Trade, Tragedy, and the Commons

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Abstract: We develop an infinite horizon dynamic general equilibrium model of renewable resource extraction with an ongoing birth and death process. We assume the resource stock is managed to maximize a utilitarian objective function defined over all generations and implemented via rules governing agent's access to the resource stock. Agents choose to abide by the rules or cheat and risk ostracism and reduced access to the commons. We show how changes in world prices alter the effective property rights regime changing some countries from de facto open access situations to ones where management replicates that of an unconstrained social planner. Not all countries can follow this path of institutional reform and we identify key country characteristics (mortality rates, resource growth rates, technology) that divide the world's set of resource rich countries into three classes. Class I countries will never be able to develop control over access to their renewable resources. Class II countries exhibit open access for low resource prices, but can maintain a more limited form of resource management at higher prices. Class III countries are those for which the first best can be obtained. For Class III countries open access and the limited management are but transitory phases they pass through.

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1. Introduction

Concern over the sustainability of major renewable resource stocks has emerged as a significant international policy issue. For example, there have been widely publicized claims that forests in countries such as Brazil, Canada and Indonesia are being harvested excessively. And other renewable resources, including fish, wildlife stocks and the biosphere, are also alleged to be under threat. Not surprisingly then there is now considerable interest in incorporating trade rules focused on resource management into the World Trade Organization (WTO) and other international arrangements. Unfortunately there is at present a rather large gap between what we know about the relationship between international trade and renewable resource management, and what we would need to know in order to evaluate policy proposals, design new international treaties, or amend WTO obligations.

While there is now a growing "trade and environment" literature this research has for the most part focused on the link between international trade and various industrial pollutants. For example, see the empirical work on the Environmental Kuznets' curve by Grossman and Krueger (1993, 1995), the work of Antweiler, et al. (2001) and Copeland et al. (1994,1995, 2002), and the many studies linking pollution abatement costs to either trade flows or foreign investment decisions (see Levinson (1996) for a review).[1]

This focus on industrial pollutants may be justified since the majority of the developed world's population lives in cities where air quality is a key measure of environmental quality, but it has necessarily downplayed the role of renewable resources in determining environmental quality. Resources and their raw material products however constitute a significant fraction of merchandise exports for much of the developing world.[2] Since the proper management and

[1] See also the review of the policy literature by Ulph (1998), the book by Rauscher (1997), and for an example of recent empirical work see List et al. (2000).

[2] For example, in 1995 raw materials represented 73% of merchandise exports for Argentina, 55% for Brazil, 75% for Columbia, 39% for India, 22% for the Phillipines, and 95% for Zambia, etc. See Table 1.1

exploitation of these resources must play an important role in their development and growth, it is important to understand how access to international markets affects resource management.

The purpose of this paper is to investigate the impact of international trade on renewable resource use when the strength of renewable resource management varies endogenously. To do so we develop a theory of resource management where the strength of regulation is determined by the interplay of country characteristics and economic conditions brought about by international trade. The degree to which renewable resource sectors escape the tragedy of the commons is endogenously determined and explicitly linked to changes in world prices and other possible effects of market integration.

An approach where the strength of regulation is endogenous is necessary for several reasons. For example, a major theme in the ongoing policy debate is the extent to which income gains brought about by trade can lead to beneficial changes in regulation that may promote greater environmental quality. In the industrial pollution context, this change in regulation creates a "technique effect" and holds out the possibility that even a dirty good exporter may become cleaner with trade.[3] Many authors have found a strong relationship between income gains and tighter pollution regulation; and this evidence is highly suggestive of a strong link between trade-inspired income gains and endogenous changes in regulation.[4] If a similar effect is present for renewable resources, then assuming policy is unresponsive to these income gains may yield misleading results.

It is of course very natural to think that if a change in world prices raises the value of a domestic resource, rational agents will have an incentive to protect it more carefully. This simple, but powerful intuition is largely missing from the theoretical literature. Instead, the

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in Ascher (1999) for a list of these figures for over 30 countries. Raw material exports does include some non-renewables, but the property rights issues raised here are relevant to non-renewables as well.

[3] See Copeland and Taylor (1994) for a theoretical model detailing the scale, composition and technique effects of international trade on industrial pollution.

[4] See Pargal et al. (1996), Grossman and Krueger (1993, 1995), Hilton et al. (1998), and Antweiler, et al. (2001).

literature has adopted the assumption of an unchanged regulation regime. This assumption generates outcomes that are just too stark. With perfect regulation, there is nothing to fear from trade liberalization, and even if resource prices fall towards zero government regulation remains in place. With open access, there is much to worry about (see for eg. Brander and Taylor (1997a)) and even if resource prices approach infinity government's somehow never find it in their interests to regulate the resource more effectively.

A model where the efficacy of regulation can move between these two extremes can investigate the more realistic middle ground where international trade alters the rents available to the resource sector and thereby alters the incentives for its protection. At the same time a model of endogenous regulation will allow us to draw a much needed distinction between the impact of a change in world prices brought about by trade and the impact of a whole set of other possible changes brought about by "market integration". As we show increases in resource prices tend to strengthen de facto property rights, but if market integration also means access to new goods, improved technologies or more attractive options for those working in the resource sector these changes tend to weaken property rights regimes. As result, the debate over trade's effect on renewable resource use can only be answered by careful empirical work isolating the role of price changes from other confounding influences.

The literature addressing the relationship between international trade and renewable resource management came in two waves. In the 1970s and early 1980s researchers focused on optimal extraction problems and generalizations of trade theories four core theorems to the renewable resource context.[5] In the late 1980s public concern over tropical forests, biodiversity, and fishery stocks rose and this led in the 1990s to a second wave of research investigating the link between international trade and renewable resources. This later literature differed from its predecessor in several ways, but the most important difference was the later literature's

[5] See the review by Kemp and Long in the Handbook of International Economics, Vol I. (1984), and the early work of Markusen (1976).

assumption of either imperfect property rights or complete "open access" in the renewable resource sector.

This change in assumptions was to be expected because much of the concern over renewable resource use arises from the "open access" problem.[6] Open access problems are alleged to be very important, and in cases where renewable resources are exported, there is often particular emphasis on the potentially damaging role of international trade. Much of this second wave of research examined the impact of trade with either full open access or some form of limited but less than perfect regulation of renewable resources.[7]

While the first and second waves of research differ dramatically in their assumptions regarding the efficacy of resource management policy – i.e. it was either perfect as in the optimal extraction problems or entirely absent as in the open access case – they were alike in that the policy regime itself was taken to be exogenous. As a result, a change in world prices or market size brought about by international trade could not alter the efficacy of policy. This exogeneity limits the ability of the existing theoretical literature to be a guide for current policy debates, or a stepping-stone to empirical work.

There is in turn an extremely large literature investigating the problem of open access and its many potential solutions.[8] Our intention is not to propose **the** solution to the open access problem, but rather to present a simple model useful for our subsequent work in general equilibrium. In doing so we are guided by common principles gleaned from the large case study literature examining the success and failures in resource management. While there are many approaches, the theoretical and empirical work of Elinor Ostrom, and the theory of repeated

[6] It has been well established (starting with the classic paper by Gordon (1954)) that resource over-exploitation may occur when a common property resource is subject to no control on entry or harvesting efforts. "Open access" refers to this no controls case.
[7] See for example Chichilnisky (1994), Brander and Taylor (1997, 1998, 1999), and Karp et al. (2000) and *forthcoming,* Hannesson (2000), and Francis (2000). Empirical work is contained in Lopez (1998).
[8] For a book length treatments on renewable resource use see Clark (1990), and see Ostrom's (1990) book for a discussion of institutions governing common property. More recent reviews are Seabright (1993), Brown (2000) and Ostrom (2000).

games, suggests that any model we develop should at minimum allow for: (1) forward looking agents who fear explicit punishments if cheating occurs; (2) imperfect monitoring of behavior; and (3), a link between market prices, technology, and the incentive to cheat. Our model will exhibit these attributes.

But given space constraints and our plan for extensions in various directions we make three key assumptions. First, we adopt a relatively simple renewable resource model taken from Brander and Taylor (1997). Second, for much of the paper we focus on the link between country characteristics and property rights regimes in steady state. An examination of the transition between regimes is itself worthy of a paper length treatment and as such is left to a companion paper.[9] Third, for most of the paper we assume the resource planners are benevolent utilitarians maximizing the welfare of both current and future generations. We adopt this approach because it is a useful to begin in a familiar setting before introducing the possibility of government corruption, malfeasance or pliability. While some blame bad or irresponsible government policy for all of the many disasters in resource management, our framework demonstrates that even benevolent governments may have little power to stop agents from over using resources or forestalling a collapse in property rights regimes. A thorough understanding of how the constraints faced by benevolent governments affect their policy choices will allow us to ask what remaining features of resource management must be accounted for by political economy elements.[10] Extensions of our framework to allow for corruption and political economy elements are discussed in the penultimate section.

[9] Many of these issues are discussed in "Transition, Reform and Collapse: the Creation and Destruction of Property Rights Institutions", Copeland and Taylor (in process).
[10] Introducing uncertainty regarding government turnover or policy reversals is relatively easy to do in our framework. Since this type of uncertainty seems important in explaining deforestation (Deacon (1994)) we discuss this in the final section.

At present there are only a few papers investigating endogenous regulation in the context of renewable resources.[11] There are many papers on enclosure some of which discuss incentive schemes to limit over-grazing in static contexts (See recent work by McCarthy (2001), Margolis (2000), or important early work by Weitzman (1974)). There are papers examining entry deterrence in natural resource settings (See Mason and Polasky (1994) for one example), and there are papers examining poaching (see Long et al. (2000)). Of these, Long et al. (2000) is perhaps the closest because it contains both renewable resources and international trade. Long et al. (2000) presents a model of poaching from a renewable resource stock where the incumbent owners allocate effort to building fences to enforce property rights. Poachers are static optimizers, there are no punishments for poaching and no monitoring occurs. The author shows how free trade may be welfare reducing even when the level of enforcement is affected by trade. While this immizerizing trade result is of theoretical interest, the paper does not shed light on the conditions determining when free trade may lead to better or worse resource management; nor does it allow for an examination of how discount rates, the size of punishments, and improvements in monitoring technology may affect the consequences of freer trade.

The rest of the paper is organized as follows. In Section 2, we set out the model. In section 3 we examine the model's steady state implications in a small open economy context, define our categories of countries, and link property rights regimes to world prices, population size, mortality, resource growth rates, etc. In section 4 we consider extensions to allow for government corruption, political economy elements, investments in monitoring and discuss out of steady state dynamics. Section 5 concludes. An appendix contains all proofs and lengthy calculations.

2. The Model

[11] If we include extensions of Grossman and Helpman's (1994) political economy framework the list becomes longer. See for example, Damania (2001) and Boyce (2002).

We consider a resource rich small open economy with an ongoing birth and death process. There is a continuum of agents with mass N and following Blanchard (1985) we assume agents face a constant instantaneous probability of death given by θ. Every instant in time has new births equal to gN and new deaths equal to θN. For simplicity we take $g = \theta$; therefore N is the steady state population.[12] Agents are endowed with one unit of labor per unit time. Labor may be allocated to either harvesting from the renewable resource or production of an outside good that we will refer to as manufactures. A group of Elders (or Resource Managers) maximizes the surplus from the resource by restricting access to the commons. They maximize a utilitarian objective function defined over the welfare of both current and future generations subject to the incentive of agents to cheat on their level of allowed harvesting. The Elders set the rules on resource use, but monitoring of compliance is imperfect. Agents and Elders share a common rate of time preference. We will sometimes illustrate our results by employing the special case where this rate of time preference approaches zero. To go further we must determine individual decision rules of agents and specify the enforcement mechanism.

2.1 Agents

Agents consume two goods: H the harvest from the renewable resource sector, and M a manufacturing good. Agents neither borrow nor lend. Tastes are homothetic, hence indirect utility can be written as a function of real income.[13] Agents are risk neutral and we index generations of agents by their vintage or birth year v. Denote by U(R(v,t)) the instantaneous utility flow from consumption when an agent of vintage v at time t has real income of R(v,t). Then the expected present discounted value of lifetime utility for a representative member of vintage v becomes:

[12] Since the population size is fixed, regulation chooses conservation rules to manipulate the aggregate harvest. In practice excluding outsiders can be as difficult a problem for resource managers as is limiting effort by insiders. Expanding the model in this direction may lead to important insights but we leave it to future work.

