which yields

$$p^d = 2wp^w/(\alpha K p^w - 1). \tag{21}$$

When the price changes from p^w to p^d, the steady-state harvest does not change. However, unlike the case of p^c, the steady-state stock level is lower at p^d than p^w.

Then, I consider another world price $p^{w\prime}$ for which $p^{w\prime} < \bar{p}_{ss}$ holds.[12] Although it is outside of the model, a lower world price prevails because the world demand for timber may be lower. I analyze the effects of this price fall separately in two cases. I first examine the case of low enforcement cost and then analyze the case of high enforcement cost. These two cases are depicted in Figures 4 and 5, respectively.

3.1 Low enforcement cost case

Consider first the case of low enforcement cost. Since $p^{w\prime} < \bar{p}_{ss}$ holds, the forest owner does not enforce property rights at this price and the economy is now in the open-access regime. Under certain conditions, this regime switch results in a larger supply of timber throughout the transition and in steady states. However, forest stock is lower than in the former case. A formal result is presented in the following proposition:

Proposition 1 *Consider the low-enforcement cost case. Let p^w and $p^{w\prime}$ be (exogenous) world prices of timber, where $p^w > \bar{p}_{ss} > p^{w\prime}$ holds, so that property rights are enforced at p^w and not enforced at $p^{w\prime}$. Then, in this small open economy (i) the forest stock is smaller and the output of good H is larger in a steady state at $p^{w\prime} > p^c$ than at p^w unless $p^w > p^x$ and $\bar{p}_{ss} > p^d$ and (ii) the output of good H is larger at $p^{w\prime}$ than at p^w throughout the transition if $S_0 > 1/\alpha p^{w\prime}$.*

Proposition 1 shows that a reduction in p results in a lower forest stock and larger timber production in steady state unless the gap in price before and after the change is too large. The condition for (ii) in Proposition 1 excludes the case in which p^w and $\bar{p}$ are too high.

[12] I assume that the initial resource stock level is the same in these two cases.

3.2 High enforcement cost case

I now turn to the case of high enforcement cost. Similar to the previous case, I consider a price change such that $p^w > \bar{p} > p^{w\prime}$ holds. As depicted in Figure 3, there is an upward jump at $\bar{p}_{ss}$. Thus, unlike the previous case, if p^w and $p^{w\prime}$ are sufficiently close to $\bar{p}_{ss}$, the price change yields a *lower* steady state supply of good H, despite the regime switch from enforced property rights to open-access.

There are three possible cases: (a) $p^{w\prime}$ is high (i.e., $p^{w\prime} > p^d$), (b) $p^{w\prime}$ is medium (i.e., $p^c < p^{w\prime} < p^d$), and (c) $p^{w\prime}$ is low (i.e., $p^{w\prime} < p^c$). Timber production in a steady state becomes larger only in case (b), while the forest stock in a steady state becomes lower in cases (a) and (b). The effects of a reduction in p in the case of high enforcement cost are formally presented in the following proposition:

Proposition 2 *Consider the high-enforcement cost case. Let p^w and $p^{w\prime}$ be (exogenous) world prices of timber, where $p^w > \bar{p}_{ss} > p^{w\prime}$ holds. Then, in this small open economy the forest stock in a steady state is lower at $p^{w\prime}$ than at p^w if $p^{w\prime} > p^c$ and the output of good H in a steady state is larger at $p^{w\prime}$ than at p^w if $p^c < p^{w\prime} < p^d$.*

As p^w is higher, the case where a fall in p yields a larger steady-state supply of good H is less likely to hold. This is because p^c and p^d become close to each other as p^w is higher, which is seen in Figure 5.

4 Large Exporting Countries of Timber

In this section, I extend the analysis to the case of large countries. Suppose that there are n large exporting countries of timber. The rest of the world imports timber and exports manufactures to these n countries. For simplicity, I assume that the rest of the world is not endowed with forest.

I also assume that these n countries are identical except for L_R, the cost of enforcing the property rights. Let L_{Ri} be the cost of enforcing the property rights in country i ($i = 1, 2, \ldots, n$). Order the countries so that

$$L_{R1} > L_{R2} > \ldots > L_{Rn}. \tag{22}$$

Let $\bar{p}_i$ be the steady-state price at which the resource owner in country i ($i = 1, 2, \ldots, n$) is indifferent between enforcing property rights and not doing so. Since the threshold price is determined by $V^* = 0$, where V^* is given by (16), in each country, condition (22) implies that $\bar{p}_1 > \bar{p}_2 > \ldots > \bar{p}_n$ holds, assuming that the initial resource stock S_0 and all parameters other than L_R is the same for all countries and that all countries face the same prices throughout the transition to steady states.

As is shown in the previous section, the case in which a reduction in p results in a larger production of timber is less likely to hold under the condition of high enforcement cost. Thus, in this section I focus on the case of low enforcement cost. More precisely, I consider the case in which $p^x > \bar{p}_1$ holds, which means that the condition for the case of low enforcement cost holds for all timber-exporting countries.

4.1 Steady-state equilibrium under free trade

Let J be the number of countries in which property rights are not enforced. Then, the world supply of timber in steady states, $H^W_{ss}(p)$, is given by a combination of $H^R_{ss}(p)$ (Eq. (12)) and $H^O_{ss}(p)$ (Eq. (19)):

$$H^W_{ss}(p) = \begin{cases} nH^R_{ss}(p), & \text{for } \bar{p}_1 \leq p, \\ (n-J)H^R_{ss}(p) + JH^O_{ss}(p), & \text{for } \bar{p}_{J+1} \leq p < \bar{p}_J,\ J = 1, 2, \ldots, n-1, \\ nH^O_{ss}(p), & \text{for } p < \bar{p}_n. \end{cases} \tag{23}$$

Then, assuming that the world demand for timber is not too weak or too strong and expands as p falls, the following proposition is obtained.

Proposition 3 *Assume $H^{WD}(1/\alpha K) > 0$, $\lim_{p\to\infty} H^{WD}(p) < nrK/4$, and $dH^{WD}(p)/dp < 0$. (i) A steady-state equilibrium exists; (ii) Multiple equilibria may exist in steady states; (iii) If $H^{WD}(\bar{p}_i - \varepsilon) > H^W_{ss}(\bar{p}_i - \varepsilon)$, where $\varepsilon > 0$ is small, equilibrium must exist for $p \geq \bar{p}_i$; (iv) If $H^{WD}(\bar{p}_i) < H^W_{ss}(\bar{p}_i)$, equilibrium must exist for $p < \bar{p}_i$.*

This proposition ensures the existence of steady-state equilibrium. There may be multiple equilibria because $H^W_{ss}(p)$ is discontinuous at $\bar{p}_i,\ i = 1, 2, \ldots, n$. The third part of the proposition shows that when the demand is higher than the supply at price just below a threshold price, equilibrium must exist above the threshold price. The fourth part of the proposition, on the other hand, shows that when the demand is lower than the supply at a threshold price, equilibrium must exit below the threshold price.

The situation in an example of $n = 2$ is illustrated in Figure 6. The world supply of timber in steady states is illustrated by thick curves denoted as H_{ss}^{W}, which is discontinuous at $\bar{p}_1$ and $\bar{p}_2$. This world supply curve of timber can be constructed by combining relevant parts of the steady-state supply curves of timber in each country. In the figure, the original steady-state supply curves of timber under enforced property rights and open-access are depicted by thin curves. For the price below $\bar{p}_2$ property rights are not enforced in either country. Thus, the world supply curve of timber at this part is constructed by summing horizontally two supply curves under open-access. For the price between $\bar{p}_2$ and $\bar{p}_1$ property rights are enforced in country 2 but not in country 1. Thus, the world supply curve at this part is given by adding horizontally the supply curve under enforced property rights and that under open-access. Finally, for the price above $\bar{p}_1$ property rights are enforced in both countries. Thus, the world supply curve at this part is obtained by summing horizontally two supply curves under enforced property rights.

