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IS FREE TRADE GOOD FOR RENEWABLE RESOURCES:
BRANDER & TAYLOR REDUX

M. Scott Taylor

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I wrote this paper in honor of my friend, mentor, and co-author, James Brander, on the occasion of his retirement. Without early help and guidance from Jim and Barbara (Spencer), my career would have been nasty, brutish, and short. I would like to thank Hanqi Liu for excellent research assistance, participants at the Brander Festschrift at UBC, and my discussant Werner Antweiler for his many very useful comments. The usual disclaimer applies. The views expressed herein are those of the author and do not necessarily reflect the views of the National Bureau of Economic Research.

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ABSTRACT

This paper generalizes the original Brander and Taylor model of open-access renewable resource use and trade to address three common critiques. First, I introduce heterogeneity across agents in harvesting productivity to smooth out the model's extreme specialization patterns while maintaining its Ricardian structure and tractability. Second, I move beyond the original assumption of open access by constructing a policy stringency function allowing for partial, first-best, and endogenous resource policy. Third, by exploiting the smooth substitution possibilities generated by agent heterogeneity and the insight that policy stringency functions are likely to vary across countries, I show how the model's core predictions can be evaluated using empirical methods related to those in growth econometrics.

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I Introduction

Too little is known about the relationship between openness to world markets and resource over use. Despite decades of research, both theoretical and empirical, the sum total of empirical knowledge is contained in a handful of studies.[1] Moreover, the strongest evidence comes from a series of single-country case studies whose empirical strategy is often only distantly related to the underlying theory. As a result, we are left with a set of potentially interesting examples which may have limited application elsewhere, and some more general findings which are difficult to interpret and assess.

The purpose of this paper is to present a new but relatively simple model for examining the relationship between international trade and resource use more generally. The goal is to provide a model sufficiently general to provide a guide to future empirical work tightly tied to theory, but sufficiently simple to allow for widespread use in answering many questions.

I do so by building directly on earlier work, primarily Brander and Taylor (1997). The original Brander and Taylor (1997) (henceforth BT) model combines a two good Ricardian model structure with the resource harvesting and growth assumptions drawn from Gordon (1954) and Schaefer (1957). The result is an incredibly simple and useful model of international trade with open-access renewable resources, which has been extended in numerous directions.[2]

Despite its simplicity or perhaps because of it, the model left many questions unanswered. The purpose of this paper is to provide answers to three of these questions. First, are the extreme - and clearly counterfactual - specialization patterns created by the Ricardian structure responsible for the losses from trade results? Second, how important is the open access assumption to the model's simplicity and results - can we move beyond open access to consider partial or even first best protection? And finally, how could the model's core predictions be examined empirically?

[1]For overviews of the literature on international trade and resource use see Fischer (2010) or Copeland (2013). Excellent single country studies of resource use tied to growth or trade include Foster and Rosenzweig (2003), Taylor (2011), Eisenbarth (2018). Many country studies include Deacon (1994) and Bohn and Deacon (2000).

[2]Brander and Taylor (1998*c*) adds to the autarky version of the model, a Malthusian mechanism; Copeland and Taylor (2011) adds imperfect information to generate an endogenous property rights regime; Taylor (2011) employs a variant to motivate empirical work on the extinction of the North American Bison; see also Takarada, Dong and Ogawa (2020) and González-Val and Pueyo (2017) for recent applications.

Although there have been some attempts over time to address these questions, they remain largely unresolved. My goal here is to answer all of these questions by developing a tractable generalization of the original BT model.

I assume there are two goods - a resource good denoted by the harvest, H, and an outside sector good I refer to as manufactures M. All agents are equally productive at manufacturing, but their ability to harvest varies across the population of N. Heterogeneity across agents smooths out the model's Ricardian features making outcomes continuous functions of parameters, and ensures that diversified production is the standard outcome.

To capture this heterogeneity, I adopt a Pareto distribution for productivity.[3] This leads to closed-form solutions for most magnitudes of interest and allows me to alter features of the distribution at will. One important feature of the distribution is its variance, and I exploit two limiting cases throughout.