[13] Nothing important hinges on homotheticity. We employ it only when constructing a relative demand curve to illustrate possible trading solutions.

$$W(v) = \int_{v}^{\infty} U(R(v,t))e^{-(d+q)(t-v)}dt \tag{1.1}$$

where δ is the pure rate of time preference. In writing (1.1) we have exploited the fact that when the instantaneous probability of death is θ per unit time, an agent's time of death is distributed exponentially with Prob {Death at $\tau \leq t$} = 1-F(t) and F(t) = 1- exp(-θt)}.

Agents have three decisions. They must decide how to allocate their income across consumption of the two goods. They must decide whether to work in manufacturing or the resource sector. And if in the resource sector, they must decide whether to cheat on the rules governing the harvest from the renewable resource sector. The first decision leads to the indirect utility function U(R(v,t)). The second and third decisions are determined by the costs and benefits of cheating. To determine these we need to specify technologies, endowments and the enforcement mechanism.

2.2 Technologies and Endowments

The resource stock is renewable (such as a fish or forest stock) and it is held in common by all agents. Denote the stock level by S. The growth function for the renewable resource is assumed to be logistic and given by:

$$G(S) = rS(1 - S / K) \tag{1.2}$$

where r is the intrinsic rate of resource growth, K is the carrying capacity of the resource stock and G(S) denotes natural growth. Harvesting from the resource depends on labor input and the prevailing stock. Adopting the Schaefer model for harvesting we have:[14]

$$H = a L_h S \tag{1.3}$$

[14] See Schaefer (1957), The Schaefer model is to resource economists what the H-O-S model is to trade economists and what the Solow-Swan growth model is to macroeconomists – i.e. incredibly useful but not without its deficiencies.

where α is a productivity parameter, and L_h denotes the labor allocated to harvesting. Production in manufacturing is constant returns and uses only labor, hence by choice of units we have:

$$M = L_m \tag{1.4}$$

Finally with agents having one unit of labor, and a constant population of N, we must have:

$$N = L_m + L_h \tag{1.5}$$

2.3 The Incentive Constraint

The community's Elders manage the resource stock to maximize the welfare of current and future generations. To achieve this, they devise a set of rules to maximize overall welfare subject to the incentive constraints facing villagers. Each member of the community is allocated a fixed amount of harvesting time to exploit the commons.[15] If the villager follows the rules he or she can keep all of the harvest produced. If a villager cheats however, then the community Elders will punish the individual. A variety of punishments are available. As Ostrom (1990) notes, many villages use a system of fines for small offences. Serious offenses can lead to ostracism from the village. We will assume the worst punishment available is ostracism, which in our model is captured by a permanent ban on access to the commons.[16] Denote the relative price of the harvest as p, and denote by $l^* \leq 1$ the amount of labor time an individual is authorized to allocate to harvesting. If a villager obeys the rules, he or she obtains a harvest equal in value to:

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[15] We could think more generally about regulation as choosing the technology for harvesting, the length of season (this is harvesting time), and investing in detection (raising the probability of detection when cheating). We have chosen to focus on harvesting time as the regulators choice variable since this is the simplest and most common form of regulation. Future work will consider more general policy choices. As we proceed it will become apparent that using less efficient technologies and investments in better monitoring technologies can be welfare enhancing in some circumstances.

[16] As Baland and Platteau (1996; chapter 12) note fines or punishments typically escalate with ostracism being a final recourse. It is relatively easy to incorporate mistaken or smaller punishments as should become clear as we proceed. The motivation for small initial fines may be to limit Type II errors; i.e. punishing an individual who is innocent or to allow the resource stock to play an insurance role for villagers facing idiosyncratic shocks. Neither motivation is present in our framework.

$$ph^* = pa\, l^*\, S \tag{1.6}$$

In addition, this villager earns an income of (1-l*)w in the manufacturing sector. On the other hand, an individual who cheats will allocate all of his or her effort to harvesting the resource, yielding a harvest:

$$ph^c = paS \tag{1.7}$$

There is however a probability ρ of being detected at cheating, in which case the villager is ostracized and must work full time in the manufacturing sector earning a return of w.

The decision to cheat is an investment decision. Since the villager is risk neutral, and prices are fixed in our small open economy, this decision will rest on a comparison of the expected present discounted value of the income stream earned by each activity. To render this decision interesting in what follows we assume it is not desirable for agents to produce only manufactures in steady state.[17]

To investigate further, let V^C represent the expected present discounted value of a villager's income stream that is currently cheating on his allocation while working in the resource sector. Let V^{NC} be defined similarly for a villager who is not cheating, and let $V^R(t)$ be the max over these two options at time t. Consider the returns to cheating over some small interval dt. Over a small dt, the agent earns the cheating level of harvest, $ph^c dt$, but will be ostracized to manufacturing at the end of dt, with probability ρdt achieving a continuation value of $V^M(t+dt)$. With probability $1-\rho dt$ the villager is not caught and remains in the industry. In this case the villager can once again choose between the options of cheat or not cheat and achieves a continuation value of $V^R(t+dt)$. However with probability θdt the agent dies over the interval. With the time to death and the time to being caught independently and exponentially distributed, the expected present discounted value of being in the resource sector and cheating at time t, $V^C(t)$, can be written as:

[17] This requires p be sufficiently high (i.e. $p>w/\alpha K$) so that resource harvesting is lucrative. Agents may find it advantageous to specialize in manufacturing during the transition between steady states.

$$V^{C}(t) = ph^{c}\,dt + [1-d\,dt][1-q\,dt]\Big[\,r\,dtV^{M}(t+dt) + [1-r\,dt]V^{R}(t+dt)\Big] \qquad (1.8)$$

where we have exploited the fact that exp{-aΔt} is approximately equal to 1-aΔt for Δt small.

Alternatively, if the villager does not cheat he/she remains in the industry with probability one. And hence the value of this option is given by:

$$V^{NC}(t) = [\,ph^{*} + (1-l^{*})w]dt + [1-d\,dt][1-q\,dt]\Big[V^{R}(t+dt)\Big] \qquad (1.9)$$

where h* is the harvest obtained when the rules are followed, (1-l*)w is the income earned in manufacturing when l* time is allocated to harvesting, and V^{NC} is the expected present discounted value of a villager's income stream who does not cheat on his allocation.

Comparing the cheating and not cheating options is made difficult by the dynamic structure of the problem and the common value to being in the industry at t+dt. This value, V^R(t+dt), is common to both cheaters who were not caught and agents who did not cheat because at t+dt these agents have identical options and hence must share the same continuation value. To put things in common terms recall the value of being in the industry at time t is given by the max over the cheating and not cheating options. That is:

$$V^{R}(t) = \max[V^{C}(t), V^{NC}(t)] \qquad (1.10)$$

Now assume V^C(t) is the max in (1.10). Then equate V^R(t) to the right hand side of (1.8) to find the value of being in the resource industry under this assumption. To simplify terms use the Taylor series approximations:

$$\begin{aligned} V^{R}(t+dt) &= V^{R}(t) + \dot{V}^{R}(t)dt \\ V^{M}(t+dt) &= V^{M}(t) + \dot{V}^{M}(t)dt \end{aligned} \qquad (1.11)$$

cancel common terms and let dt approach zero. To find the prospective value of the not cheating option assume $V^{NC}(t)$ is the max in (1.10) and equate $V^R(t)$ to the right hand side of (1.9) to find the value of being in the resource industry under this assumption. Cancel common terms and let dt approach zero.[18] Finally, substitute these values into (1.10) to find the agent's decision to cheat or not cheat is governed by:

$$V^R(t) = \max\left[\frac{ph^* + (1-l^*)w + \dot{V}^R(t)}{d+q}, \frac{ph^c + rV^M(t) + \dot{V}^R(t)}{d+q+r}\right] \tag{1.12}$$

Therefore the agent will choose the not cheat option at t when the first argument in (1.12) exceeds the second. Manipulating this condition yields:

$$\left(\frac{r}{d+q}\right)\left[ph^* + (1-l^*)w + \dot{V}^R - w\right] \geq \left[ph^c - [ph^* + (1-l^*)w]\right] \tag{1.13}$$

The right hand side is the flow benefit of cheating. This is simply the difference between the flow rewards under the two options. The left hand side is the expected present discounted value of losses from cheating. If an agent cheats with probability ρ they lose the difference between the not cheating option and the flow return when ostracized. Therefore the left hand side of (1.13) is the expected present discounted value of the costs of cheating.

Although we have not written in the time arguments in (1.13), it should be clear that this constraint links rewards and punishments at t to the prevailing stock level at t - since S(t) appears in both h^c and h* - and expectations regarding the future evolution of the stock – since this impacts on expected capital gains $\dot{V}^R(t)$. To ensure no cheating the Elder's must choose l*(t) to ensure this constraint is met at all times.

It is useful to rearrange the incentive constraint to highlight the role played by resource rents. To do so, denote by Π* = H*-L*[w/p] the aggregate resource rents created when the rules

[18] A complete derivation of (1.12) is in the appendix.

are followed, where H*=Nh* and L*=Nl*. Then employ the definition of aggregate rents and rearrange (1.13) slightly to find the incentive constraint facing the Elder's can be written as:

$$\frac{\Pi}{N} + \dot{V}^R / p \geq \left[\frac{d+q}{d+q+r}\right]\left[[h^c - w/p] + \dot{V}^R / p\right] \tag{1.14}$$

which says that current plus future expected rents per agent must be sufficiently high for the incentive constraint to be met. Rents are composed of both current period returns measured in terms of the harvest good, Π/N, but also ongoing capital gains reflecting expectations regarding future returns in the harvesting sector.

Although the capital gain terms appear on both sides of (1.14) higher expected capital gains in the resource sector work towards fulfillment of the constraint. This is natural since once cheaters are caught they no longer benefit from ongoing capital gains in the resource industry. Consequently, the incentive constraint is forward looking and can be met in situations where current returns are low but expected future returns are high. This forward-looking aspect of (1.14) is critical to discussions of out-of-steady-state behavior, but to first fix ideas consider (1.14) in steady state.

In steady state there are no ongoing capital gains or losses. This implies all time derivatives in (1.14) are zero, and it simplifies to:

$$\frac{\Pi}{N} \geq \left[\frac{d+q}{d+q+r}\right][h^c - w/p] \tag{1.15}$$

which just says steady state rents must be sufficiently high to deter cheating. To go further, use (1.6), (1.7) and the definition of rents to find (1.15) becomes:

$$L^*[p\alpha S - w] \geq \left[\frac{d+q}{d+q+r}\right] N[p\alpha S - w] \tag{1.16}$$

This constraint can be met in one of two ways. First, if resource rents are positive, then we know [pαS-w] > 0 and in this case (1.16) requires:

$$l^* = \frac{L^*}{N} \geq \left[\frac{d+q}{d+q+r}\right] \tag{1.17}$$

The fraction of time each agent spends exploiting the resource has to exceed some threshold for the incentive constraint to hold. A greater time allocation satisfies the incentive constraint by reducing the gap between the allowed and cheating effort levels since (1-l*) shrinks with l*, and by reducing the productivity of cheating by lowering the resource stock. Using (1.6) and (1.2) it is easy to show the steady state resource stock is a monotonically declining function of L*. Therefore raising L*, lowers the productivity of effort given (1.7).

The threshold itself reflects impatience, the expected lifetime of agents (which is $1/\theta$) and the probability of being caught. These in turn determine the discount rate applied to the benefits of cheating harvests and the probability of enjoying them ad infinitum.

An alternate solution occurs when L* specified in (1.17) is inconsistent with positive rents in the resource sector. We need to ensure that L* does not exceed the open access level of labor since this level eliminates all rents leading to the equality $p\alpha S = w$. Setting unit labor costs equal to the resource price, and solving for the open access level of labor, L^0, we find:

$$L^0 = (r/a)\left[1 - w/paK\right] \tag{1.18}$$

Taking this qualification into account, the incentive constraint is met, in steady state, when:

$$L^* \geq \min\left[L^0, \left[\frac{d+q}{d+q+r}\right]N\right] \tag{1.19}$$

The mechanism that deters cheating by villagers is similar to that at work in an efficiency wage model. [19] Villagers with access to the resource stock earn rents, provided they follow the rules and do not deplete the stock by over harvesting. They are deterred from cheating if the rents are sufficiently high – and hence access to the resource stock is analogous to having a good job that

[19] The mechanism limiting cheating is similar to that employed in efficiency wage models, but complicated by the fact that we are in a non-stationary environment. See Shapiro and Stiglitz (1984) for more background, Copeland (1989) for an application to international trade, and Kimball (1994) for an analysis of dynamics.

they don't want to lose. The resource managers can at least partially alter the size of available rents by increasing or decreasing harvesting as this drives changes in the resource stock and harvesting productivity. This means of control does however have it limits. In some cases, the Elder's decision rule will become "harvest all you want" producing a situation we refer to as de facto open access.[20] Therefore, the effective property rights regime is a flexible one reflecting resource conditions and the realities of imperfect monitoring and self-interested behavior.