The world demand for timber, $H^{WD}(p)$, on the other hand, is denoted as D in Figure 6. Four examples of the world demand for timber are depicted as D, $D^{'}$, $D^{''}$, and $D^{'''}$. If the world demand is D, the steady-state equilibrium is at point a, where both exporting countries adopt the enforced property rights regime. If the world demand is either $D^{'}$ or $D^{''}$, there are multiple equilibria, as is seen in the figure. Both countries may adopt the enforced property rights regime (like points b or e), or only country 2 adopts the enforced property rights regime while country 1 allows open-access (like point c), or neither country may adopt the enforced property rights regime (like points d or f). If the world demand is $D^{'''}$, the steady-state equilibrium is unique at point g, where both countries allow open-access.

Note that when there are multiple equilibria, each equilibrium in the range of $p \in [1/\alpha K, 2/\alpha K]$ and $p \in [\bar{p}_1, \infty)$ is locally stable in the sense that a small upward divergence from the equilibrium steady-state price causes an excess supply and a small downward divergence from the equilibrium steady-state price causes an excess demand. An equilibrium in the range of $p \in (2/\alpha K, \bar{p}_1)$ might possibly be unstable because the world supply curve can be negatively sloped due to the backward-bending part of $H_{ss}^{O}(p)$. In the subsequent analysis, I focus on stable equilibria.

In the case of multiple equilibria, a cocept of Nash equilibrium is useful to narrow down the number of equilibrium. Let p^{wi} be equilibrium steady-state world price in equilibrium E^i, $i = 1, \ldots, m$. Order the equilibria so that $p^{w1} > p^{w2} > \ldots > p^{wm}$. Suppose that forest owners in the timber-exporting countries play a non-cooperative game in which each forest owner simultaneously chooses either to enforce property rights with the optimal employment given by (10) or not to enforce property rights. Then, the following proposition is obtained.

Proposition 4 *When there are m equilibria in steady states, (i) E^1 is characterized as a Nash equilibrium of the non-cooperative game by forest owners; (ii) some of E^i, $i = 2, \ldots, m$, may not be characterized as a Nash equilibrium; (iii) E^1 weakly payoff-dominates all other Nash equilibria.*

This proposition shows that if forest owners in the timber-exporting countries play a non-cooperative game, the equilibrium in which the most countries enforce property rights among all possible equilibria is always a Nash equilibrium, while some of other equilibria may not be a Nash equilibrium. Although the concept of Nash equilibrium alone cannot narrow down equilibrium to one, an equilibrium selection by *weak payoff-dominance* selects a unique equilibrium outcome. One equilibrium is said to *weakly payoff-dominate* another equilibrium if all players are not worse off in the former than in the latter and if at least one player is strictly better off in the former than in the latter.[13]

4.2 The international diffusion of illegal extractions

Now, suppose that in E^1 property rights are enforced in countries k to n. In other words, $\bar{p}_k < p^{w1} < \bar{p}_{k-1}$ holds. Then, consider that the enforcement cost increases in country k, which causes $\bar{p}_k$ to become higher than p^{w1}.[14] Let $\bar{p}'_k > p^{w1}$ be the enforcement cost in country k after the change. This change results in a regime switch from enforced property rights to open-access in country k. In addition, this change in the enforcement cost in country k may also trigger a regime switch from enforced property rights to

[13]For a detailed discussion of payoff-dominance, see Harsanyi and Selten (1988). Okada *et al.* (1997) uses a concept of weak payoff-dominance.

[14]An increase in the enforcement cost may occur because a new improved logging or transport instrument became available to illegal harvesters, which makes illegal logging easier.

open-access in other countries. A formal result is presented in the following proposition:

Proposition 5 *Suppose that in E^1 property rights are enforced in countries k to n. Consider an increase in L_{Rk} in country k so that $\bar{p}'_k > p^{w1}$ holds. Because of this change, the regulatory regime switches from enforced property rights to open-access in countries k to l, where $k \leq l \leq n$, if $H^{WD}(p^{w*}) = H^W_{ss}(p^{w*})$ holds at $\bar{p}_{l+1} < p^{w*} < \bar{p}_l$ and there is no $p^{w**} > \bar{p}_l$ for which $H^{WD}(p^{w**}) = H^W_{ss}(p^{w**})$ holds.*

Take an example of $n = 2$ and $k = 1$. Figure 7 illustrates the possible effects of a change in L_{R1} in the example of two countries. Suppose that the world demand curve for timber is given by D''. In this case, there are initially two equilibria, e and f, which can be both Nash equilibria, while e weakly payoff-dominates f. At point e the world price is p^w. Then, consider that L_{R1} increases in country 1, which causes $\bar{p}_1$ to rise to $\bar{p}'_1$, where $\bar{p}'_1 > p^w$ holds. Since the threshold price for country 1 is now higher than the world price of timber, the forest owner in country 1 switches the regulatory regime from enforced property rights to open-access. Consequently, part of the steady-state world supply curve of timber changes. More precisely, the steady-state world supply curve of timber between $\bar{p}_1$ and $\bar{p}'_1$ jumps to the right. In Figure 7, the dotted part of H^W_{ss} is no longer included as part of the supply curve after the change, which implies that point e can no longer be an equilibrium point. It turns out that after the change the unique steady-state equilibrium point is point f, where country 2 as well as country 1 switches its management regime from enforced property rights to open-access. In this way, because of an increase in the enforcement cost in one country, the regulatory regime may switch from enforced property rights to open-access not only in that country but also in other countries.

4.3 Trade restrictions

In this subsection, I examine how trade restrictions can affect the management regime choice in the exporting countries. As I explained in the introduction, major importing countries of timber try to exclude illegally harvested timber from international transactions by signing bilateral agreements with exporting countries of timber. I will demonstrate that this action may not only reduce illegal logging in the country that signed the bilateral agreement but also reduce illegal logging in other countries.

A more traditional trade measure for importing countries to control illegal goods is quantitative restrictions on imports of the goods. As I discussed in the introduction, the issue of legality falls in the category of NPR-PPMs. Trade restrictions only on illegally logged timber are likely to be judged as violating the GATT/WTO rules. Therefore, trade restrictions must be imposed on imports of timber in general in order to conform to the GATT/WTO rules. As I will demonstrate below, however, import restrictions on timber in general may not be an effective means to reduce illegal logging. Here, import restrictions are modeled as a fall in the world demand for good H. Let $H_{ir}^{WD}(p)$ be the world demand for good H under import restrictions, where the subscript ir stands for "import restrictions." Then, $H_{ir}^{WD}(p) < H^{WD}(p)$ holds for all relevant p. The following proposition presents the possible perverse effects of import restrictions.

Proposition 6 *Permanent import restrictions on timber in general (i) do not eliminate E^i such that $p^{wi} < \bar{p}_n$, if it exists before the restrictions are imposed, (ii) may eliminate E^i such that $p^{wi} \geq \bar{p}_n$, (iii) may create an equilibrium for $p < \bar{p}_1$, and (iv) may facilitate the international diffusion of illegal harvests.*

Proposition 6 shows that permanent import restrictions on timber in general do not eliminate an equilibrium where no country enforces property rights. They may eliminate an equilibrium where property rights are enforced in some countries and/or create an equilibrium where property rights are enforce in less countries. They may also facilitate the international diffusion of illegal harvests in the sense that an increase in the enforcement cost in one country may trigger the regime switch in some other countries with import restrictions, while such a phenomenon occurs in less countries without import restrictions.