In one limiting case, I push the variance of productivities towards zero, which generates the original BT model where marginal harvesting costs are constant. Another useful limiting case is the polar opposite, where the Pareto distribution becomes increasingly fat-tailed. This limiting case generates linear marginal costs increasing in effort. Both cases lead to explicit solutions for steady-state magnitudes, and they span the entire set of model possibilities.

Heterogeneity across agents, implies harvesting decisions are continuous functions of prices, and this continuity is put to good use in the empirical section where I develop a log-linear approximation to the model's key dynamic equation. Using this equation, I then propose three possible empirical methods for investigating the model's core predictions. Therefore, introducing heterogeneity provides differentiability of key relationships, eliminates extreme specialization patterns, and provides a gateway to a testable empirical formulation.

I also move beyond the original assumption of open access to consider active and even first-best resource management. I start by defining a parametric measure of policy stringency that measures

[3] After the writing of this paper I discovered, perhaps not surprisingly, that others have adopted the Pareto in related areas. See, for example, Quaas and Skonhoft (2022).

the gap between effort in the open access case and that in an arbitrarily restrictive constrained case. This initial parametric measure of policy stringency, together with world prices, determines outcomes in our small open economy but as I show, it is unlikely to be optimal. Consequently, I show how first-best outcomes and constrained second-best optimal outcomes, such as those introduced in Copeland and Taylor (2009), require the stringency of resource policy to vary with world prices. This response, which is conditional on country characteristics, defines what I call a policy stringency function. Apart from its theoretical appeal, the conditional nature of this stringency function implies that common world shocks, or a fall in trade frictions worldwide, will have impacts that are conditional on specific country characteristics. For those blessed with good characteristics, an increase in world prices is a boon; to others less blessed, it can be a curse.

The conditional nature of this response, together with the dynamics inherent in the model, suggests we adopt an empirical strategy where a country's movement towards its new steady state is conditional on deep parameters; i.e. convergence is conditional. To make this connection precise, I provide a log-linear approximation to the model and show how it can be used to evaluate how common shocks, like those mentioned above, have differential impacts, conditional on a country's institutional capital, strength of its legal system, and enforcement regime.

There is a somewhat disjoint literature linking international trade to renewable resource use. The earliest work was heavily influenced, perhaps even hamstrung, by the confines of the HOS model then dominant in the profession. At the same time attempts from resource economists were confined to very simple market models and planning solutions (e.g. Clark (1990)). Early work by Chichilnisky (1994) posed the question of over use but eschewed resource dynamics thought critical to the issue. In contrast, Brander and Taylor (1997) presented a very simple renewable resource model along Ricardian lines to show how stock depletion was necessary for losses from trade. A key finding of this work is that in situations where property rights are poorly defined or enforced, the losses from trade may in fact be larger the more attractive are world markets for resource products.

All of this early work assumed resource policy, or the property rights regime, was fixed and immutable. An important qualification was provided by Copeland and Taylor (2009) which shows how international trade may affect resource policy by changing the value of the resources. Resource regulation should be thought of as endogenous to the market system, and therefore respond to the changed conditions brought about by trade. There is considerable evidence showing that the enforcement of property rights varies across communities, over time, and by resource type.

There is also a large literature examining trade in particularly exotic products such as ivory or rhino horn. This literature has been focused on understanding when, if ever, international markets can be helpful in fostering conservation for endangered species. A pioneering contribution is Barbier et al. (1992) with following important work by Kremer and Morcom (2000), and Bulte, Horan and Shogren (2003).

The empirical work is similarly heterogeneous in its approach and success. There are many individual case studies examining trade in a single species or resource type. For example, Taylor (2011) examines the relationship between international trade and the destruction of the North American bison, while Erhardt and Weder (2016) pose a similar question about present-day shark populations. Similarly, Foster and Rosenzweig (2003) examine forests in India.[4] In contrast, Eisenbarth (2018), Erhardt (2018) and Bohn and Deacon (2000) study the impact of markets on many resource types (species of fish or resources) in settings where property rights are insecure. Erhardt (2018) argues that trade may foster the conservation of resource stocks in insecure property rights countries by shifting demand to other countries with better-managed resources. In contrast, Eisenbarth (2018) develops an ingenious method to show how trade can transmit a resource collapse in one country (Japan) to others raising the likelihood of collapse elsewhere.