2.4 The Regulators Problem

The resource management problem is made difficult by the prospect of cheating and the necessity of the Elder's weighing utility gains accruing to different generations. We adopt here a utilitarian objective function developed by Calvo and Obstfeld (1988) that aggregates across the utility levels of representative agents from different generations and leads to time-consistent optimal plans. Time consistency is an important property in our context as agents make their decisions conditional on a resource management plan l*(t).

Recall the size of each new cohort is θN and we have assumed the planner and agents share the same rate of pure time preference. In this situation, Calvo and Obstfeld's objective function yields social welfare at time t=0 given by:

$$\begin{aligned} SW(0) = & \int_0^\infty \left\{ \int_v^\infty U(R(v,t)) e^{-(\theta+\delta)(t-v)} dt \right\} \theta N e^{-\delta v} dv \\ & + \int_{-\infty}^0 \left\{ \int_0^\infty U(R(v,t)) e^{-(\theta+\delta)(t-v)} dt \right\} \theta N e^{-\delta v} dv \end{aligned} \tag{1.20}$$

This objective function has two components. The first bracketed term is the expected discounted value of lifetime utility for agents yet-to-be-born as of t=0. Note agents of vintage v have their utility flows discounted to their birth date v, by the sum of their pure rate of time preference, δ, and their instantaneous probability of death, θ. Hence the innermost bracket in this first

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[20] Baland and Platteau (1996) provide case study evidence showing that both conservation and access rules vary quite markedly depending on the circumstances of harvestors and the resource.

component is the expected discounted utility for an agent of vintage v given in (1.1). We then integrate over all future vintages accounting for the fact that they are each of size θN.[21]

The second component consists of the utility of generations already alive at t=0. These agents were born sometime in the past, came in cohorts of size θN, and we likewise discount their utility streams by the sum of their own pure time preference and their probability of death. Discounting is again to their birth date v, but only utility flows from time t=0 onwards of course count. The planner again aggregates over the living generations taking into account their size θN and puts individual utility in social terms by reverse discounting to time t=0.

Equation (1.20) aggregates up to social welfare by aggregating over time first and generations second. It is more convenient however to aggregate over vintages first and then time second. By changing the order of integration, the social welfare criteria becomes:

$$SW(0) = \int_0^{\infty} \left\{ \int_{-\infty}^{t} Nq \bullet U(R(v,t)) e^{-(d+q)(t-v)} e^{+d(t-v)} dv \right\} e^{-dt} dt \tag{1.21}$$

Hence the flow of social welfare at time t is the sum of utility flows from all living generations at time t. This utility flow for any given vintage v is discounted to the birth date of the vintage by θ+δ, and then this total is put in time t = 0 units by exponentiation using the planner's discount at rate δ.

We can further simplify (1.21) by noting that all agents alive at time t are identical regardless of vintage;[22] hence real income is independent of v and we can simplify our social welfare function as follows:

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[21] We are weighing each generation similarly over time, despite the fact the size of any generation is falling exponentially at rate θ with time. This implies that the objective function is taking generations as the unit of account to weigh equally in utility. If we adopt a stricter utilitarian interpretation where social welfare is written over an equally weighted sum of individual's utility, then we need to account for the size of the surviving population from vintage v at time t. This adds to the complexity of the expression but in the end only adds a constant to our welfare function.

[22] With no agent heterogeneity either all obey the incentive constraint or none do. Hence real income is the same for all agents alive at any time t. Allowing for heterogeneity is relatively simple.

$$SW(0)=\int_{0}^{\infty}U(R(t))\left\{\int_{-\infty}^{t}Nq\bullet e^{-q(t-v)}dv\right\}e^{-dt}dt$$
$$SW(0)=N\int_{0}^{\infty}U(R(t))e^{-dt}dt \tag{1.22}$$

Equation (1.22) has three important properties. First, social welfare is independent of individual specific risk of death, θ. This arises because agents discount by the probability of death – they are mortal – but the planner does not because society is infinitely lived. Second, utility flows are discounted by the common (to both agents and the planner) pure rate of time preference. Third, the welfare function is just N times the utility of a hypothetical infinitely lived representative agent with real income path R(t). This last feature simplifies the planning problem tremendously.

The Elder's maximize (1.22) by choice of a rule giving maximal labor in harvesting, subject to technologies given in (1.3), (1.4), full employment in (1.5), biological growth in (1.2) and the incentive constraint (1.14).

3. The Steady State Economy

The solution to the regulatory problem may take many forms depending on whether the incentive constraint is binding or not. To determine when, if ever, the incentive constraint binds it is useful to start by considering the three possibilities in steady state. The first occurs when the incentive constraint is not binding. In this case we ignore (1.14) and proceed to solve a standard optimal control problem using L_h as the control. Denote the steady state allocation of labor to harvesting as L* and steady state stock as S*, then routine calculations show they are defined by:[23]

$$d=G'(S^*)+\frac{L^*/S^*}{pa\,S^*-1} \tag{1.23}$$

[23] See the appendix for a derivation.

$$S^* = K(1 - \frac{a L^*}{r}) \tag{1.24}$$

We refer to this solution as the first best optimum as property rights are perfect in this case. By differentiating (1.23) and (1.24) it is possible to show that the resource stock falls and labor allocated to harvesting rises as the discount rate rises. The stock is at its highest (and labor in harvesting at its lowest) when δ approaches zero. In this case, the right hand side of (1.23) must approach zero. The value of labor's marginal product in the resource sector is $p\alpha S$, the value of marginal product in manufacturing is 1; hence rents per unit of harvest are given by $[p\alpha S^*-1]$ which must be non-negative. Therefore, if δ goes to zero this (greatest) optimal resource stock must be such that $S^* > K/2$ which is necessary for $G'(S^*) < 0$. This is just the standard result that when the future is not discounted at all, the planner chooses an allocation of labor to ensure the stock lies to the right of maximum sustainable yield.[24]

The other extreme arises when the social discount rate approaches infinity. In this case the right hand side of (1.23) must approach infinity and since $G'(S)$ is bounded this requires $p\alpha S$ approach 1. Therefore, when δ approaches infinity the planning solutions approaches that of open access. The open access resource stock is the (lowest) optimal resource stock and involves the greatest amount of labor. This is just the standard result that if the planner is infinitely impatient he/she acts to implement a solution mimicking open access conditions.[25]

Finally, it is relatively simple to show that the optimal stock falls and the optimal labor allocation rises, when the relative price of the harvest rises.

A second possibility is that the incentive constraint binds in steady state, but the Elders are still able to maintain a degree of protection for the resource. This occurs when the first best labor L^* is too low violating (1.19). Accordingly, agents who cheat would obtain a great windfall. To offset this incentive, the planner distorts the first best allocation and drives the

24 And hence the solution mimics that of Brander and Taylors' (1997b) Conservationist society.
[25] And hence the solution would be that of Brander and Taylors (1997b) Consumer society.

resource stock downwards. When the incentive constraint binds in steady state, (1.15) holds with equality. The steady state harvest must also equal the natural growth and hence using (1.2) and (1.3) we find that in a constrained steady state:

$$L^C = \left(\frac{q+d}{q+r+d}\right)N \tag{1.25}$$

$$S^C = K\left(1 - \frac{a}{r}\frac{N(q+d)}{(q+r+d)}\right) \tag{1.26}$$

We refer to these solutions as the constrained optimum and note that de facto exercise of property rights is now limited by the incentive constraint.

Finally, the Elder's may have no ability whatsoever to limit resource harvesting. This occurs when the constraint continues to bind as the labor in the resource sector approaches the open access level. In this case, open access obtains and we have:

$$L^0 = \frac{r}{a}\left[1 - \frac{1}{paK}\right] \tag{1.27}$$

$$S^o = K\left(1 - \frac{aL^o}{r}\right) \tag{1.28}$$

Since these are the only possible steady state solutions, we record:

Proposition 1 Any steady state exhibits either de facto open access, limited property rights protection, or perfect property rights protection.
Proof: see Appendix.

3.1 The Infinitely Patient Regulator

To examine which of the three possibilities emerges in any given situation it proves useful to consider the limiting case when δ approaches zero. This case is simple to present graphically and highlights the role the incentive constraint plays in altering behavior. It does so because when δ approaches zero, the first best solution is the furthest it can be from open access;

therefore, if we find a result of de facto open access it must arise from the incentive constraint alone and not from impatience on the part of regulators.

To investigate this possibility we depict the steady state solution to the Elder's problem in Figure 1. To understand the figure it is useful to note that when δ approaches zero, the solution to our optimal control problem mimics that of the static problem of the Elder's maximizing sustainable surplus subject to(1.15). Surplus, in units of the harvest, is given by:

$$\Pi = H(L) - [w/p]L \tag{1.29}$$

where we have written the aggregate harvest, H, as a function of L. To find the sustainable surplus note that sustainability requires the harvest equal natural growth, or:

$$aLS = rS(1 - S/K) \tag{1.30}$$

Solving (1.30) for S as a function of L we obtain:

$$S = K(1 - \frac{aL}{r}) \tag{1.31}$$

Employing (1.31) in (1.6) yields H(L) as follows:

$$H(L) = aLK[1 - aL/r] \tag{1.32}$$

Therefore our possible steady state solutions can be found by maximizing (1.29) subject to (1.15) and (1.32).

In the upper quadrant of Figure 1, we have plotted the sustainable harvest, H(L) as a function of aggregate labor input L. This function is concave as shown given the properties of (1.32). The opportunity cost of labor is measured by the straight-line wL/p. There are two points of note in the top quadrant. The first is the open access point found at the intersection of the straight line labeled wL/p and the H(L) function. At $L = L^o$, the resource produces no rents and hence L^O represents the labor allocated to the resource sector when it is open access. L* is the