The intuition is rather simple. When import restrictions are imposed on timber in general without distinguishing between legally harvested timber and illegally harvested timber, the world demand for timber simply shifts to the left. This tends to reduce the equilibrium price. While a lower price reduces an incentive for illegal logging, it may cause more countries to switch the management regime from enforced property rights to open-access. For example, suppose that the world demand for timber is initially given by D' in Figure 7. In this case, an increase in L_{R1} will result in a change in equilibrium from point b to either point c or point d. Since point c is a Nash equilibrium but point d is not, the new steady-state equilibrium is likely to be at point c, where the regime switch occurs only in country 1. If import restrictions are imposed on timber in general, the demand curve could shift to D''. If that is the case, then an increase in L_{R1} will result in a shift of equilibrium to point f, where neither country enforces property rights. In this way, import restrictions on timber in general may facilitate the international diffusion of illegal logging, which is against the intension of the import restriction.

Although I only analyzed the effects of permanent import restrictions in Proposition 6, temporary import restrictions may also cause a regime switch. Temporary import restrictions on timber in general do not directly affect steady-state equilibrium. However, since those restrictions decrease the value of V^* (Eq. (16)), they reduce the forest owners' incentive to enforce property rights. A forest owner may change his/her choice to open-access due to temporary import restrictions.

I next examine the effects of bilateral agreement between one exporting country and importing countries to eliminate exports of illegally logged timber from that country. Call the exporting country that signed the agreement country s. I assume that the bilateral agreement requires country s to supply only legally logged timber.[15] For simplicity, I assume that there is no problem of asymmetric information in the sense that legally harvested timber and illegally harvested timber can be perfectly distinguished without any additional costs. However, for consumers these two types of timber are perfect substitutes.

Let $H_{ba}^W(p)$ be the world supply of timber under the bilateral agreement between exporting country s and importing countries, where the subscript ba stands for "bilateral agreement." $H_{ba}^W(p)$ can be expressed as

$$H_{ba}^W(p) = \begin{cases} H_{ss}^W(p), & \text{for } p \geq \bar{p}_s, \\ H_{ss}^W(p) - \Delta(p), & \text{for } p < \bar{p}_s, \end{cases} \tag{24}$$

where $\Delta(p)$ is defined by Eq. (A.1).

The effects of a bilateral agreement are then presented in the following proposition .

Proposition 7 *A bilateral agreement that requires the signed exporting country s to supply only legally*

[15] In order to execute the agreement, the governments of country s and signed importing countries would provide financial and technical support to the forest sector in country s.

logged timber (i) does not disturb an equilibrium E^j for $p^{wj} > \bar{p}_s$ that exists, if any, before the agreement is signed, (ii) may eliminate an equilibrium E^i for $p^{wi} < \bar{p}_s$, and (iii) may create an equilibrium for $p \in [\bar{p}_l, \bar{p}_s)$ when there exists an equilibrium E^k for $p^{wk} < \bar{p}_l$ before the agreement is signed.

This proposition implies that if property rights are enforced in country s in a steady-state equilibrium before the agreement is signed, that equilibrium is retained after the agreement is signed. Moreover, before the agreement is signed, property rights may not be enforced in countries 1 to l, including country s. However, because of the agreement, the management regime is switched from open-access to enforced property rights in countries g to n as well as country s, where $g \in [s+1, l]$. This is due to the creation of a new equilibrium. The price in the new equilibrium is higher than that in the existing equilibria.

An important implication of Proposition 7 is that a bilateral agreement between one exporting country and importing countries to exclude illegally logged timber from trade may be able to mitigate illegal logging in some other countries by reducing the world supply of timber and raising the equilibrium price of timber.

Figure 8 shows an example of $n = 2$. Suppose that country 1 signs the agreement and stops exports of illegally logged timber. In this situation, the world supply curve of timber is given by thick curves denoted H^W_{ba}. Broken curves are the initial world supply. When the world demand for timber is D''', point g was initially a unique steady-state equilibrium in which property rights are not enforced in either country. Because of the agreement, the world supply shifts to the left in the range of $p \in [\bar{p}_2, \bar{p}_1)$ and $p \in [1/\alpha K, \bar{p}_2)$. Equilibrium point g moves to g$'$ and a new equilibrium point h emerges. Property rights are enforced in both countries at point h. Thus, the bilateral agreement between country 1 and importing countries can change the management regime in country 2 as well as in country 1.

5 Concluding Remarks

In this paper, I examined how illegal extractions of renewable resources in one country could affect harvest and conservation of the renewable resources in other countries through a change in the world price of the resources. Since the enforcement of property rights over the resources is costly, the resource owner decides whether or not to enforce these rights. If the owner chooses not to enforce the property rights, illegal extractors harvest the resource under open-access condition. In order to illustrate the results clearly, I assumed a fixed cost of enforcement so that the decision of the resource owner is binary: either to enforce or not to enforce the property rights.

I demonstrated that in the case of small open economy an exogenous reduction in the world price of the resource good may lead to its higher output with lower level of the resource stock in steady states. This could happen due to a switch in the regulatory regime from enforced property rights to open-access triggered by a fall in price. Moreover, I extended the analysis to the case of several large countries exporting the resource good. I assumed that these countries are identical except for the (fixed) enforcement cost. In this framework, I showed that when the enforcement cost rises in one country so that the regulatory regime in that country changes from enforced property rights to open-access, the regulatory regime in some other countries may also change from enforced property rights to open-access. This is because the regulatory regime switch in one country expands the world supply of the resource good, placing a downward pressure on the world price of the resource good.

A major implication of the analysis in this paper is that the current efforts by the world community to exclude illegally logged timber from the international market by signing bilateral agreements may be effective in not only controlling illegal logging in countries that sign the agreements but also mitigating illegal logging in other countries.

Several extensions and generalizations of the analysis in this paper can be considered. First, I used a specific functional form for the natural growth function of the resource stock. Although the functional form that I used in this paper is quite standard in the literature, some other functional forms may be more appropriate to some types of renewable resources. A well-known example of another type of the growth function is the one that is said to exhibit *critical depensation*, that is, a function with growth rates becoming negative when population drops below a critical level (Clark, 1990). For resources with critical depensation, the depletion of resources along with the transition to steady states is more likely to occur under the open-access regime. Consequently, the effects of illegal harvests are more serious.

Second, the harvest function can also be generalized. I used the standard Schaefer production function. If the sensitivity of harvest costs to the stock size is taken into account, the harvest function looks like $H = \alpha S^{\beta} L_H$, where $\beta \in [0,1]$. A decrease in β compresses the steady-state supply curve under open-access. However, as long as β is positive, the results in this paper do not qualitatively change.

Third, although I assumed a fixed enforcement cost and a binary regime choice, it will be more general to allow intermediate levels of enforcement of property rights and a variable cost of enforcement, as in Hotte, Long, and Tian (2000). In such a case, both legally and illegally harvested resource goods may be supplied in one country in equilibrium, which is more realistic. Some additional results may be obtained. However, Hotte, Long, and Tian (2000) show that the owner of the resource will choose to deter completely the entry of illegal harvesters and that a mixed supply of legally and illegally harvested resource goods will not happen in one country as long as all the sites of the resources are symmetric. Moreover, when intermediate levels of enforcement are allowed, the results may become less clear. However, the main finding in this paper, that a fall in price may possibly cause a higher supply with lower resource stock, will generally hold as long as the effect of the price fall on the incentive for enforcement overrides the effect on the incentive for illegal harvests.

Finally, I did not analyze the effects of a change in price of the resource good on harvests and the resource stock in importing countries. Since trade restrictions of the resource goods by importing countries might possibly be motivated by protecting the domestic resource sector in these countries, it would be important to attempt such an analysis.