The rest of the paper proceeds as follows. Section two sets out the basic model and develops some preliminary results. Following this, in section three, I introduce resource regulation and develop two different steady-state solutions. Section four provides the causal connection between

[4] Other studies examining forests includes Ferreira (2004) and Faria and Almeida (2016).

trade liberalization, resource use and welfare. It also provides several empirical methods we might use to evaluate the theory's core predictions. A short conclusion ends the paper. Lengthy calculations are relegated to an appendix.

II The Model

II.I Tastes, Technologies and Endowments

At any point in time, a mass of N agents can allocate their one unit of effort to manufacturing, M, or harvesting, H. If employed in manufacturing one unit of effort delivers one unit of M. If employed in harvesting, one unit of effort delivers αS units of H. S measures the current state of the resource stock. It can vary from zero to the carrying capacity of its habitat K. α is an agent-specific productivity that is distributed across the population according to $T(\alpha)$. For simplicity, $T(\alpha)$ is given by the Pareto distribution whose cumulative distribution function (CDF) and associated probability distribution function (PDF) are given by:

$$T(\alpha) = 1 - (b/\alpha)^{\gamma} \quad \text{where} \quad b > 0, \quad \gamma \geq 2 \tag{1}$$

$$T'(\alpha) = t(\alpha) = \frac{\gamma b^{\gamma}}{\alpha^{\gamma+1}} \tag{2}$$

The distribution has two parameters b and γ. b is the minimum value any agent's harvesting productivity could obtain; while $\gamma \geq 2$ determines the overall shape of the distribution. The expected value of α is,

$$E(\alpha) = b \cdot [\gamma/(\gamma - 1)] \tag{3}$$

and its variance is simply:

$$VAR(\alpha) = b^2[\gamma/[(\gamma-1)^2(\gamma-2)]] \tag{4}$$

The PDF and CDF of a typical Pareto distribution are shown in the two panels of Figure 1. Three features of the Pareto are critical to what follows.

First, both $VAR(\alpha)$ and $E(\alpha)$ fall when we increase the parameter γ. Increasing γ shifts more and more of the probability mass towards the minimum value of b, and the CDF becomes steeper. In the limit when $\gamma \rightarrow \infty$, the distribution $T(\alpha)$ collapses to a point where $\alpha = b$ for all agents. In the left panel, the PDF becomes a spike at b; in the right panel, the CDF becomes a step function from zero to one at b (not shown). This is a very useful feature of the distribution. It allows me to connect the analysis here to that in the original BT model which featured only one "α" for all workers by taking the limit as $\gamma \rightarrow \infty$.

Second, if we instead let $\gamma \rightarrow 2$, the distribution's variance increases. The distribution becomes more and more fat-tailed. This means it will become easier to draw similarly skilled workers into harvesting when it expands. It will, in the limit, imply linear cost curves, which facilitate closed-form solutions for magnitudes of interest.

The last useful feature of the distribution is its constant elasticity PDF. Constant elasticity functions often imply marginal and average cost curves are proportional to one another, and this will be true here regardless of our chosen value of γ. Marginal costs will simply be $\gamma/[\gamma-1]$ times average costs, which in our two limiting cases implies marginal costs are either equal to average costs or twice average costs.

Together these three properties turn what could be an intractable generalization into a rather simple one.