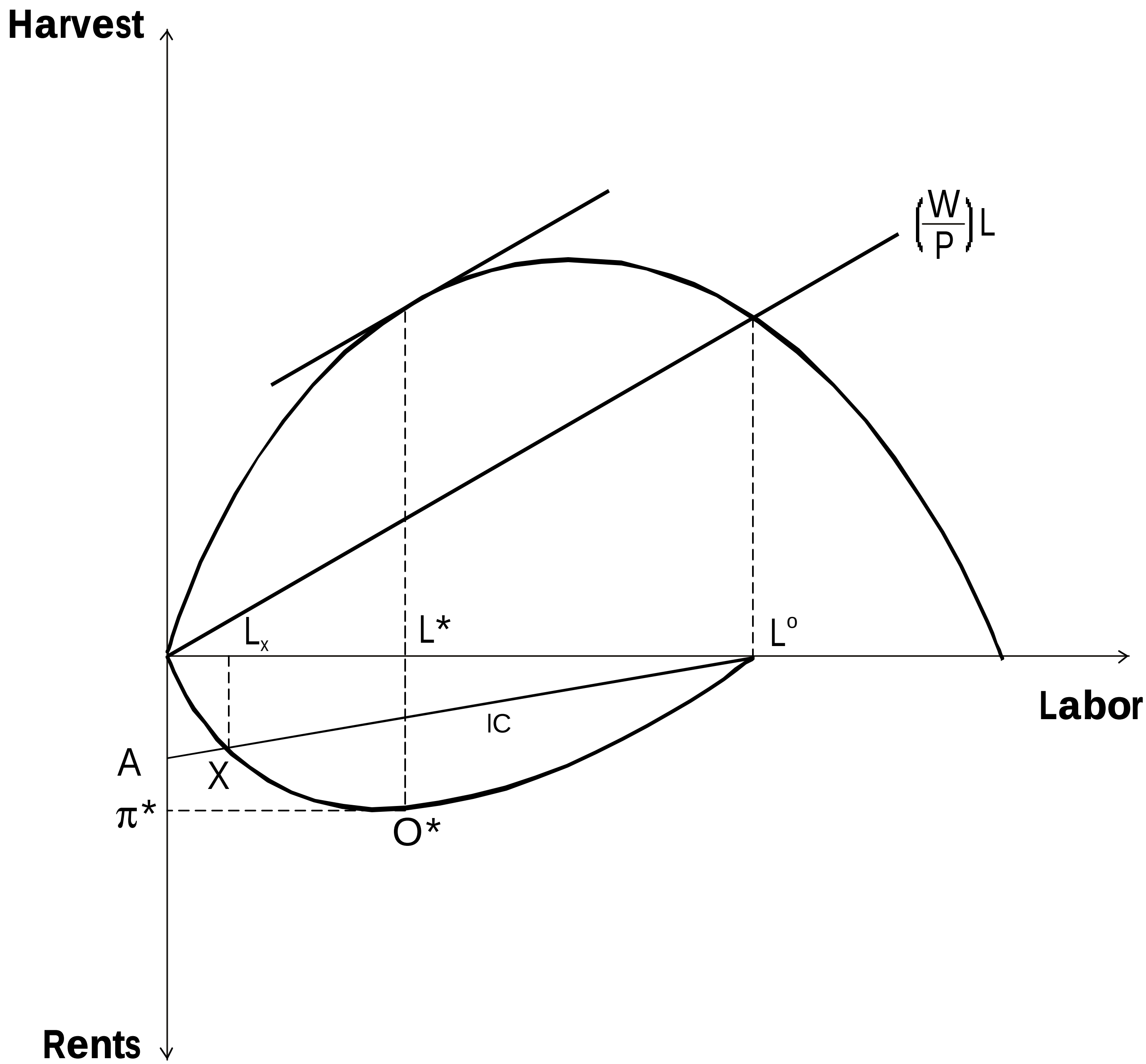

Figure 1
The Regulation Problem

second point of note because it represents the allocation of labor that maximizes surplus (ignoring the incentive constraint).

To investigate when the incentive constraint binds, we have plotted in the bottom quadrant the sustainable surplus. This is found by subtracting the opportunity cost line from the harvest curve H(L), and must reach a maximum at L* and be zero at both L=0 and L = L^o. This surplus is the left hand side of (1.14) (evaluated in steady state) multiplied by N. To find the right hand side, note that $h^c = \alpha S = H/L$. That is, a villager who cheats allocates his one unit of labor to harvesting and obtains the aggregate average harvest per unit labor or H/L. Using (1.31) to solve for S, N times the right hand side of (1.14) becomes:

$$N\left[\frac{q}{q+r}\right][aK - w/p - a^2KL/r] \tag{1.33}$$

which is a linear function of L as shown by the line labeled IC originating at the open access labor allocation L^o and intersecting at point X. Note the vertical height of the IC constraint falls with more labor in harvesting since more labor in harvesting reduces the stock and reduces the incentive to cheat. The IC can just barely be met at point X, and is trivially met at the open access point. Routine calculations show at X, labor in the resource sector is given by:

$$\tilde{L} = N\left(\frac{q}{q+r}\right) \tag{1.34}$$

which, not surprisingly, is just (1.25) evaluated at δ equal to zero. Therefore Figure 1 depicts a situation where the IC does not bind because L*(p) satisfies:

$$L^*(p) \geq \min\left[L^0(p), \left[\frac{q}{q+r}\right]N\right] \tag{1.35}$$

To understand the workings of the model we now link country characteristics to the strength of property rights regimes.

3.2 Country Characteristics and Property Rights Regimes

The incentive constraint given in (1.19) relies on a relatively small number of parameters: world prices, population size, mortality rates, etc. To avoid being sidetracked by the possibility of extinction as a first best outcome we rule it out via a simple parameter restriction: $\delta < r$. Since δ is routinely taken to be .05-.10 per year, this is not a serious limitation.[26] Moreover any important qualifications introduced by this restriction will be discussed in footnotes.

We start by considering the impact of changes in population size because changes in population size are often linked to the collapse of informal property rights arrangements and deforestation.[27] To start note the harvest function H(L) and the optimum L* are unaffected by N, the number of villagers. Therefore the sustainable rent locus drawn in the lower quadrant is unaffected by changes in N. The incentive constraint does however depend on N as a higher N requires each and every villager harvest less from the resource. Recall, L*=l*N. As N grows the intercept of the IC constraint moves down the vertical axis and point X, where the incentive constraint intersects the sustainable rent locus, moves towards O*. Eventually, N is large enough that X and O* coincide and the incentive constraint just binds at the maximum sustainable surplus. Further increases in N, require the Elder's increase access to the resource stock. As N rises further, the labor allocated to the resource stock rises, and from (1.31) it is apparent the resource stock falls monotonically.

Eventually the incentive constraint fails to bind at any point with L* less than the open access level L^o. That is, the Elder's are unable to sustain any rent in the resource at all and de

[26] For example the intrinsic growth rate of Pacific Halibut is .71; even an extremely slow growing resource – like the Antartic fin whale – has a growth rate of .08. (See Clark (1990) and references therein)

[27] This is noted by several authors: for example, Ostrom (2000), Seabright (2000) and Place (2001). Empirical evidence directly on this point is provided in Deacon (1994);

facto open access obtains.[28] The incentive constraint just binds at the open access equilibrium when the following holds with equality:

$$\tilde{L} = N\left[\frac{q}{q+r}\right] \geq \frac{r}{a}\left[1 - w/paK\right] = L^{o} \tag{1.36}$$

When (1.36) holds as a strict inequality, open access is the equilibrium outcome, as more workers cannot be forced into the resource sector when all rents are dissipated and manufacturing offers a constant reward of w.[29] Hence for N greater than that implicitly defined in (1.36), the Elder's incentive mechanism fails entirely.

There are several features to note from (1.36). First in order for the resource to generate any rents at all it must be true that the value of labor's marginal product must exceed its costs. Using (1.3), this requires for some S, that $paS > w$. Hence, since S cannot exceed K we know that the term in brackets on the right hand side of (1.36) must be positive for any resource capable of generating rents. If the right hand side of this equation were negative no villager would have an incentive to harvest at all. Restricting access in this case is not a concern.

Second, note that N must be sufficiently large for the open access equilibrium to obtain. If the population is small, restricting access is relatively easy.[30]

Third, note that even if resource prices are extremely high, some resources will always be subject to open access and never be protected. As p goes to infinity and w/p goes to zero, we can rewrite (1.36) as:

$$\left[\frac{q}{q+r}\right] \geq \frac{r}{aN} \tag{1.37}$$

[28] It is not that everyone cheats and the Elder's are frustrated; the Elder's forsee the incentives and provide a rule whereby no one is in violation. This is de facto open access.

[29] If more workers entered the resource sector they would drive down the stock and lower the value of labor's marginal product below that in manufacturing.

[30] This may explain why many still hang on to the romantic notion of ancient man being a conservationist and friend of nature. As we proceed with the analysis it will become apparent that having a primitive technology and relatively low population density (both which were true for most of human history) makes the enforcement of harvesting rules either simple or superfluous.

When (1.37) holds with a strict inequality, the resource stock can never be protected and open access is always the result. This parameter restriction defines an important class of countries and generalizes easily to the δ not equal to zero case. We record:

Proposition 2 Category I countries will always exhibit de facto open access in steady state. For any finite relative price of the harvest good we have $L^*(p) = L^0(p)$. Category I countries satisfy

$$\left[\frac{q+d}{q+d+r}\right] \geq \frac{r}{a\,N} \tag{1.38}$$

Proof: see Appendix.

Proposition two tells us there exists a set of countries that may never solve their open access problems. For any finite but perhaps extremely high resource price, if the intrinsic rate of resource growth is low for the resource, then it will never be protected; if the productivity of resource harvesting is high, it will never be protected, if N is large it cannot be protected, and if the probability of detection is low or agents expected lifetime too short it will never be protected. In all these cases, open access is the only equilibrium outcome regardless of how valuable the resource may be either domestically or internationally!

The condition given in (1.37) guarantees open access as an endogenous outcome rather than as an assumption, and this obtains even with an infinitely patient regulator. One justification for earlier literature's exogenous assumption of open access is that a condition like (1.37) always holds. The benefit of this current framework is that while open access is a necessary outcome for a Category I country, it is not certain outcome for all countries. Consequently for countries other than those in Category I, observing de facto open access at one world price may be a poor guide to the property rights regime at higher world prices. Alternatively, a country with limited or even perfect property rights at one world price may collapse into an open access situation at other world prices or because of other changes brought about by market integration. These possibilities are absent in the existing literature, and as we show below, the model predicts that all countries will exhibit de facto open access under some circumstances, some will graduate to tighter resource management practices as incomes rise, but others will be left behind.

3.3 From Open Access to Full Rent Maximization

Our primary interest is in how developing countries may adjust their resource management practices with greater access to international markets. This is a difficult question to address because greater access to international markets or "market integration" can mean many different things. A trade theory view of market integration would focus quite narrowly on the impact of changes in relative prices, but other broader definitions would allow the process of market integration to include changes in technologies, choice sets and even societal norms. We start by adopting the narrow definition in this section to discuss how changes in world prices alone can affect the strength of property rights protection.

We examine the impact of an exogenous increase in the price of the resource good starting from some existing low price. Note that for a resource exporting country, this is exactly the change in prices we would expect to see as it moved from autarky to free trade. And to allow for a possible transition in the enforcement of property rights we must now assume that (1.37) fails.

To start, note that for very low resource prices we must obtain the open access equilibrium. This is apparent from (1.35) and (1.36). By lowering p sufficiently we make the resource sector very unattractive and this lowers $L^o(p)$ making it the min in (1.35). At low prices, the stock is relatively high and deterring cheating is impossible.[31] Hence when the resource good price is sufficiently low, open access is the equilibrium outcome.

[31] The stock could in fact be very close to zero in the open access equilibrium; hence the word relative, which means relative to the level it will obtain as prices rise.

Now consider increasing p from this low level. As p rises (from (1.27)) labor in the resource sector rises and the resource stock falls (recall(1.28)).[32] Since labor in the resource sector rises monotonically with p, and since we assume (1.37) fails (or else we could never have a transition to even some limited protection for the resource), eventually for some p we will have:

$$L^0(p+) = L^C(d=0) = N\left[\frac{q}{q+r}\right] \tag{1.39}$$

We denote by p+ the price making (1.39) true and note, for future reference that p+ is a function of country characteristics. The price increase brought more labor into harvesting, drove down the stock and relaxed the incentive constraint.

If resource prices continue to rise, two possibilities emerge. The first is that the incentive constraint continues to bind for all finite p. This occurs if the first best level of labor L*(p) remains less than L^C for all finite p. When $\delta = 0$, it is apparent from Figure 1 that the optimal allocation of labor L*(p) must occur at a point to the left of the maximum sustainable yield. Routine calculations show this implies $L^*(p) < r/2\alpha$. Hence if $N(\theta/(\rho+\theta)) > r/2\alpha$, then as p rises further, entry into the resource sector is blockaded and labor in the resource industry remains constant. Rents rise linearly with p. In this situation both the costs and benefits of cheating rise proportionately with p, and the regulatory regime holds labor in harvesting constant to balance these incentives.

Define Category II countries as those for which higher resource prices will bring only limited property rights protection and not allow full rent maximization. When δ is not zero, our analysis in the text needs only slight amendment and we record:

<u>Proposition 3</u> Category II countries exhibit de facto open access for low resource prices, but limited management at higher prices. Category II countries have characteristics that satisfy:

[32] The harvest may rise or fall as this result depends on whether the original open access equilibrium occurs to the right or left of the maximum sustainable yield harvest.

$$\frac{r}{a\,N} \geq \left[\frac{q+d}{q+d+r}\right] \geq \frac{r}{2a\,N}\left[1-\frac{d}{r}\right] \tag{1.40}$$

then for any finite p, there exist a set of countries which exhibit

i) de facto open access, with $L^*(p) = L^0(p)$, for prices $p \leq p^+$;

ii) limited property rights with $L^*(p) = N[(\theta+\delta)/(\theta+\delta+\rho)]$, for prices where $p > p+$;

iii) the transition price, p+, is higher in economies with higher populations (N), lower life expectancy ($1/\theta$), and higher rates of time preference, δ; it is lower in economies with a faster growing resource (r), a larger resource base (K), or a greater probability of detecting cheating (ρ).

iv) the transition price p+ is higher in economies with better harvesting technologies, α, if $L^C < L^{MSY}$; it is lower otherwise.