Appendix

Proof of Lemma 1. Differentiate π_{ss}^{H*} with respect to p_{ss} and L_R to yield $d\pi_{ss}^{H*}/dp_{ss} = rw_{ss}/4\alpha^2 K p_{ss}^2 > 0$ and $d\pi_{ss}^{H*}/dL_R = -1 < 0$, respectively. ∎

Proof of Proposition 1. (i) By definition, $H_{ss}^R(p^w) = H_{ss}^O(p^{w\prime})$ and $S_{ss}^R(p^w) = S_{ss}^O(p^{w\prime})$ at $p^{w\prime} = p^c$. From (18) with $w = 1$ it yields that $\mathrm{d}S_{ss}^O(p_{ss})/\mathrm{d}p_{ss} = -1/\alpha p_{ss}^2 < 0$. Thus, for $p^{w\prime} > p^c$ it holds that $S_{ss}^O < S_{ss}^R(p^w)$. Similarly, from (19) with $w = 1$ it yields that $\mathrm{d}H_{ss}^O(p_{ss})/\mathrm{d}p_{ss} = (r/\alpha p_{ss}^2)(2/\alpha K p_{ss} - 1)$. Then, $\mathrm{d}H_{ss}^O(p_{ss})/\mathrm{d}p_{ss} >$ (resp. $<$) 0 for $S_{ss}^O = 1/\alpha p_{ss} >$ (resp. $<$) $K/2$ and $H_{ss}^R(p^w) = H_{ss}^O(p^d)$ with $S_{ss}^O(p^d) < K/2$. If $p^w < p^x$, then $H_{ss}^R(p^w) = H_{ss}^O(p)$ holds only at $p = p^c$. Thus, $H_{ss}^R(p^w) < H_{ss}^O(p)$ holds for any $p \in (p^c, \bar{p}_{ss})$. If $\bar{p}_{ss} < p^d$, property rights are enforced at $p = p^d$, which implies that $H_{ss}^R(p^w) < H_{ss}^O(p)$ holds for any $p \in (p^c, \bar{p}_{ss})$. (ii) The temporary VMP_{L_H} at $p^{w\prime}$ is given by $p^{w\prime}\alpha S^R$. Since this economy becomes diversified in the steady state that corresponds to $p^{w\prime}$, it holds that $S^O = 1/\alpha p^{w\prime}$, which implies $\mathrm{VMP}_{L_H}(p^{w\prime}, S) > 1$ if $S > S^O$. Then, if $S_0 > S^O = 1/\alpha p^{w\prime}$, all workers engage in illegal logging throughout the transition. Thus, the output of good H must be larger. ∎

Proof of Proposition 2. The result for the forest stock can be proved in the same way as Proposition 1 (i). Since $\bar{p}_{ss} > p^x$, it holds that $H_{ss}^R(p^w) = H_{ss}^O(p)$ for $p = p^c$ and $p = p^d$. Then, use the proof for Proposition 1 (i) to show that $H_{ss}^R(p^w) < H_{ss}^O(p^{w\prime})$ for $p^{w\prime} \in (p^c, p^d)$. ∎

Proof of Proposition 3. (i) Country i's steady-state supply function is given by $H_{ss}^O(p)$ for $p < \bar{p}_i$ and $H_{ss}^R(p)$ for $p \geq \bar{p}_i$. $H_{ss}^R(p) = H_{ss}^O(p)$ holds only for $p = 1/\alpha K$ and $p = p^x$. $H_{ss}^R(p) < H_{ss}^O(p)$ holds for $p < p^x$. Since countries differ only in L_R, the same $H_{ss}^R(p)$ (Eq. (12)) and $H_{ss}^O(p)$ (Eq. (19)) apply to all countries. Thus, the steady-state supply function is given by Eq. (23), which is discontinuous at $\bar{p}_i$. Define

$$\Delta(p) \equiv H_{ss}^O(p) - H_{ss}^R(p) = (r/\alpha p)(\alpha K p - 1)(3 - \alpha K p)/4\alpha K p. \tag{A.1}$$

Since $p^x > \bar{p}_1$, $H_{ss}^W(\bar{p}_i - \varepsilon) - H_{ss}^W(\bar{p}_i) = \Delta(\bar{p}_i) > 0$. $H_{ss}^W(p)$ is continuous for $p \geq \bar{p}_1$, $p \in [\bar{p}_i, \bar{p}_{i-1})$, $i = 2, 3, \ldots, n$, and $p < \bar{p}_n$. Then, if $H^{WD}(p)$ satisfies the conditions specified in the proposition, $H^{WD}(p)$ and $H_{ss}^W(p)$ must intersect with each other. (ii) Since $H_{ss}^W(p) < H_{ss}^W(p')$ can hold for some p and p' with $p > p'$, $H_{ss}^W(p) = H^{WD}(p)$ and $H_{ss}^W(p') = H^{WD}(p')$ can also hold for $H^{WD}(p)$ such that

$\mathrm{d}H^{WD}(p)/\mathrm{d}p < 0$. (iii) Suppose that $H^{WD}(\bar{p}_i - \varepsilon) > H^W_{ss}(\bar{p}_i - \varepsilon)$ holds. Since $\mathrm{d}H^{WD}(p)/\mathrm{d}p < 0$, then $H^{WD}(p) < H^{WD}(\bar{p}_i - \varepsilon)$ for $p \geq \bar{p}_i$. On the other hand, $H^W_{ss}(\bar{p}_i) < H^W_{ss}(\bar{p}_i - \varepsilon)$ and $\lim_{p\to\infty} H^W_{ss}(p) > H^W_{ss}(\bar{p}_i - \varepsilon)$. Moreover, $H^W_{ss}(\bar{p}_j - \varepsilon) - H^W_{ss}(\bar{p}_j) = \Delta(\bar{p}_j) > 0$ for all $j \leq i$ and $H^W_{ss}(p)$ is continuous for $p \geq \bar{p}_1$ and $p \in [\bar{p}_j, \bar{p}_{j-1}),\ j = 2, 3, \ldots, i$. Thus, $H^{WD}(p)$ and $H^W_{ss}(p)$ must intersect with each other for $p \geq \bar{p}_i$. (iv) Suppose that $H^{WD}(\bar{p}_i) < H^W_{ss}(\bar{p}_i)$. Since $\mathrm{d}H^{WD}(p)/\mathrm{d}p < 0$, then $H^{WD}(p) > H^{WD}(\bar{p}_i)$ for $p < \bar{p}_i$. On the other hand, $H^W_{ss}(\bar{p}_i) < H^W_{ss}(\bar{p}_i - \varepsilon)$ and $H^W_{ss}(1/\alpha K) = 0$. Moreover, $H^W_{ss}(\bar{p}_j - \varepsilon) - H^W_{ss}(\bar{p}_j) = \Delta(\bar{p}_j) > 0$ for all $j > i$ and $H^W_{ss}(p)$ is continuous for $p < \bar{p}_n$ and $p \in [\bar{p}_j, \bar{p}_{j-1}),\ j = i+1, i+2, \ldots, n$. Thus, $H^{WD}(p)$ and $H^W_{ss}(p)$ must intersect with each other for $p < \bar{p}_i$. ∎