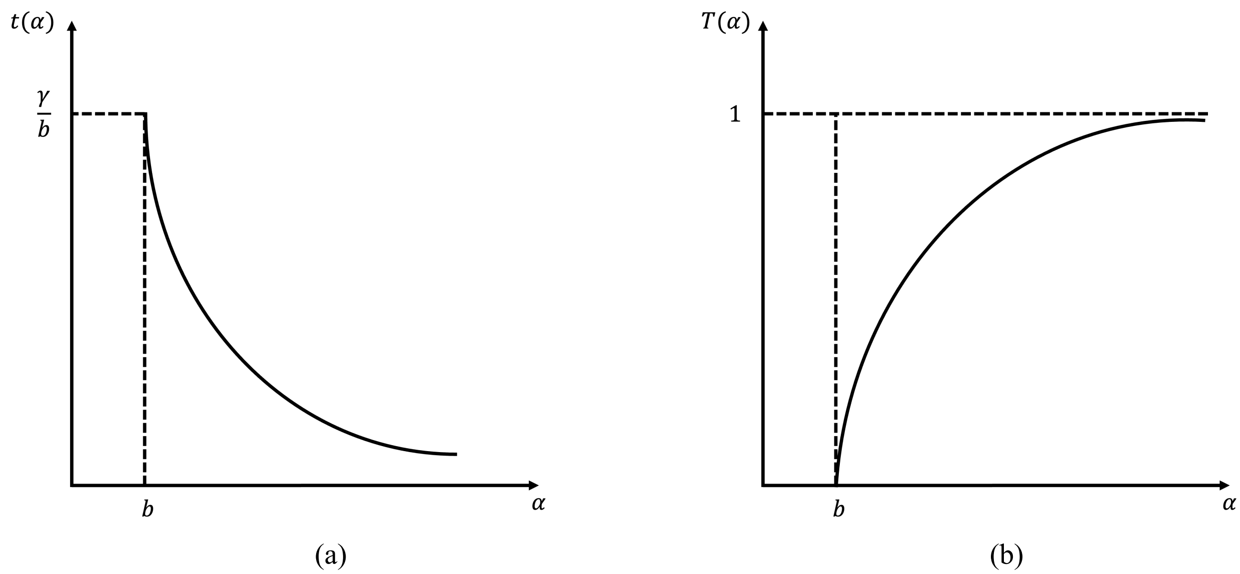


Figure 1: The Pareto Distribution

II.II The Marginal Harvester

With given product prices for both goods and free entry into occupations, typically only a fraction of the N agents in the economy will find it in their interest to harvest. As a result, at every point in time, workers will sort across sectors according to their comparative advantage. When both goods are produced there will exist an agent with productivity α^* who is indifferent to working in one sector versus the other. Naturally, a more productive agent prefers to harvest, while a less productive one works in manufacturing. I will refer to α^* as the marginal harvester.

If $\alpha^* < b$, then all agents prefer to harvest; otherwise the economy produces both goods and is diversified in production. When the economy is diversified, the production of goods can be written:

$$H = NS \int_{\alpha^*}^{\infty} \alpha t(\alpha) d\alpha \qquad M = T(\alpha^*)N \tag{5}$$

$T(\alpha^*)N$ are employed in manufacturing and $[1 - T(\alpha^*)]N$ workers are employed in harvesting.

Substituting for $T(\alpha)$ in (5) and using the properties of (1), reveals the production of H is given by:

$$H = \delta NS(\alpha^*)^{1-\gamma} \tag{6}$$

where $\delta = \gamma b^\gamma/(\gamma - 1) > 0$. The harvest is proportional to both the mass of agents N and the resource stock S. When the cut-off productivity for entering harvesting is higher (α^*), the harvest H is naturally lower.

II.III The Short Run Production Possibility Frontier

Equation (5) implicitly defines the economy's production possibility frontier (PPF) for any given resource stock S. To find this PPF explicitly, isolate α^* from H in (5), substitute in M, and rearrange to obtain:

$$M = N\left[1 - b^\gamma \left[\frac{H}{\delta NS}\right]^{\frac{\gamma}{\gamma-1}}\right] \tag{7}$$

This is the economy's short run production possibility frontier. When $H = 0$, it is simple to find maximum manufacturing output, $\bar{M}$, equals N. When $M = 0$, algebra shows the maximum harvest is $\bar{H} = [\gamma/(\gamma - 1)]bNS$. Using our knowledge of the Pareto distribution, this is simply $\bar{H} = N/a_{LH}$ where a_{LH} is the average unit labor requirement in harvesting when everyone is employed in harvesting.