Proof: see Appendix.

Category II countries exhibit characteristics more favorable to enforcement of property rights, and will make the transition to at least partial control over their resources at higher world prices. The conditions determining the point of transition are very similar to those classifying the country itself. Faster growing resources, good detection technologies and low populations are all conducive to making the transition early. Alternatively, a late transition is possible and hence for some countries in this category the variation in prices may need to be very large to precipitate a transition.

There are several features of the proposition that need discussion. One is the restriction that $\delta < r$. This restriction arises very naturally once we reinterpret the first best solution for S* in asset terms. Rewriting (1.23) and denoting by $c^H(S)$ the unit cost of extracting a unit of Harvest we find the optimal S* satisfies:

$$d = G'(S^*) - H^*\frac{\partial c^H(S^*)}{\partial S} \tag{1.41}$$

The return on a marginal unit of resource kept in situ is equal to its contribution to overall growth of the resource – its marginal product $G'(S^*)$ – plus its contribution in lowering harvesting costs evaluated at the steady state harvest level – the second term in (1.41). Harvesting costs are measured in labor and as resource prices rise, this component of the return to the resource becomes vanishingly small leaving only the first term on the right of (1.41). As a consequence, the optimal resource stock must be set so that its marginal product exactly equal the rate of time preference. This necessitates $G'(S^*) > 0$ and (1.41) can only be met with a positive resource stock if $Max[G'(S)] = r > \delta$. In this case as prices rise the optimal stock level remains positive, and it is possible to find the associated labor force generating this stock level. This labor force is in fact the right hand side of (1.40) divided by N. If L^C exceeds this level, then a Category II country exists since this country will never employ the first best level of labor.

Alternatively, if $r < \delta$, then as prices rise towards infinity the resource stock approaches zero and the optimal labor force approaches that necessary to cause extinction. In this case, there does not exist a fixed L^C that both does not lead to extinction, but exceeds the first best level for all finite prices. That is, a Category II country will not exist. The reader should note how our simple infinitely patient regulator case always admits a Category II country.

A second feature of note is that the transition price sometimes rises and sometimes falls when the economy obtains better harvesting technology. When the resource is under severe depletion prior to a transition, then the resource stock is close to zero and below its maximum sustainable yield level. In this severe overuse case, an improvement in technology leads to less labor being allocated in the open access case. Therefore to make a transition, a higher price for the resource is necessary to now raise open access labor above the constrained level making a transition harder in severely depleted environments.

Alternatively, when open access is currently leading to mild overuse of the resource then a productivity improvement raises the level of labor employed under open access. Therefore, a now lower resource price will suffice to raise open access labor above that needed to generate a transition. These two results together suggest that the ability of a country to make a transition can depend quite delicately on the prevailing situation under open access and countries having severely depleted resources will have more difficulty in making the transition.

We now consider the possibility that N(θ+δ/(ρ+θ+δ)) < L*(p) for some p. In this case there exists some higher resource price p++ such that for p > p++, L*(p++) > N(θ+δ/(ρ+θ+δ)) and the unconstrained rent maximizing solution for L* can be sustained while meeting the incentive constraint. We refer to countries that can sustain the full rent maximizing solution for some set of prices as Category III countries. We have already depicted such a solution in Figure 1. Category III countries will exhibit open access and only limited protection for some resource prices, but for sufficiently high prices full rent maximization will result. And hence, for high resource prices Category III countries exhibit "optimal extraction" as in the earlier 1970s and 1980s literature. It is now straightforward to show:

Proposition 4. Category III countries exhibit open access for low resource prices, limited management for higher prices, and full rent maximization for still higher prices. Category III countries have characteristics that satisfy:

$$\frac{r}{2aN}\left[1-\frac{d}{r}\right] \geq \left[\frac{q+d}{q+d+r}\right]$$

and Category III countries then:

i) exhibit de facto open access, $L^*(p) = L^0(p)$, for resource prices p < p+;

ii) limit harvesting, L*(p) = N[θ/(θ+ρ)], for resource prices p++> p > p+;

iii) have full rent maximization for prices p > p++;

iv) the transition price, p+, is higher in economies with higher populations (N), lower life expectancy (1/θ), and higher rates of time preference, δ; it is lower in economies with a faster growing resource (r), a larger resource base (K), or a greater probability of detecting cheating (ρ).

v) the transition price, p++, is higher in economies with higher populations (N) and lower life expectancy ($1/\theta$); it is lower in economies with a larger resource base (K), or a greater probability of detecting cheating (ρ); increases in α, δ and r have ambiguous effects on p++.

Proof: see Appendix

As we vary world prices a Category III country can move from an original situation of open access to one with blockaded entry to one with entry into the resource sector being accommodated as rents rise even further.[33] Throughout the process the resource stock (weakly) falls but rents rise monotonically.

For both Category II and III countries effective or de facto property rights over the resource strengthen with the higher resource price. The mechanism for this response is quite simple and transparent in our regulatory regime, but it captures a commonly voiced element in the policy debate. That is, freer trade should raise the value of resource stocks for resource rich less developed countries and this rise in value should raise the incentive to manage their resources more effectively.[34] Therefore, even though open access may be the de facto regulatory regime at low resource prices (read autarky), tighter regulation may follow from the increase in prices brought about by trade. This is exactly what occurs in the model we have developed, at least for a subset of possible country characteristics. It remains true however that for some countries, open access will remain the equilibrium outcome even with infinitely high resource prices.

3.5 An Index of Effective Property Rights

We now illustrate how "effective property rights" vary with the resource good price for all three categories of countries. To create a unit free measure of effective property rights, we

[33] Note that we are referring to unexpected variation in world prices and then tracing out the steady state implications. There is no sense in which p is smoothly changed or that the changes are forseen. See Copeland and Taylor (2002, in process) for out of steady state dynamics.

[34] We will demonstrate that although the stock falls with the resource price, the shadow value of the entire resource base rises with p. Therefore, the value of the stock rises even though the physical size of the stock falls with p. This result is related to the gains-from-trade motivation for property rights described by Besley (1995).

divide the labor *that would be* employed in the resource sector with full rent maximization by the labor actually employed in the resource sector. Since open access or incomplete property rights brings in more labor than full rent maximization, this ratio is less than one for all partial property rights situations, but equals one when full rent maximization is possible. Let $L^{FR}(p)$ be the labor employed in the full rent maximization solution when there is no incentive constraint. Then our index of effective property rights is given by:

$$EPR = L^{FR}(p) \,/\, L^{*}(p) \tag{1.43}$$

And in Figure 2 we have depicted a graph of effective property rights for all categories of countries for the case where δ approaches zero.

First consider Category I countries. These countries have open access for all resource prices, and since L_H^0 is proportional to L_H^* (in our formulation), this becomes a horizontal line for all resource prices.

Second consider Category II countries. These are countries for which open access is the equilibrium for prices less than p+(II),[35] and hence these countries have identical EPR with Category I countries over the [0, p+(II)] range. But when prices rise further, labor is held fixed at the corner solution discussed earlier. And since $L_H^*(p)$ rises with p to reach a maximum at $r/2\alpha$, this ensures the EPR locus for category II countries asymptotes as shown. Note that effective property rights over the resource are rising even though the labor allocation to the resource sector is held constant. The reason for this is that as p rises, the optimal solution for L_H^* is rising and hence the extent of "excessive harvesting" falls with p. Consequently, in terms of our EPR metric the corner solution leads to a continuous upgrading of effective protection as resource prices rise.

Finally, consider category III countries. They also have an open access component from [0, p+(III)]. From Proposition 4 and the definition of Category III countries we can conclude that this open access portion is shorter than that for Category II countries. As prices rise above p+(III)

[35] Recall, p+ depends on country characteristics: it is straightforward to show that p+(III) < p+(II).

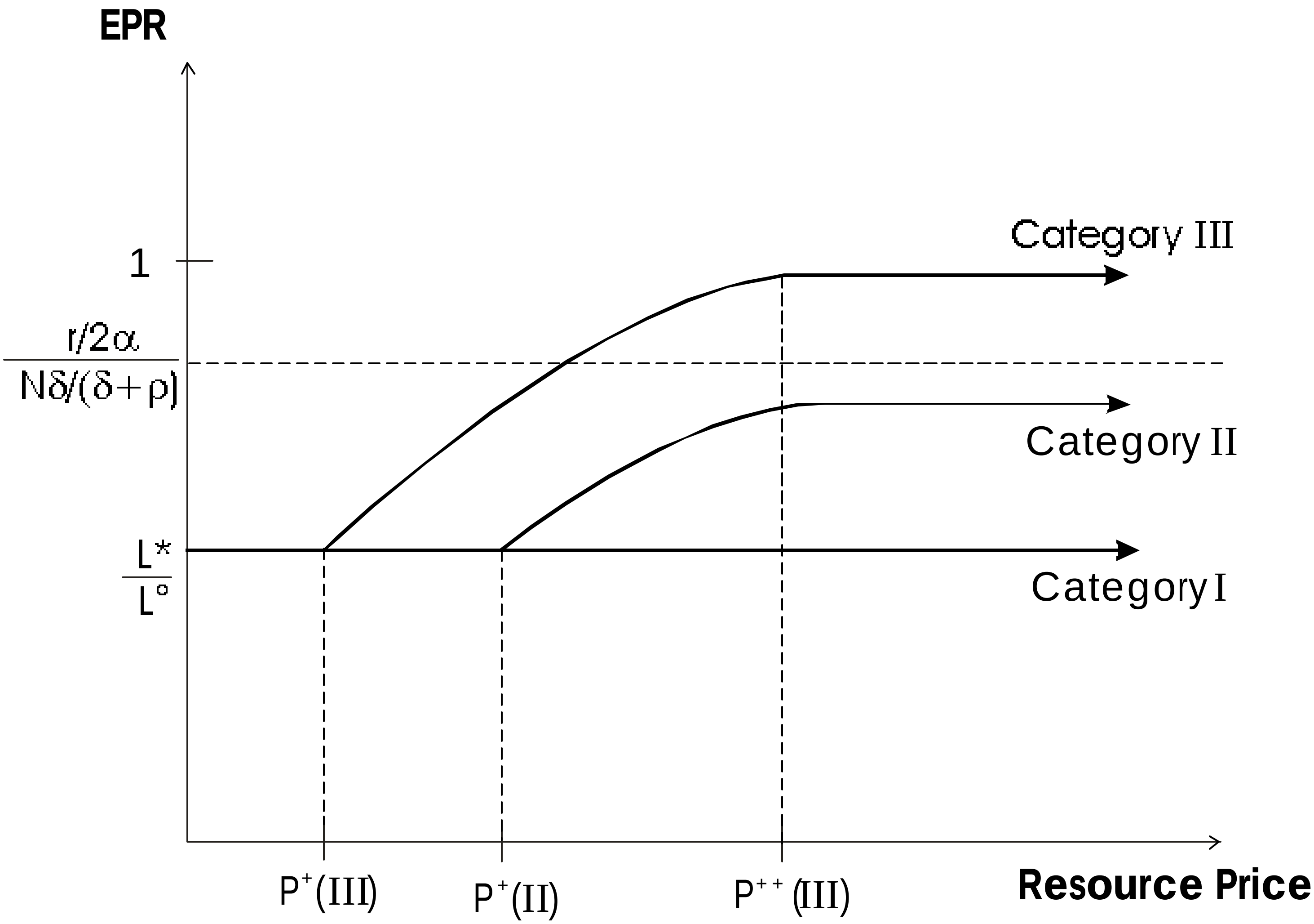

Figure 2
Effective Property Rights

effective property rights start to rise and eventually this country is able to support full rent maximization. At this point, our EPR metric reaches unity and remains there. As a consequence the EPR profile in qualitative terms is that shown in Figure 2.

While we have depicted this heterogeneity under the assumption that δ approaches zero, the heterogeneity in effective property rights and its link to world prices is quite general. In general we can show:

Proposition 5 Assume countries of type Category I, II and III exist and let them share the same minimum price $p^{min} = 1/\alpha K$ at which rents in the resource sector are zero. Then there exists a $p^{low} > p^{min}$ such that for any p below this mark, all countries exhibit de facto open access. There also exists a finite $p > p^{high} > p^{low}$ such that at this p there is heterogeneity in the world's resource management with some countries at open access, others with limited management, and some with perfect property rights protection and full rent maximization.
Proof: see Appendix.