Proof of Proposition 4. (i) Suppose first that $\bar{p}_1 < p^{w1}$, implying that property rights are enforced in all exporting countries in E^1. Let V_i^* be the present value of rents from forestry defined by (16) in country i. Then, in E^1 it holds that $V_i^* > 0$, $\forall i$. A deviation from E^1 results in $V_i^* = 0$ for all forest owners, implying that E^1 is a Nash equilibrium. Suppose next that $\bar{p}_{k+1} < p^{w1} < \bar{p}_k$. In E^1, property rights are enforced in countries $k+1$ to n and not enforced in countries 1 to k. Since $\bar{p}_{k+1} < p^{w1}$, for forest owners in countries $k+1$ to n it holds that $V_i^* > 0$ by enforcing property rights, implying no incentive to deviate from E^1 by changing unilaterally his/her own choice from enforced property rights to open-access. Since $p^{w1} < \bar{p}_k$ and there is no equilibrium above $\bar{p}_k$, forest owners in countries 1 to k end up with $V_i^* < 0$ if he/she deviate from E^1 by changing his/her own choice from open-access to enforced property rights. Thus, E^1 is a Nash equilibrium. (ii) Consider an equilibrium E^i. Suppose that there is another equilibrium E^{i-1} such that $\bar{p}_{k+1} < p^{wi} < \bar{p}_k$ and $\bar{p}_k < p^{wi-1} < \bar{p}_{k-1}$. In E^i, property rights are enforced in countries $k+1$ to n and not enforced in countries 1 to k. Since $\bar{p}_{k+1} < p^{wi}$, forest owners in countries $k+1$ to n have no incentive to deviate from E^i by changing unilaterally his/her own choice from enforced property rights to open-access. Similarly, since $p^{wi-1} < \bar{p}_{k-1}$, forest owners in countries 1 to $k-1$ have no incentive to deviate from E^i by changing his/her own choice from open-access to enforced property rights. However, the forest owner in country k *does* have an incentive to deviate from E^i by changing his/her own choice from open-access to enforced property rights, because $\bar{p}_k < p^{wi-1}$ holds in E^{i-1}. Thus, E^i cannot be a Nash equilibrium. (iii) Compare payoffs of forest owners in E^1 with those in another Nash equilibrium E^l, $l \neq 1$. Since $p^{w1} > p^{wl}$, those who enforce property rights in E^l also do so in E^1. Some of those who do not enforce property rights in E^l enforce property rights in E^1. Then, those who do not enforce property rights both in E^1 and in E^l are indifferent between these two Nash equilibria. Since $p^{w1} > p^{wl}$, those who enforce property rights both in E^1 and in E^l are strictly better off in E^1 than in E^l because of Lemma 1 (i). Those who enforce property rights in E^1 but do not in E^l are also strictly better off in E^1 than in E^l. Thus, E^1 weakly payoff-dominates E^l. ∎

Proof of Proposition 5. By construction, $H^W_{ss}(p^{w1}) = H^{WD}(p^{w1})$ holds. When L_{Rk} rises so that $\bar{p}'_k > p^{w1}$ holds, the supply of country k changes from $H^R_{ss}(p)$ to $H^O_{ss}(p)$ for the price $p \in [\bar{p}_k, \bar{p}'_k)$. Consequently, $H^W_{ss}(p)$ discontinuously expands for the price $p \in [\bar{p}_k, \bar{p}'_k)$. Since $p^{w1} \in (\bar{p}_k, \bar{p}'_k)$, $H^W_{ss}(p^{w1}) > H^{WD}(p^{w1})$ may hold after the change. If $H^{WD}(p^{w*}) = H^W_{ss}(p^{w*})$ holds at $\bar{p}_{l+1} < p^{w*} < \bar{p}_l$ and there is no $p^{w**} > \bar{p}_l$ for which $H^{WD}(p^{w**}) = H^W_{ss}(p^{w**})$ holds, p^{w*} is the highest possible equilibrium price among the remaining equilibria. Since $\bar{p}_{l+1} < p^{w*} < \bar{p}_l$, the regime switch occurs in all countries from country k up to country l. By Lemma 4 (i) and (iii), E^1 was a Nash equilibrium and weakly payoff-dominated all other Nash equilibria. After the disappearance of E^1, Lemma 4 (i) and (iii) suggest that the equilibrium that corresponds to p^{w*} be a Nash equilibrium and weakly payoff-dominate other Nash equilibria. ∎

Proof of Proposition 6. (i) Since $H^W_{ss}(1/\alpha K) < H^W_{ss}(\bar{p}_n - \varepsilon)$ and $H^W_{ss}(p)$ is continuous for $p \in [1/\alpha K, \bar{p}_n)$ and since $H^{WD}_{ir}(p) < H^{WD}(p)$, then $H^{WD}_{ir}(p)$ must intersect with $H^W_{ss}(p)$ at $p < \bar{p}_n$ if $H^{WD}(p)$ intersects with $H^W_{ss}(p)$ in this range. (ii) E^i exists for $p \in [\bar{p}_j, \bar{p}_{j-1})$ if $H^W_{ss}(\bar{p}_j) < H^{WD}(\bar{p}_j)$ and $H^W_{ss}(\bar{p}_{j-1}) > H^{WD}(\bar{p}_{j-1})$. Since $H^{WD}_{ir}(p) < H^{WD}(p)$, E^i is eliminated if $H^W_{ss}(\bar{p}_j) > H^{WD}_{ir}(\bar{p}_j)$. (iii) No stable equilibrium exists for $p \in [\bar{p}_{k+1}, \bar{p}_k)$ if $H^W_{ss}(\bar{p}_k - \varepsilon) < H^{WD}(\bar{p}_k - \varepsilon)$. Then, since $H^{WD}_{ir}(p) < H^{WD}(p)$, an equilibrium is created in this range if $H^W_{ss}(\bar{p}_k - \varepsilon) < H^{WD}_{ir}(\bar{p}_k - \varepsilon)$ holds. (iv) Suppose that there exists E^1 such that $\bar{p}_k < p^{w1} < \bar{p}_{k-1}$. Suppose also that $H^{WD}(p^{w2}) = H^W_{ss}(p^{w2})$ holds at E^2 where $\bar{p}_j < p^{w2} < \bar{p}_{j-1}$ holds with $k \leq j-1$. Then, E^2 may be eliminated by the import restrictions, as shown in part (ii). Consider an increase in L_{Rk} described in Proposition 5. Without import restrictions, because of this change E^2 becomes a Nash equilibrium that weakly payoff-dominates other remaining equilibria. Thus, the regulatory regime switches from enforced property rights to open-access in countries from country k to country $j-1$. With import restrictions, on the other hand, the regulatory regime switches from enforced property rights to open-access in countries from country k to country l, where $j-1 < l$, if the import restrictions eliminate E^2. ∎

Proof of Proposition 7. (i) Under the bilateral agreement, the supply of country s is given by $H^R_{ss}(p)$ for all p. Thus, as part of the world supply of timber, $H^O_{ss}(p)$ is replaced by $H^R_{ss}(p)$ for $p < \bar{p}_s$, yielding Eq. (24). As Eq. (24) shows, $H^W_{ba}(p) = H^W_{ss}(p)$ for $p \geq \bar{p}_s$. Thus, there is no change in this range. (ii) Before the agreement is signed, there is E^j such that $\bar{p}_{i+1} \leq p^{wj} < \bar{p}_i$ if $H^{WD}(\bar{p}_i - \varepsilon) < H^W_{ss}(\bar{p}_i - \varepsilon)$ and $H^{WD}(\bar{p}_{i+1}) > H^W_{ss}(\bar{p}_{i+1})$. Since $H^W_{ss}(p)$ shifts to the left by $\Delta(p)$ for $p < \bar{p}_s$, E^j is eliminated under the bilateral agreement if $H^{WD}(\bar{p}_i - \varepsilon) > H^W_{ba}(\bar{p}_i - \varepsilon)$ or $H^W_{ss}(\bar{p}_i - \varepsilon) - H^{WD}(\bar{p}_i - \varepsilon) < \Delta(\bar{p}_i - \varepsilon)$. (iii) Suppose that $H^{WD}(\bar{p}_l) < H^W_{ss}(\bar{p}_l)$. Then, from Proposition 3 (iv) there must exist an equilibrium E^k such that $p^{wk} < \bar{p}_l$. If $H^{WD}(\bar{p}_i) < H^W_{ss}(\bar{p}_i)$ holds for all $i = 1, 2, \cdots, l$, no equilibrium exists for $p \geq \bar{p}_l$. Then, if $H^W_{ss}(\bar{p}_l) - H^{WD}(\bar{p}_l) < \Delta(\bar{p}_l)$ or $H^W_{ba}(\bar{p}_l) < H^{WD}(\bar{p}_l)$ and $H^W_{ss}(\bar{p}_s - \varepsilon) - H^{WD}(\bar{p}_s - \varepsilon) > \Delta(\bar{p}_s - \varepsilon)$ or $H^W_{ba}(\bar{p}_s - \varepsilon) > H^{WD}(\bar{p}_s - \varepsilon)$, then $H^W_{ba}(p)$ and $> H^{WD}(p)$ must intersect with each other in the range of $p \in [\bar{p}_l, \bar{p}_s)$. This is because $H^W_{ss}(\bar{p}_i - \varepsilon) - H^W_{ss}(\bar{p}_i) = \Delta(\bar{p}_i) > 0$, $H^W_{ss}(p) - H^W_{ba}(p) = \Delta(p)$, and $H^W_{ba}(p)$ is continuous for $p \in [\bar{p}_i, \bar{p}_{i-1})$. ∎