It is now easy to show:

$$\frac{dH}{dM} = -\left[\frac{\delta NS^\gamma}{H}\right]^{\frac{1}{\gamma-1}} < 0 \tag{8}$$

and substituting in using $\alpha^* = [H/(\delta NS)]^{1/(1-\gamma)}$ we find, even more simply, that:

$$\frac{dH}{dM} = -\alpha^* S < 0 \tag{9}$$

is the slope of the PPF, as shown in Figure (2) (ignore for the moment the line with slope $\mathcal{R}/p$). This slope is, of course, the ratio of marginal productivities of labor in harvesting versus manufacturing at any given point.

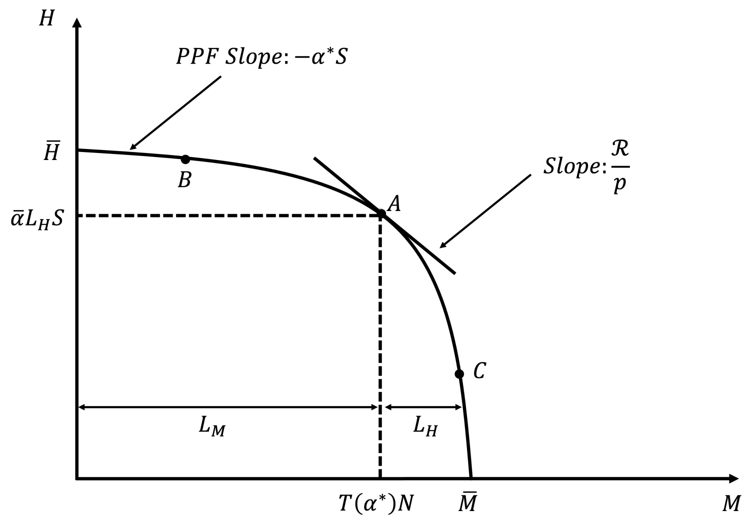


Figure 2: Temporary Equilibrium with Policy Stringency $\mathcal{R}$

As shown by the figure, when H is close to zero, only the most efficient harvesters will be employed, $\alpha^* \to \infty$, and the PPF is very steep. Alternatively, when M is close to zero, almost everyone is harvesting, $\alpha^* = b$, and the PPF is relatively flat. The shape of the frontier is very natural once we recognize that it is the limiting case of a many-harvester Ricardian model which would have a piece-wise linear PPF.

Also shown is that if the economy operates at point A, the number of agents in manufacturing can be simply read off as $L_M = T(\alpha^*)N$ and those in harvesting number $L_H = [1 - T(\alpha^*)]N$. I have written the harvest produced at point A as a function of labor input, the current resource stock, and $\bar{\alpha}$, which is the average productivity of harvesters currently employed in H. I define this measure of average productivity shortly.

Finally, if the resource stock was higher than the S shown, the PPF would shift upwards raising $\bar{H}$ but leaving $\bar{M}$ unchanged. It becomes steeper at any M because the marginal product of labor in harvesting is higher when the resource stock is higher. For the same reasons, if the resource stock was lower, the PPF shifts downwards becoming flatter at any M.

III Resource Regulation

We need a mechanism to determine the marginal harvester. One option is to let market forces dictate entry decisions, producing a situation of free and open access to the resource. This was the case originally studied by Gordon (1954), later popularized by Hardin (1968), and adopted throughout by Brander and Taylor (1997).