Figure 2 and Proposition 5 are useful in mapping out the relationship between the de facto property rights regime and world prices. They clearly demonstrate that for any given world price we should expect heterogeneity across countries in their protection for resources. At a low level of world prices all countries exhibit open access in their resource sectors, but at higher prices only some will. Therefore, even absent any allowance for political economy elements or the addition of corruption, we should find a great degree of heterogeneity in property rights protection worldwide. While political economy motivations and corruption are surely the dominant forces governing resource use in some situations, these results force us to ask what part of the observed variation in property rights protection worldwide is consistent with utilitarian government's doing the best they can under difficult situations.

These results also demonstrate how any given country may make a transition from open access to a greater degree of control over its natural resources and link this possibility to a relatively simple and intuitive set of country characteristics. Not all countries can undergo this transition, but it would be foolish to conclude that failure to provide tight controls over resource management at one world price implies poor management at all world prices. At the same time it would be equally foolish to assume that higher world prices will be a panacea for poor management practices. If new technologies are also introduced with market integration then it is entirely possible that the beneficial effects of higher prices are more than undone by the new technologies raising the incentive to cheat.

The figure also illustrates how a domestic policy reform (starting from a position with no regulation in place) that brings in an element of enforcement and monitoring of resource use will always fail in some countries (Category I) whereas it will be at least partially successful in others (Category II and III). Moreover for both Category II and III countries, international trade at higher world prices may be a necessary precondition for successful policy reform. Therefore making environmental policy reform a precondition for trade liberalization may be entirely counterproductive. It may instead be the higher prices that trade engenders that make a environmental policy reform successful.

4. Extensions and Suggestions for Future Work (Preliminary)

In setting out a theory of property rights protection we have abstracted from many real world phenomena sometimes thought to be important in determining the success or failure of resource management. We have abstracted from political economy elements arising from heterogeneity across agents, ruled out the possibility of government corruption and its violent turnover, and assumed a relatively simple enforcement technology. Throughout we have focused on steady states and said nothing about how our small open economy moves from one steady state to the other when world prices, or other factors, change. In many cases extensions can be made to the model incorporating these factors but at some cost in terms of model complexity.   We leave the full examination of these issues to future research but sketch here some of the new insights these may bring.

4.1 Shirtsleeves to Shirtsleeves

In constructing Figure 2 we focused on the steady state mapping from country characteristics to effective property rights regimes. By doing so we may have inadvertently misled the reader into thinking the degree of property rights protection in steady state – holds out of steady state as well. This is however false because the incentive constraint is dynamic and forward-looking, and hence out-of-steady state behavior can in some cases be quite different.

Perhaps the best example of how the dynamic incentive constraint affects typical results is shown by the impact of an increase in world prices on a Category I country. Even though this country will move from one open access steady state to another and will have lower real income after the price shock during the transition a Category I country can and will maintain a degree of property rights control. Moreover, when this control erodes it will lead to a last minute frenzy of harvesting activity followed by a collapse and finally a resumption of harvesting at a moderate level. Therefore the model predicts a dramatic boom and bust response to resource price shocks. Since in the long run real incomes are no higher than before – and in fact lower - we refer to this boom and bust pattern as the "shirtsleeves to shirtsleeves" phenomena.

To start our examination we need to identify the equations of motion relevant to a Category I country. We first observe that since the first best stock level is far in excess of the open access stock level - the incentive constraint will always bind during the transition to the new steady state.[36] This implies, that we can take (1.13) as an equality and rearrange to find:

$$(paS-1)l^*(t) = (paS-1)\left(\frac{(d+q)}{(d+q+r)}\right) - \left(\frac{r}{(d+q+r)}\right)\dot{V}^R \qquad (1.44)$$

Next notice that since l*(t) is chosen so that agents do not cheat, from (1.12) we have that the value to being in the resource sector must be given by:

---

[36] The first best calls for zero harvesting until the stock is rebuilt; this is true because, when the constraint doesn't bite, the Hamiltonian is linear in labor and produces a MRAP solution.

$$\dot{V}^{R}(t) = (d+q)V^{R} - [\,ph^{*} + (1-l^{*})w] \tag{1.45}$$

where l*(t) satisfies (1.44). Now substituting (1.45) into (1.44) to eliminate the time derivative we obtain a very important expression:

$$(pa\,S-1)[1-l^{*}(t)] = r[V^{R}(t) - 1/(d+q)] \tag{1.46}$$

which defines l*(t) as an implicit function of S(t) and V(t) under the assumption that $p\alpha S > 1$. When rents are positive, (1.46) tells us that at any point in time the extent to which we can limit l*(t) from 1 is determined by the gap between the value of being in the resource sector, $V^R(t)$, and the value of being in manufacturing ad infinitum, $1/(\theta+\delta)$.

This equation is critical because it tells us that when a resource boom creates even short-term rents, the Elders will be able to exercise a degree of property rights control. This is true because when $p\alpha S > 1$ the static optimizing level of effort in open access is l*(t) = 1, but (1.46) shows that l*(t) < 1. When rents are exactly zero, l*(t) is no longer defined by (1.46) and has to be determined by other equations of the model.

To create our two equation dynamic system we employ (1.45) plus the evolution of the other state variable, S(t), which is given by:

$$\begin{aligned} &if\ \ pa\,S > 1,\ \dot{S}(t) = rS(1-S/K) - l^{*}(t)a\,NS\ ,\ l^{*}(t)\ defined\ above \\ &if\ \ pa\,S = 1,\ \dot{S}(t) = rS(1-S/K) - l^{O}a\,NS\ ,\ l^{0} = L^{O}/N\ defined\ \ previously \end{aligned} \tag{1.47}$$

where l*(t) is given implicitly by (1.46) when rents are positive, and by the open access level $l^*(t)=l^O$ when rents are zero.

To examine the dynamics of our system we must characterize the slopes of the isoclines around an open access steady state. Start with the V-dot isocline, set (1.45) to zero and differentiate to obtain:

$$\left.\frac{dV}{dS}\right|_{\dot{V}=0} = \frac{pa\,l^{*} + (pa\,S-1)[\partial l^{*}/\partial S]}{d+q-(pa\,S-1)[\partial l^{*}/\partial V]} > 0 \tag{1.48}$$

Now using (1.46) as an implicit function linking l*(t) to V and S we can eliminate the partial derivatives in the above to find:

$$\left.\frac{dV}{dS}\right|_{\dot{V}=0} = \frac{p\alpha[V - 1/(d+q)]}{[p\alpha S - 1]} = \frac{p\alpha\, l^*}{d+q} > 0 \tag{1.49}$$

which, since we employed (1.46) must hold only where rents are positive.

Next we do the same thing for (1.47) to find the slope of the S-dot equal zero isocline as:

$$\left.\frac{dV}{dS}\right|_{\dot{S}=0} = \frac{rS/K + \alpha NS[\partial l^*/\partial S]}{-\alpha NS[\partial l^*/\partial V]} > 0 \tag{1.50}$$

Again using (1.46) as an implicit function linking l*(t) to V and S we can eliminate the partial derivatives in the above to find:

$$\left.\frac{dV}{dS}\right|_{\dot{S}=0} = \frac{r(p\alpha S - 1)}{K\, r\, \alpha N} + \frac{p\alpha[V - 1/(d+q)]}{[p\alpha S - 1]} > 0 \tag{1.51}$$

which, since we employed (1.46) must hold only where rents are positive.

To compare the isocline slopes near the steady state it is necessary to determine l*(t) close to the steady state. We know that *in the steady state* l*(t) must be set to its open access level $l^O(t)$, but if we are even epsilon away then pαS > 1 and l*(t) is determined by (1.46) which is close to 1 as we approach open access. To calculate the limiting value for l*(t) as we approach suppose we are converging to an open access steady state. Then it appears from (1.46) that l*(t) must approach one. To see if this is true suppose we are converging from a stock level above the open access level and agents know that we will be in the steady state in the next dt.[37] Then use the incentive

[37] Convergence to the open access stock level must occur in finite time. If S(t) approached asymptotically then S(t) would be near the open access stock for an infinite amount of time. This implies rents from the resource are arbitrarily small and hence V(t) is arbitrarily close to the

constraints we developed in (1.8) and (1.9) and label t+dt = T. Since all rents in the resource sector are gone at T we must have $V^R(T) = V^M(T)$ and the continuation value from cheating and not cheating are identical. Therefore, in period T-dt the Elders have no ability to restrict harvesting at all and l*(T-dt) must be set to 1. Since dt is arbitrarily small, the limiting value of l*(t) is equal to one when we converge from above.

Now using this result in (1.49) we find the limiting slope of the V-dot equal to zero isocline when we approach the open access stock from above is just (1.49) evaluated at l*(t) = 1. To compare the slopes of the S-dot and V-dot equal to zero isoclines we need to pick a point of comparison. A natural point of comparison is of course the steady state values, but S-dot is not defined at the steady state but is defined arbitrarily close to it. Using (1.51) and (1.49) we find that arbitrarily close to the steady state, we have:

$$\left.\frac{dV}{dS}\right|_{\dot{S}=0} = \frac{r(p\alpha S-1)}{K r \alpha N} + \frac{p\alpha[V-1/(\delta+q)]}{[p\alpha S-1]} > \left.\frac{dV}{dS}\right|_{\dot{V}=0} = \frac{p\alpha[V-1/(\delta+q)]}{[p\alpha S-1]} \tag{1.52}$$

Therefore the S-dot isocline is steeper and we can now depict the dynamics as shown in Figure 3. In Figure 3 we start at point A with an open access steady state at the world price of p^A, , with $p^A S^A \alpha = 1$, labor at its open access level, and the value of being in the resource sector just equal to that of manufacturing.

It is now straightforward to establish that our system exhibits saddle path stability. Points below the V-dot isocline have V falling; points above have V rising. This follows from inspection of (1.45) and using (1.46) to show that l*(t) falls with V. Points to the right of the S-dot equal to zero isocline have S falling; points to the left have S rising.

---

return in manufacturing. This implies from (1.46) that l* must be close to 1 for an infinite amount of time. But this is inconsistent with approaching asymptotically as l*(t) = 1 extinguishes the resource in finite time. Therefore, convergence to the open access stock level must occur in finite time.

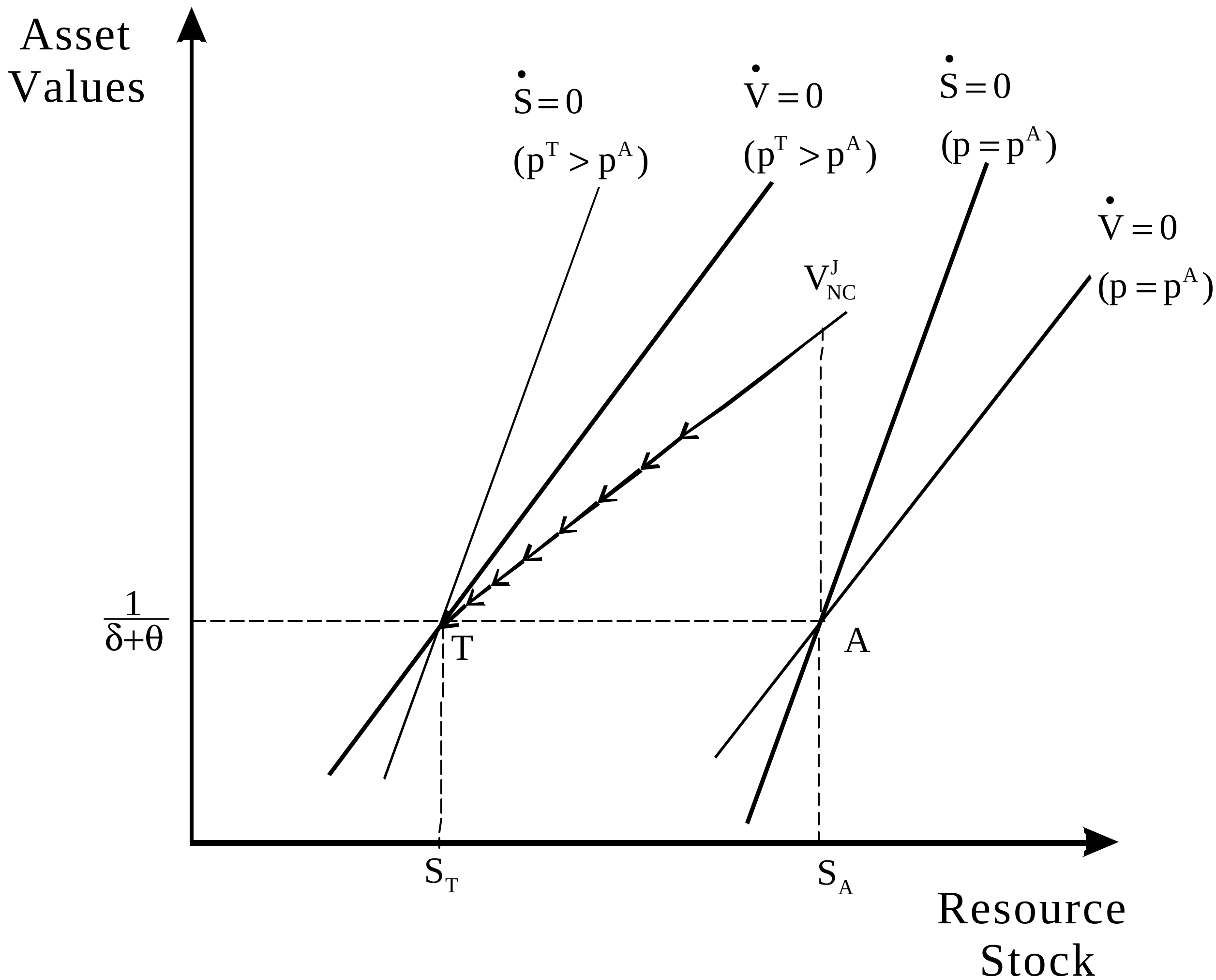

Figure 3
Shirtsleeves to Shirtsleeves

This follows from inspection of (1.45) and using (1.46) to show that l*(t) rises with S. Drawing in the arrows of motion indicates that the model has a stable saddle path as shown.