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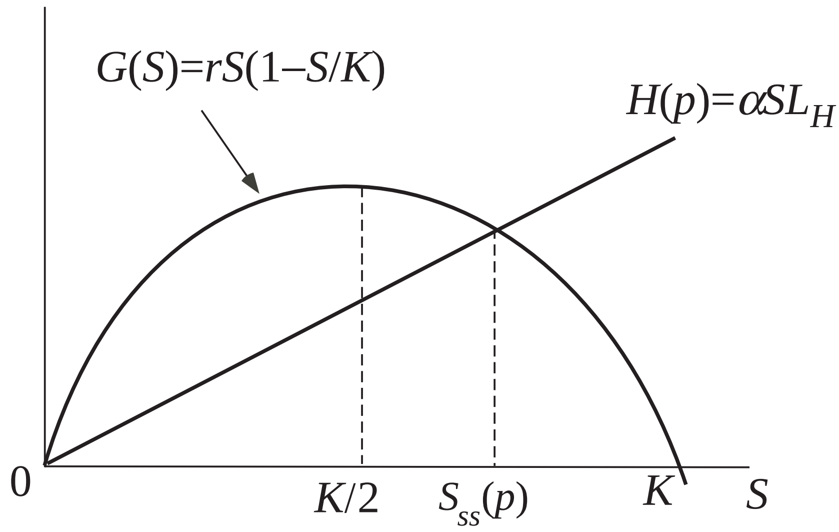