In an open access situation there is a simple relationship among the marginal harvester, prices and the prevailing resource stock. Let p_H and p_M denote the prices for one unit of H and M respectively. In the absence of any regulation limiting entry, every agent compares their value of marginal product in harvesting $p_H \alpha S$, to that in manufacturing, p_M. Individual optimization implies that when a marginal harvester exists their productivity α^* must equal:

$$\alpha_O^* = \frac{1}{pS} \tag{10}$$

where p is the relative price of harvesting $p = p_H/p_M$, and I have denoted by α_O^* the marginal harvester's productivity when there is free and open access to the resource.[5]

The marginal harvester earns zero rents in the resource sector because equation (10) implies $p_H S \alpha_0^* = p_M$. As long as manufacturing is produced, the wage in manufacturing equals the product price, $p_M = w$, and this is any agent's opportunity cost. Therefore, agents with $\alpha > \alpha^*$, earn more than their opportunity costs. These are rents and since they accrue from productivities higher than the current productivity of our marginal harvester, I refer to them as inframarginal rents. A key distinction between the Redux model and the original BT model is that free entry under open access does not extinguish all rents from the resource sector.

[5] Going forward, prices refers to relative prices. For example, a higher price or prices means a higher relative price or prices.

Another way to determine the marginal harvester is to assume resource policy restricts entry into harvesting. Any efficient resource policy will restrict harvesting by limiting access to only the most skilled agents.[6] Under a resource policy that restricts effort efficiently, the marginal harvester will have a productivity $\alpha^* > \alpha_0^*$. Such a policy limits entry, may raise economy-wide rents above that obtained under open access, and would naturally require monitoring and enforcement to be credible.

It proves useful to start with a simple parametric measure of policy stringency. Let the degree of regulatory stringency, $\mathcal{R}$, be captured by the ratio $\alpha^*/\alpha_0^* \geq 1$. This measure represents the ability of the planner to enforce a resource policy more restrictive than open access. With no enforcement power, $\mathcal{R} = 1$, and the planner is left with open access. With $\mathcal{R} > 1$, some harvesting is deterred because $\alpha^* > \alpha_0^*$. We can use $\mathcal{R}$ to find a solution for the marginal harvester when regulation with stringency $\mathcal{R}$ is in place. It is given by:

$$\alpha^* = \mathcal{R}\alpha_O^* \rightarrow \frac{\mathcal{R}}{p} = \alpha^* S \tag{11}$$

With this definition in hand, return to Figure 2. It is now easy to see that the tangency of the line with slope $\mathcal{R}/p$ with the PPF at A is exactly the equality in (11). Therefore, point A represents a Temporary Equilibrium for a small open economy facing given prices p, having enforcement power $\mathcal{R}$, and current resource stock S. Alternatively, for a given stringency of regulation but a lower price for the harvest good, the price line would be steeper, leading to a Temporary Equilibrium at a point like C. Therefore, very naturally, the interplay of world prices, policy stringency, and resource abundance, dictate production in the temporary equilibrium.

Since the ratio $p/\mathcal{R}$ will occur frequently, it is useful to give it a name. Since p is the relative price of the harvest good, and $p/\mathcal{R} < p$ whenever policy constrains harvesting, I refer to $p/\mathcal{R}$ as

[6] A proportionate harvest restriction on all workers is inefficient because agents differ in their comparative advantage. The first best policy makes two decisions: who should harvest (only the most efficient), and how much should agents in total harvest to manage the resource stock over the long run (which depends on time preference rates and the cost savings created by stock fattening). Choosing a marginal harvester appropriately solves both problems simultaneously.

the shadow price of the harvest good since its magnitude reflects a choice on the part of regulators to limit harvesting and raise the resource stock.