With these preliminaries in hand consider the impact of an unexpected price shock from p^A to p^T (autarky to trade?). Recall that at A all rents to the resource are gone and the stock is such that $p^A\alpha S^A = 1$. The new steady state will also exhibit open access, but at the lower stock level given by $p^T\alpha S^T=1$. Steady state labor in the resource is also higher at T than it is at A. With the price shock the entire set of isoclines shifts to again intersect at T.

Upon impact the value of being in the resource sector immediately jumps to V^J at B and now exceeds $1/(\delta+\theta)$. This implies using (1.46) that the Elder's can now enforce some restriction on harvesting. We now know that l*(t) is less than 1 – which is the pure open access level of labor when $p^T\alpha S^A > 1$ and $V > 1/(\delta+\theta)$. Therefore effective property rights to the resource have risen with the resource boom. As the economy moves along the saddle-path towards the new steady state however the effectiveness of controls over harvesting dwindle as the value to being in the resource sector falls. Labor in harvesting rises along the adjustment path and the resource stock falls. It is important to note that while no restriction on harvesting is possible in the very last instant some control can occur in earlier periods. This is true since an implication of l*(T-dt) =1 and $p\alpha S(T)=1$ is that S(T-dt) > S(T). And since $p\alpha S(T\text{-}dt)> 1$, at period T-2dt, the Elder's can exercise some control over resource harvesting since access to the resource stock (next period) in T-dt has some value. Further backwards induction of this sort shows how this control grows as the stock moves further away from its steady state value.[38] When we are dt away from reaching the open access solution, l*(t) goes to 1 and in the next instant the economy enters the open access solution. Since the open access level of labor is discretely less than 1, l*(t) is discontinuous and harvesting effort crashes as we enter open access.

Note that as in BT (1997a) the higher world price for the resource created a short-term boom where resource rents were positive and utility far above previous levels. But eventually the economy moves back to its new steady state where despite the increase in the world price, its consumption possibilities are even lower. And hence the title of this section – from shirtsleeves to shirtsleeves – although it is unclear how many generations enjoy the short term gains from higher prices.

There are however some very important differences created by the dynamic incentive constraint. The first is simply that the resource boom at first enhances property rights protection but then slowly these new rights bleed away as we approach the steady state. Agents born early in the transition period benefit greatly from the boom in the early periods but see these gains, and the Elder's controls over the resource, dwindle over time.[39] Each new generation inherits a resource stock lower than the one before it and faces a more difficult incentive problem as well. Consequently the Elder's must allow increased harvesting to forestall the rising incentives to cheat. Therefore we find a

---

[38] Game theorists might want to think of this result in the following way. In the very last dt you could either be in the group ostracized or in the group receiving the last bit of rents. You prefer to be in the group getting the last rents. Therefore one period back you can be induced to cooperate and not take all the rents you could by the threat of being ostracized for the duration of this last dt. This is similar to the method of generating cooperation in finitely repeated games. In the last period there are (at least) two Nash equilibria and agents prefer one to the other. In period T-1 agents will cooperate because this can get them their preferred Nash equilibrium in T.

[39] Whether agents gain or not depends on their consumption pattern. If this country is a net exporter of resource products then there are gains in the short run.

gradual unwinding of property rights protection with each generation perhaps only seeing a small diminution in its control over resources. But towards the end of the resource boom comes a dramatic bust. In the very last dt maximal effort is expended in extracting the resource because in a very real sense there is no tomorrow. This frenzy of harvesting activity is then followed by an equally dramatic crash. In summary we have:

<u>Proposition 6</u>. Consider a small unanticipated increase in the relative price of the resource good for a Category I country starting from an original steady state with $p = p^A$ then we have:

i) the value of cheating and not cheating take a positive jump in value on impact and overshoot their long run value. These asset values and the resource stock fall throughout the adjustment period.

ii) During the transition the Elders are able to constrain harvesting, $l^*(t) < 1$, until the last instant T-dt and hence there is some measure of effective property rights. At T, harvesting crashes.

iii) Steady state welfare is lower in the new steady state. Agents born late in the transition necessarily lose from the price shock.

Proposition 6 details the behind the scenes microeconomics at play in a country with de facto open access. When trade is announced at higher prices, the value of resource rents rises and this by itself raises the value of not cheating and strengthens the incentives for the Elders to limit harvesting. Therefore a resource boom can lead to improved property rights over the short run, but because individuals have rational expectations and hence predict open access as the steady state outcome they also predict a fall in resource stocks along the transition path. But a falling resource stock implies losses in productivity and hence capital losses. This implies that the value of the being in the resource sector must take a discrete jump upwards at announcement and then fall throughout. Every agent realizes the boom is short-lived and acts accordingly.

Individuals alive when the price increase takes place experience a resource boom but later generations experience lower expected utility than they would have in the absence of the now-past resource boom. In this sense, a temporary resource boom brings a permanent and negative bust for later generations.

4.2 Corrupting the Elders

Political economy elements are easily incorporated into our framework by introducing heterogeneity across agents and altering the preferences of Elders. Assume society is divided into two ethnic groups – Blues and Greens – but with the government in the hands of the Blues. We now weigh Blue utility gains more heavily into our objective function (1.20) and allow the government to give Blues preferential access to the resource. Given risk neutrality the planner will opt for large disparities in access if possible, but the access given to Greens must still satisfy the incentive constraint. Starting from an equal time allocation to each group the planner will find it in his interests to expand aggregate effort while altering access in favor of Blues. Greater aggregate effort lowers the resource stock and lowers aggregate rents but this cost is paid by both Greens and Blues, while the benefits of greater harvesting are reaped only by Blues. Therefore, a greater disparity in the distribution of rents can be maintained at the expense of a diminution in total rents. As a consequence, it appears that resources may be degraded relatively more in societies afflicted with faction and civil war.

Corruption is also easily considered. Assume corrupt elders skim a fraction $1 > s > 0$ from agent's resource rents, but in doing so face a probability of revolt given by $\sigma(s)$. Assume that when a revolt occurs it brings in a new government and a new resource management regime. Agents who were penalized by the former corrupt regime may now be rehabilitated under the new government and may once again participate in resource harvesting. Assume this rehabilitation occurs with probability μ.

The incentive constraints for the resource harvesters are modified in two ways. First the skimming reduces their revenue stream. Those who don't cheat receive only (1-σ) of their rents, because they must pay the corrupt manager σ[ph*-wl*] in "taxes" each period. Those who do cheat also make a payment for the first h* units they harvest, but do not pay any "tax" on harvesting in excess of their quota. Hence cheaters harvest more but pay the same tax as non-cheaters.

As well, those who are caught cheating know that if the corrupt regime collapses their access to the resource sector may be restored. This occurs with probablility σ(s)μdt. This modifies the return to an agent in manufacturing, which is now given by:

$$V^M(t) = wdt + (1 - d\,dt)(1 - q\,dt)\Big[(1 - ms\,(s)dt)V^M(t+dt) + ms\,(s)dtV^R(t+dt)\Big] \quad (1.53)$$

If we now modify the cheating and not cheating options to take into account the tax payments, combine with (1.53), simplify, and consider only steady states, we find that the incentive constraint in the presence of corruption is:

$$[ph^* - wl^*] \geq \left[\frac{d + q + ms\,(s)}{d + q + r(1-s) + ms\,(s)}\right][ph^c - w] \quad (1.54)$$

Corruption makes the incentive constraint harder to satisfy for two reasons. First, there is the tax evasion problem captured in the term (1-s). Second is the fact that it is harder to get the participation of agents who view the regime as illegitimate and therefore temporary in nature. From (1.54) it is easy to show the constraint gets tighter with s.

In this situation a corrupt government who cares only about expected rents will choose its level of corruption to balance the benefits of looting the resource against the probability of revolt. In doing so, the corrupt government has an incentive to ensure that over harvesting does not occur and so must take into account how the threat of ostracism has less and less force as the level of corruption rises. By skimming at too great a level not only is a revolt precipitated, but even before the revolt occurs the participation of agents in creating rents is also diminished because they recognize it as a illegitimate and temporary regime. An examination of how these incentives affect resource management and their interaction with trade seems straightforward in principle and may have great practical importance.

Finally, we have assumed a fixed probability of being caught cheating. Investments in monitoring are of course common and hold out the hope of better management. From an analytical standpoint we must face the question of who monitors the monitors. If the elders can allocate some of the labor force to monitoring what is the incentive to individuals to monitor harvesting rather than harvest the resource for themselves. To deal with this second-round incentive problem assume that of the l^* time allocated to harvesting, an agent must be spend s^*l^* of it in monitoring other agents. Self-monitoring is common in many property rights regimes and this seems a natural solution. Assume the probability of being caught cheating – either harvesting more than allowed or shirking on monitoring duty – is given by $\rho(s^*L^*)$ where ρ is an increasing and convex function of aggregate monitoring effort s^*L^*. We can again use the penalty of ostracism to enforce good monitoring. The Elders however will now face a trade-off since as s^* rises the probability of catching a cheater rises, but so to does the incentive to cheat because as $L^*(1-s^*)$ falls labor is withdrawn from the resource. With reasonable conditions on the technology for monitoring it again becomes possible for a Category I country to exist despite these investments. Again a full consideration of endogenous investments in monitoring together with its implication for trade requires a paper length treatment. It remains however an important topic for future research.

5. Conclusions

The purpose of this paper was to investigate the implications of international trade when the de facto property rights regime adjusts to the changed conditions brought about by access to international markets. We constructed a relatively simple general equilibrium model of harvesting and manufacturing where the village Elder's or Resource planners set harvests to maximize the well being of agents while being cognizant of cheating incentives. Within this context we find that countries can be divided into three categories according to their potential for providing stronger property rights and enhanced resource management as world prices rise. The model shows how cross-country heterogeneity in the effectiveness of resource management can arise quite naturally from heterogeneity in their access to world markets, technological sophistication, and the specific nature of their natural resources.

We have found that some countries may never escape the tragedy of the commons, but others will and our framework links these transitions to a relatively small number of country characteristics such as population density, technology, resource growth rates, and expected life spans. By linking the strength of the resource management regimes to more primitive parameters we hope to facilitate empirical work linking these country characteristics to outcomes. With a theory of endogenous regulation in play we have a far better chance of explaining the spectacular cross-country variation in resource management practices worldwide.

While our primary interest has been the interaction of world prices and property rights regimes, our framework may shed light on several related questions. The emergence and strength of property rights protection plays an important role in much of development and environmental economics. The role of property rights in development and growth is still an open question, as is the question of how property rights affect population growth and environmental degradation. Expanding our model to introduce a storable capital good or endogenous population size seems possible and likely fruitful. Other applications could include a discussion of how trade policy instruments affect resource management, how tropical timber bans and international transfers affect deforestation, and how the emergence of de facto property rights over our global commons may be facilitated.