Figure 1: Resource dynamics

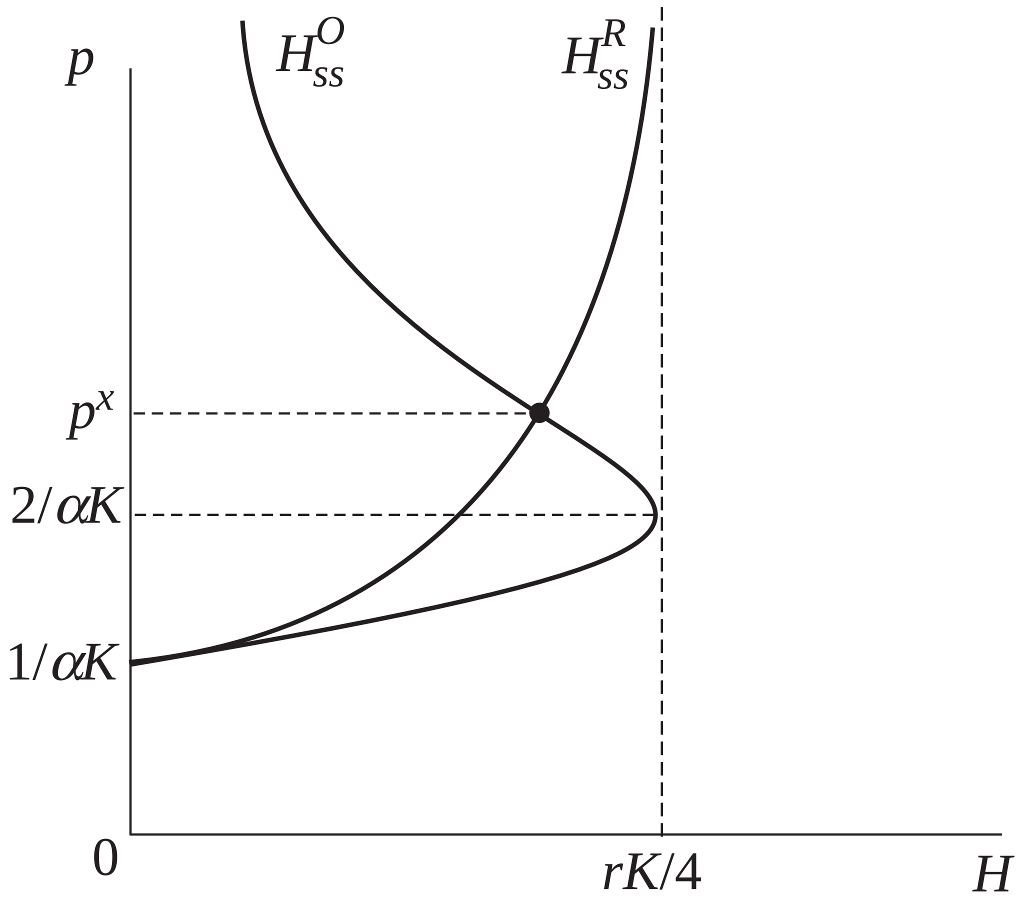

Figure 2: The steady-state supply curves of timber under two regimes

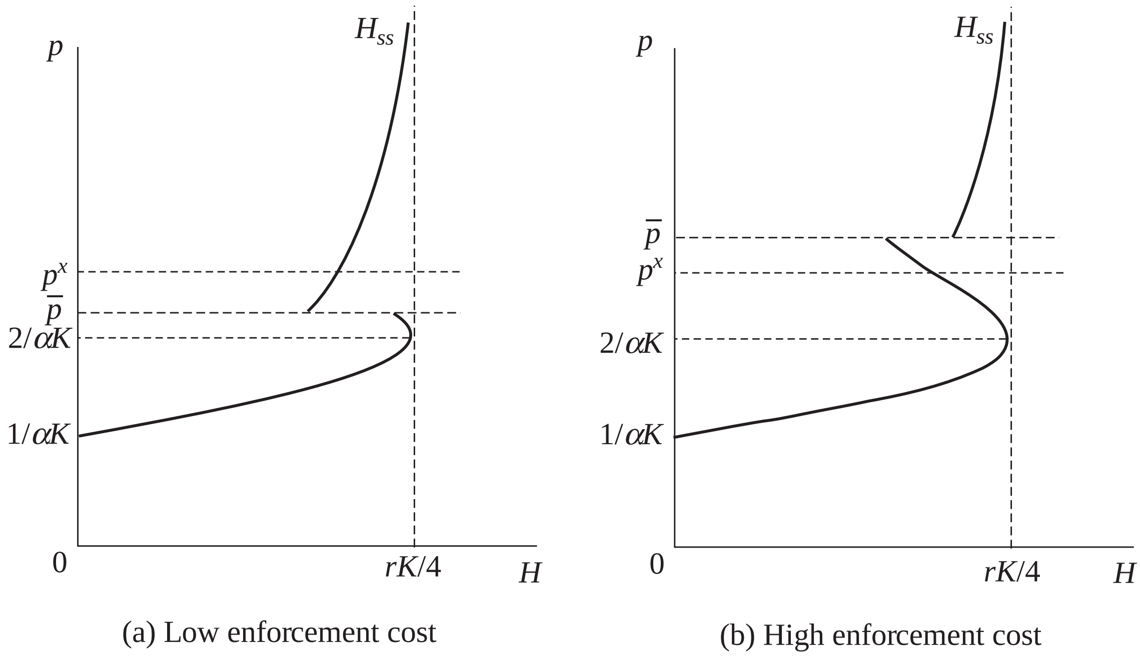

Figure 3: The steady-state supply of timber in two cases

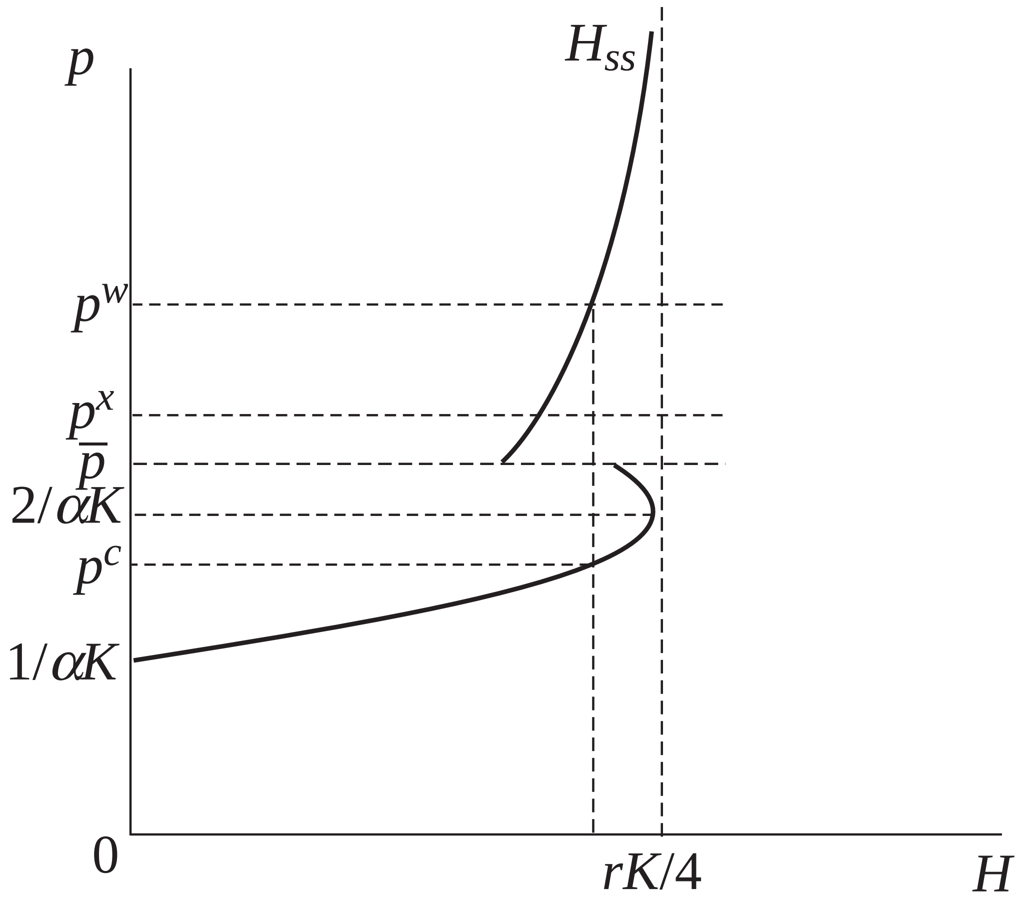

Figure 4: The steady-state supply of timber in the low-enforcement cost case

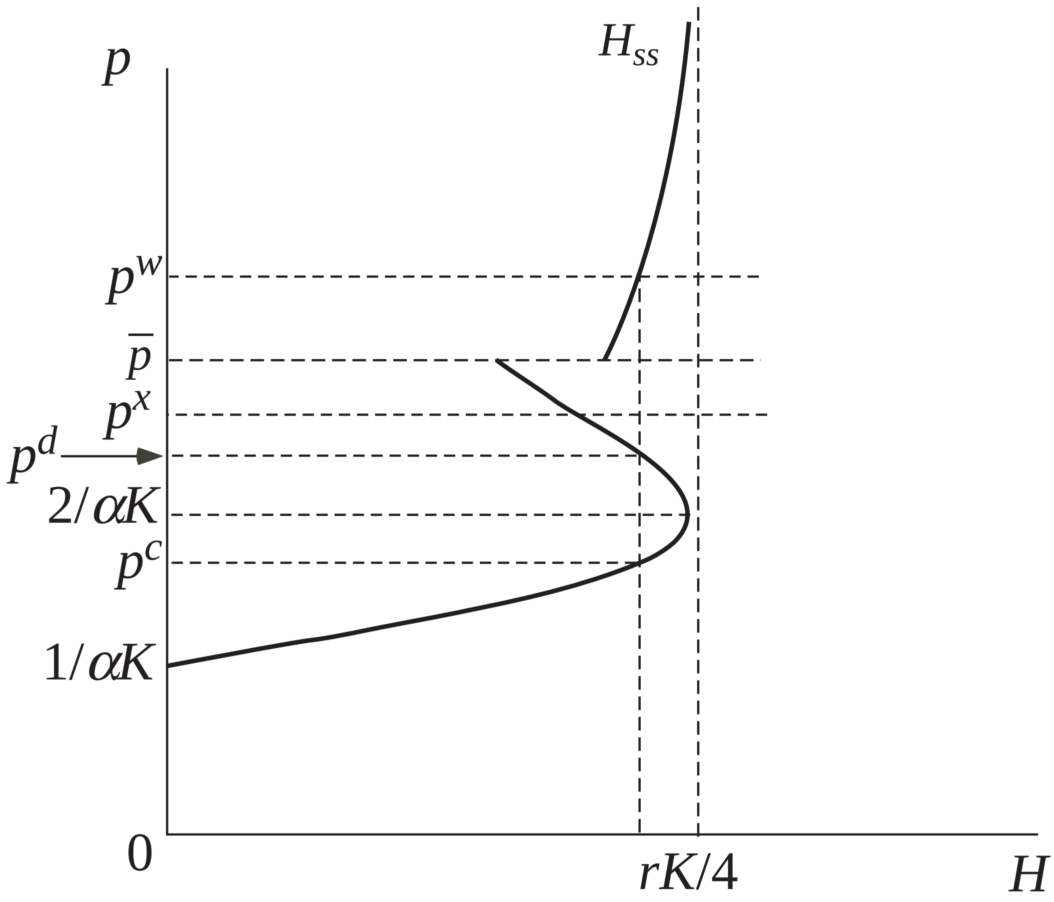