Appendix

I. Derivation of Incentive Constraint

Start with (1.9). If the first element in (1.10) is the max, then we have:

$$
\begin{aligned}
V^R(t) &= [ph^* + (1-l^*)w]dt + [1-d\,dt][1-q\,dt]\left[V^R(t+dt)\right] \\
V^R(t) &= [ph^* + (1-l^*)w]dt + [1-(d+q)dt + dq\,dt^2]\left[V^R(t) + \dot{V}^R(t)dt\right] \qquad \text{(A.1)} \\
V^R(t) &= \frac{1}{(d+q)dt}\left[\begin{array}{l} [ph^* + (1-l^*)w]dt + \dot{V}^R(t)dt \\ +[dqV^R(t) - (d+q)\dot{V}^R(t)]dt^2 + dq\,\dot{V}^R(t)^3 \end{array}\right]
\end{aligned}
$$

Cancel dt terms, and let dt go to zero. This yields the first element in the max of (1.12). Now start with (1.8). If the second element in (1.10) is the max, then we have:

$$
\begin{aligned}
V^R(t) &= ph^c dt + [1-d\,dt][1-q\,dt]\left[r\,dtV^M(t+dt) + [1-r\,dt]V^R(t+dt)\right] \\
V^R(t) &= ph^c dt + [1-(d+q)dt + dq\,dt^2]\left[\begin{array}{l} r\,dt[V^M(t) + \dot{V}^M(t)dt] \\ +[1-r\,dt][V^R(t) + \dot{V}^R(t)dt] \end{array}\right] \qquad \text{(A.2)}
\end{aligned}
$$

Cancel dt terms and let dt go to zero. This yields the second element in the max of (1.12) An atomistic agent views the time derivatives of $V^R(t)$ as equal under the two options.

II. Proofs of Propositions

Proposition 1.

Proof: In a steady state, all time derivatives are zero; therefore the optimal choice for L* must satisfy (1.19) in the text. That is, it must satisfy:

$$
L^* \geq \min\left[L^O, L^C\right] \; where L^C \equiv \left[\frac{d+q}{d+q+r}\right]N \; and \; L^O \equiv (r/a)\left[1 - w/paK\right] \qquad \text{(A.3)}
$$

There are only three possibilities. Two of these arise when (1.19) holds as an equality. In this case L* equals either L^C or L^O. The other possibility occurs when (1.19) holds as a strict inequality. When this is true, L* is found by solving the Elder's problem ignoring the constraint. This problem is given by

$$
\begin{gathered}
\underset{\{L_H\}}{Max}\, SW(t) = N\int_t^{\infty} U(R(t))e^{-d(t-t)}dt \\
subject\,to: \\
R = I/N\,b(p) \quad I = pH + M \quad H = a\,L_H S \quad M = L_M \\
L_M + L_H = N \quad \frac{dS}{dt} = rS(1-S/K) - H
\end{gathered}
\tag{A.4}
$$

The current value Hamiltonian for this problem is:

$$
H = u\left(\frac{[pa\,S-1]L_H + N}{b(p)}\right) + l\,[G(S) - a\,L_H S] \tag{A.5}
$$

The first order necessary conditions are given by:

$$
\begin{gathered}
Max_{L_H}\{H\} \\
-\frac{\partial H}{\partial S} = \dot{l} - d\,l \\
\frac{\partial H}{\partial l} = \frac{dS}{dt} \\
\lim_{t\to\infty} l\,e^{-dt}S = 0
\end{gathered}
\tag{A.6}
$$

The Hamiltonian is linear in the control and hence my use of the Max operator. Recall $L_H = N$ will drive the resource to extinction and $L_H = 0$ is inconsistent with meeting the incentive constraint in steady state. Hence any solution must be interior (recall p is finite and this rules out extinction outcomes). Setting time derivatives to zero in (A.6) and manipulating produces the following three equations:

$$
l = \frac{p - 1/a\,S}{b(p)} \tag{A.7}
$$

$$
d = G'(S) + \frac{L_H/S}{p - 1/a\,S} \tag{A.8}
$$

$$
L_H = \frac{r}{a}(1 - S/K) \tag{A.9}
$$

(A.8) and (A.9) solve for L_H and S. Equation (A.9) is a negative and linear relationship between L_H and S. At S=0, $L_H = r/\alpha < N$; at S = K, $L_H = 0$. Equation (A.8) gives L_H as a monotonically increasing function of S. At S=0, $L_H = (r-\delta)/\alpha < r/\alpha$. At S = K, we have $L_H = ((\delta+r)/\alpha)(p\alpha K-1) > 0$ by (A.7). Therefore a solution exists with L_H non-negative. It is unique.

Proposition 2.

Proof: A Category I country always exhibits open access in steady state. From (1.19) this requires $L^O < L^C$ for any finite p and L^O greater than L^B. To prove the first part note L^O is rising in p, and as p approaches infinity L^O approaches its maximum r/α. Hence when

(1.38) holds we have $L^O < L^C$ for any finite p as required. To prove the second part exploit the fact that for any finite p we have $L^O = L^B$ when δ approaches infinity and recall L^B rises monotonically with δ. Therefore, for any finite δ and finite p we have the result, $L^B < L^O$ as required.

Proposition 3.

Proof: A Category II country must have $L^C > L^O$ for low p and $L^C < L^O$ for some high but finite p. We have already established that L^O is an increasing function of p bounded below by zero and above by r/α. Since (1.38) fails and $L^O(p)$ is a continuous function, a p+ exists. Since at p+ we have open access, and since at p+ we have $L^O = L^C$, it must be true that:

$$p^{+} = 1/aS \; where S = K\left[1 - \frac{aL^{C}}{r}\right] \tag{A.10}$$

Straightforward differentiation will show p+ has the properties stated with regard to N, r, etc. Differentiation with respect to α is more delicate and leads to:

$$\begin{aligned} dp^{+}/da &> 0 \quad if \;\; L^{C} > r/2a \\ dp^{+}/da &= 0 \quad if \;\; L^{C} = r/2a \\ dp^{+}/da &< 0 \quad if \;\; L^{C} < r/2a \end{aligned} \tag{A.11}$$

Note that r/2α is the labor force that would produce a stock equal to K/2, the maximum sustainable yield level. Then let r/2α be denoted L^{MSY}. The only issue remaining is whether the possibilities listed in (A.11) are in fact consistent with the parameter restriction governing Category II countries. The first two lines of (A.11) are clearly consistent with the definition in (1.40), the last line is consistent with the definition only when δ < r which has already been assumed. A Category II country must also always exhibit $L^C > L^B$ for any finite p. This is harder to demonstrate because L^B rises with p and we have only the implicit solution given in (A.8) and (A.9). To proceed we need to take the limit of (A.8) as p goes to infinity. This limit depends on whether δ is greater or less than G'(S) at S = 0 which is given by r. Note as p rises, L^B rises and S falls. Assume S remains positive as p goes to infinity, then (A.8) requires δ = G'(S). Solving this equation for S and substituting in (A.9) yields: $L^B = [r/2\alpha][1-\delta/r] > 0$. Note such an S will only exist if δ < G'(0) = r. Therefore, when δ < r the first best level maximal level of labor is positive and is less than L^C as required. When δ > r, then as p goes to infinity S goes towards zero and the first best solution approaches extinction of the stock. In this case, a Category II country cannot exist.

Proposition 4.

Proof: The proof proceeds in three steps: it first considers existence, then derives the transition prices, and finally derives the relationship between transition prices and primitives.

Existence. Category III countries exist under two conditions. Assume δ < r, then from the proof to Proposition 3 we know as p goes to infinity, $L^B = [r/2\alpha][1-\delta/r]$ and a positive steady state stock S* exists. If L^C falls short of this level, then the first best will be obtained for some high, but finite price. If $\delta > r$, then as p goes to infinity, L^B approaches $r/2\alpha$ and the stock approaches zero. There does not exist an L^C such that $L^C < r/2\alpha$ and for all finite p, $L^C > L^B$. Suppose not, and let L^{*C} be the level satisfying both requirements. Then there is an associated steady state stock $S^{*C} > 0$. Substitute this stock level and labor force into (1.23) and solve for the p^{*C} giving this solution as the first best solution. This p^{*C} must be finite as (1.23) is well defined. Consider a $p>p^{*C}$ and exploit the fact that $L^B(p)$ is increasing in p for finite p. This generates a contradiction. Therefore, when $\delta > r$, if $L^C < r/2\alpha$ then a Category III country exists. This ends our discussion of existence.

Transition prices. As p goes to $1/\alpha K$ labor in open access approaches zero, and therefore must be less than $L^C > 0$. For any p, and finite discount rate we have $L^O < L^B$ since L^B approaches L^O as δ approaches infinity. Therefore, for p low enough open access results. As p rises we must have $L^O(p+) = L^C$ since L^C does not extinguish the resource, $L^O(p)$ is increasing in p but has as a limit $r/2\alpha$. Since L^B is an increasing function of p, and we have already shown that at some p, L^B is implemented (or else we wouldn't be talking about a Category III country) there must exist a finite price p++ such that $L^B(p{+}{+}) = L^C$. Since $L^O > L^B$ for all p, $L^O(p+) = L^C$, $L^B(p{+}{+}) = L^C$ and L^B is increasing in p, we conclude p++ > p+ as required.

Characteristics of transition prices. When $\delta < r$, the characteristics of p+ have already been established. When $\delta > r$, the characteristics of p+ are the same as those given in proposition 3, but we must now exclude the possibility of p+ falling with α. To characterize the price p++ note that L^B and S^B are solved by:

$$d = G'(S^B) + \frac{L^B / S^B}{pa S^B - 1} \quad where \quad S^B = K(1 - \frac{a L^B}{r}) \tag{A.12}$$

which admits messy, but closed form solutions. Denote the solution for the optimal labor force as $L^B = f(r,K,\alpha,\delta,p)$, equating this to L^C means p++ is implicitly defined by:

$$f(r, K, a, d, p{+}{+}) = \frac{N(q+d)}{(q+d+r)} \tag{A.13}$$

It is straightforward to show f is increasing in p, hence increases in N and in θ, or decreases in ρ lead to a higher transition price. Similarly, it is easy to show that f is increasing in K; therefore, an increase in K decreases p++. Finally, to determine the impact of α, δ and r we must differentiate (A.12) to characterize f and then employ that information in (A.13). Doing so shows the result is ambiguous. For example, suppose $\delta = 0$, then it is easy to show that S^B is independent of r, and hence L^B necessarily rises with r (see (A.12)); when δ does not equal zero, a rise in r lowers S^B and this makes the response of L^B ambiguous. If the response of L^B is ambiguous then so too is the response of p++. Similarly, a rise in δ always lowers S^B and raises L^B, but it also raises L^C; the magnitude of these derivatives depends on the magnitude of the other parameters and can be either large or small.

Proposition 5.

Proof: If all category of countries exist and we are considering $p > 1/\alpha K$, then we know that for any admissible p, Category I countries have open access; and from Propositions 3 and 4 we know that Category II and III exhibit open access for prices below p+(II) and p+(III) respectively. Note $L^O(p)$ is increasing in p for any category of country. Then choose p^{low} = min [p+(II),p+(III)]. If this min is p+(II), then we have L^O(p+(II)) < L^O(p+(III)) = L^C(III) and the Category III country must have open access as well. If this min is p+(III), then L^O(p+(III)) < L^O(p+(II))=L^C(II) and the Category II country must have open access as well. There exists such a p^{low} since some rents are possible in the resource i.e. p> $1/\alpha K$. Let p^{high} = max[p+(II),p++(III)]. By definition, and the results of Proposition4, p^{low} is less than p^{high}. p^{high} exists since both transition prices exist and are finite. Note if the max is p+(II), then L^B(p+(II))>L^B(p++(III)) for the category III country since L^B is increasing in p for all categories. Therefore, the Category II country has limited management and the Category III country has full rent maximization. If the max is p++(III), then L^O(p++(III))>L^O(p+(II)) for the category II country since L^O is increasing in p for all categories. Therefore, the Category II country has limited management and the Category III country has full rent maximization.

Proposition 6.

Incomplete.

1. Show convergence time is finite.
2. Derive saddle-path formally
3. Prove l*(t) is monotonic

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