Figure 5: The steady-state supply of timber in the high-enforcement cost case

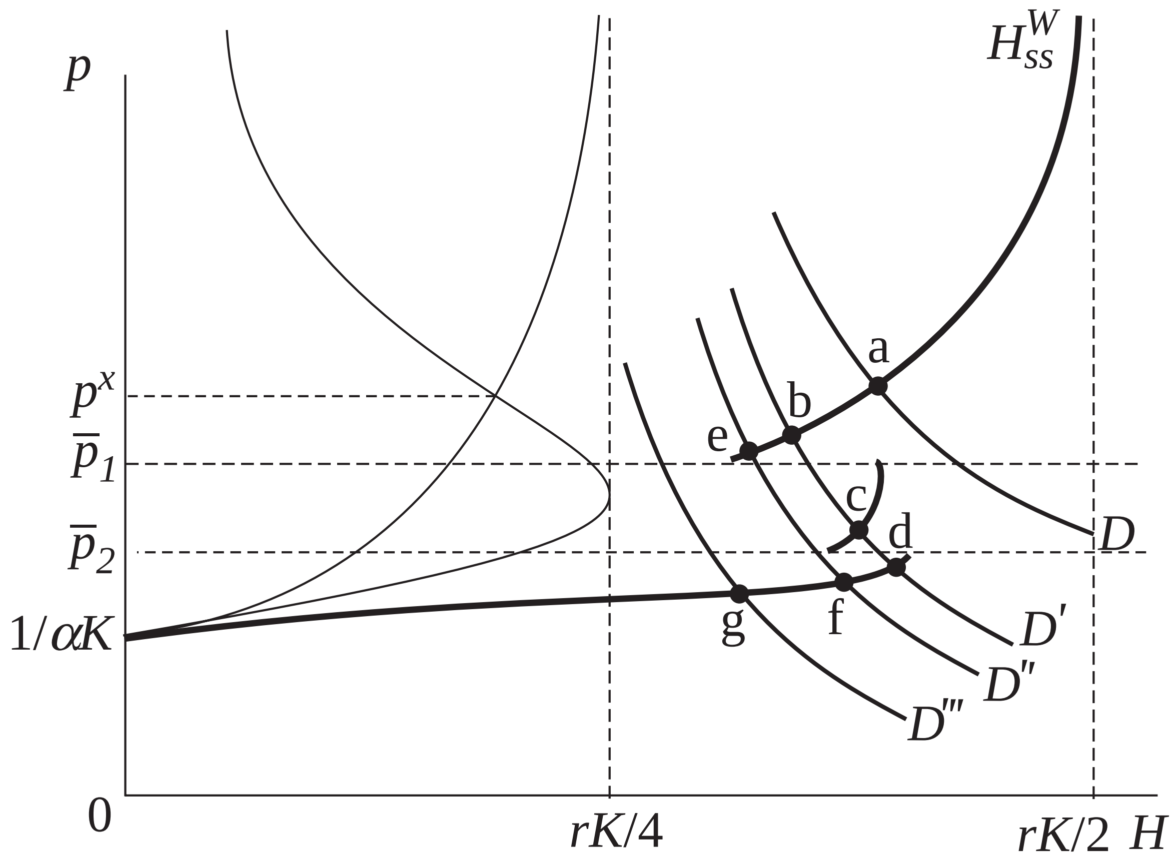

Figure 6: Two large countries exporting timber: The low-enforcement cost case

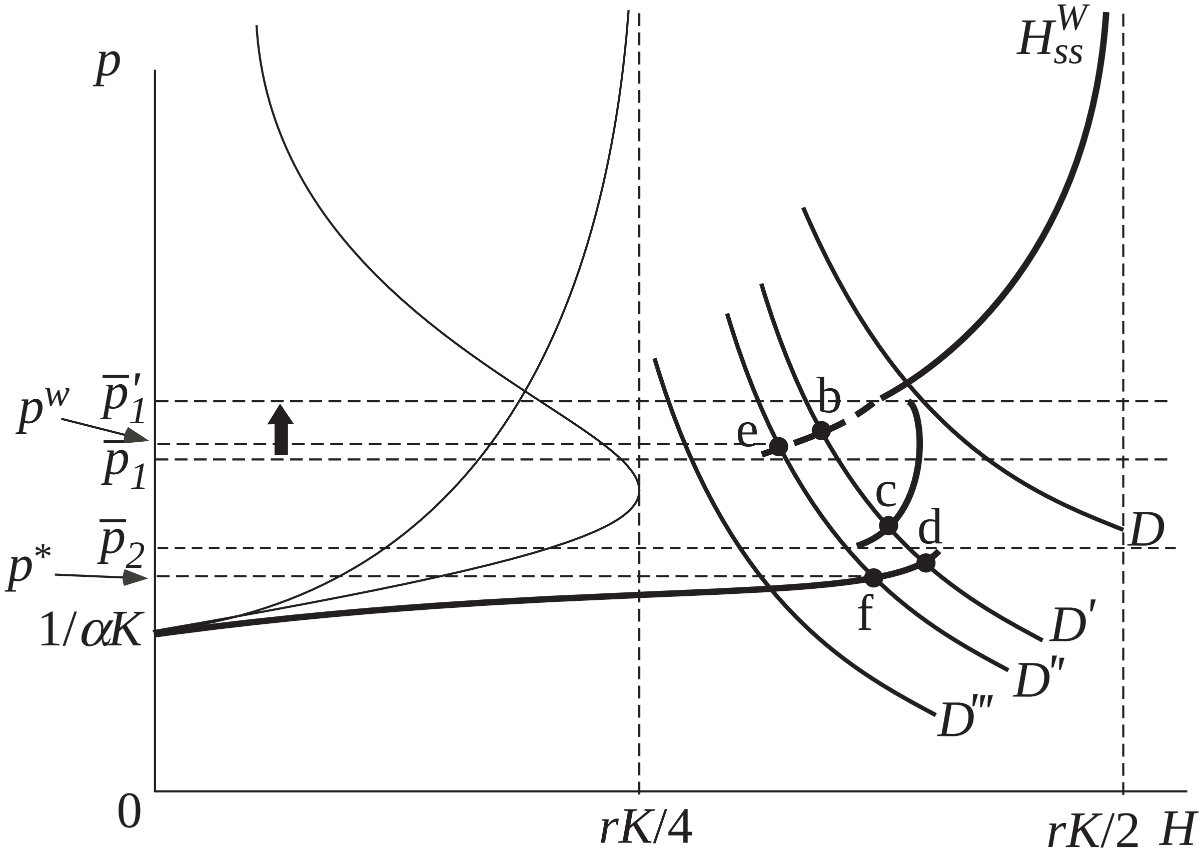

Figure 7: The regime switch due to a change in L_{R1} in a two-country case

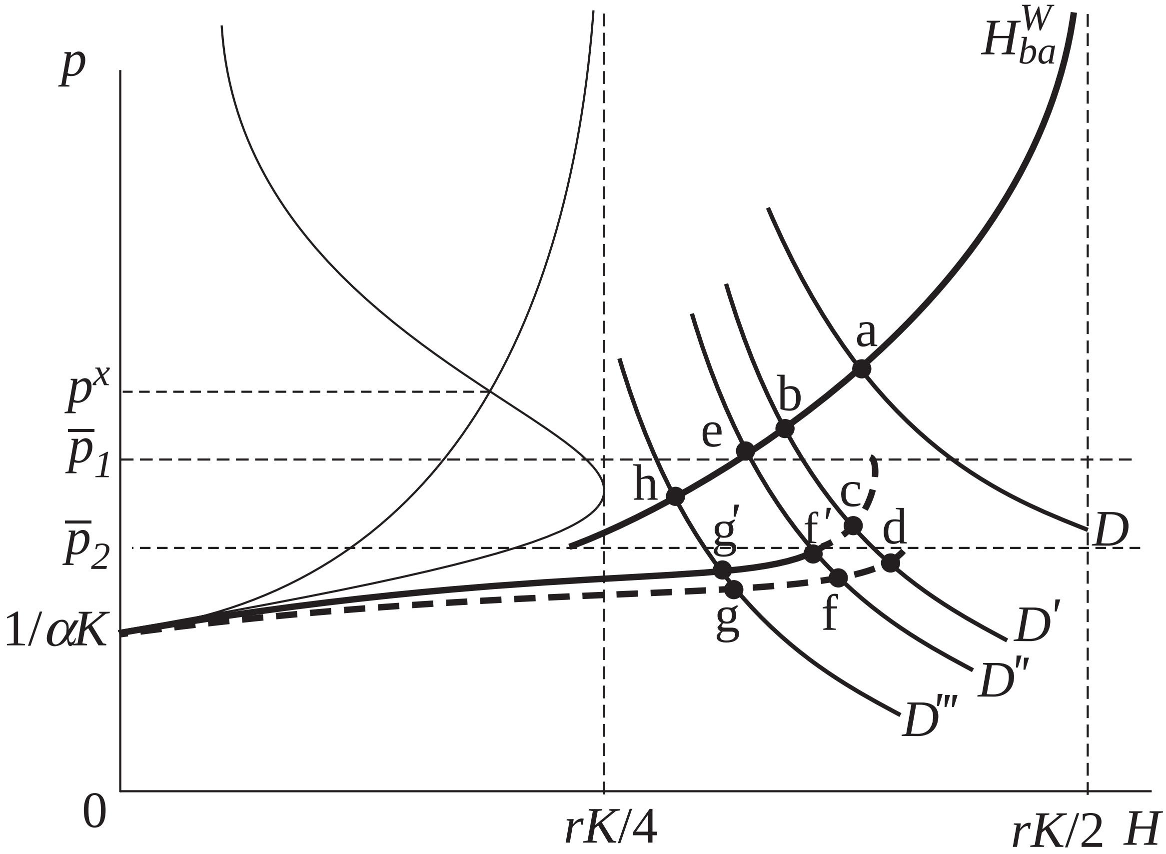

Figure 8: A bilateral agreement between country 1 and importing countries