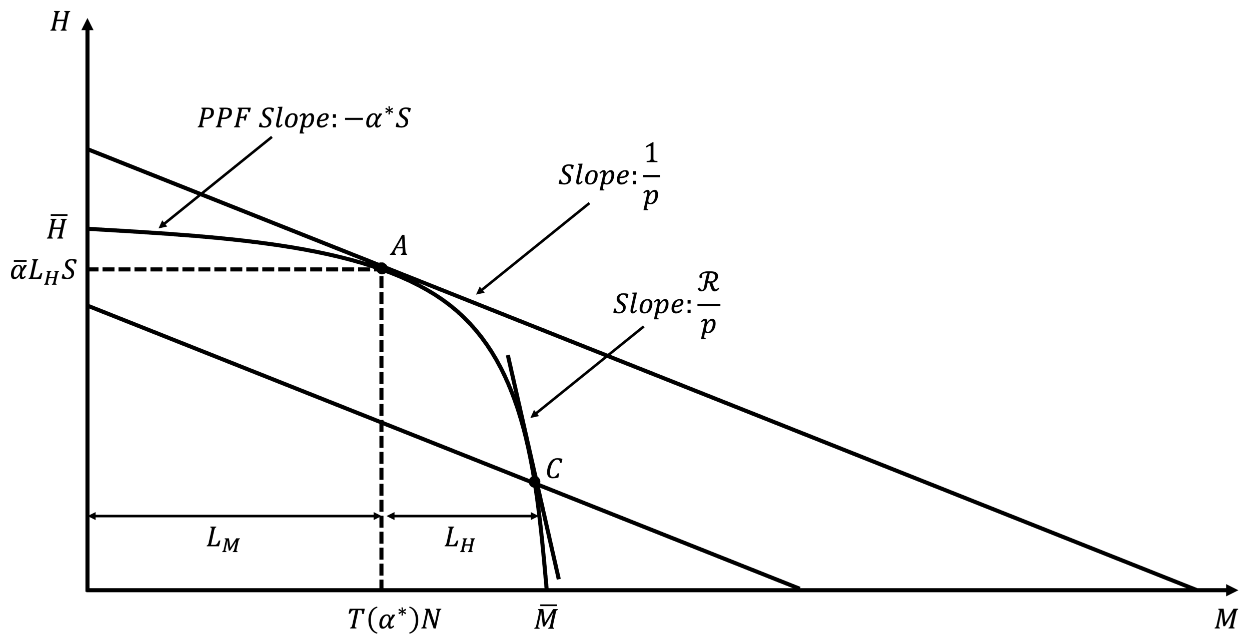


Figure 3: The Short Run Costs of Regulation

One final word on policy before continuing to a discussion of steady states. The tangency in Figure 2 suggests an efficient solution, but this conclusion is a bit premature. Ensuring that only the highest productivity harvesters are active is efficient, but choosing the optimal level of harvesting is an investment decision that we have yet to discuss. To clarify, consider Figure 3. At current prices and under open access, the economy's temporary equilibrium would be at point A. With an active and restrictive policy in place, $\mathcal{R} > 1$, and the temporary equilibrium is instead at point C. Notice that national income at this moment in time, which is measured at world prices, is represented by the economy's budget line through its production point. Therefore, national income is lower when the economy produces at C and faces prices p than if it operates at A (compare the budget sets these production points imply). This reduction in national income represents the investment an economy with stringency $\mathcal{R} > 1$ makes when it constrains harvesting to manage the long run evolution of the resource. This investment shifts income to future generations (or to the citizens' future selves) who benefit from the higher productivity a higher resource stock provides. The tangency condition in the temporary equilibrium regulation tells us labor is allocated efficiently at a point in time, but managing a resource is still costly - and will not be optimal at an arbitrary $\mathcal{R} > 1$.

III.I Steady States

To examine the steady state of this economy we need to combine harvesting with natural growth. To do so, use (11) and (6) to write harvesting as a function of prices, the resource stock, and policy stringency. It becomes:

$$H = \delta N S^{\gamma}[p/\mathcal{R}]^{\gamma-1} \tag{12}$$

I refer to (12) as the harvest function. It is strictly convex in the resource stock, and in $\{H, S\}$ space it shifts up with an increase in the mass of agents or an increase in the shadow price.

For simplicity, I follow the original BT model by assuming resource growth is given by

$$G(S) = rS\left[1 - \frac{S}{K}\right] \tag{13}$$

where $K > 0$ is the carrying capacity, and $r > 0$ is the intrinsic rate of resource growth. The carrying capacity is often measured in terms of biomass in physical units. For example, K could be measured in tons of fish, or cubic board feet of forest, or wildlife numbers within a defined habitat. Other applications treat K as atmospheric or river quality or a measure of water pressure available from underground aquifers. In these applications, K measures pristine conditions or optimal pressures.

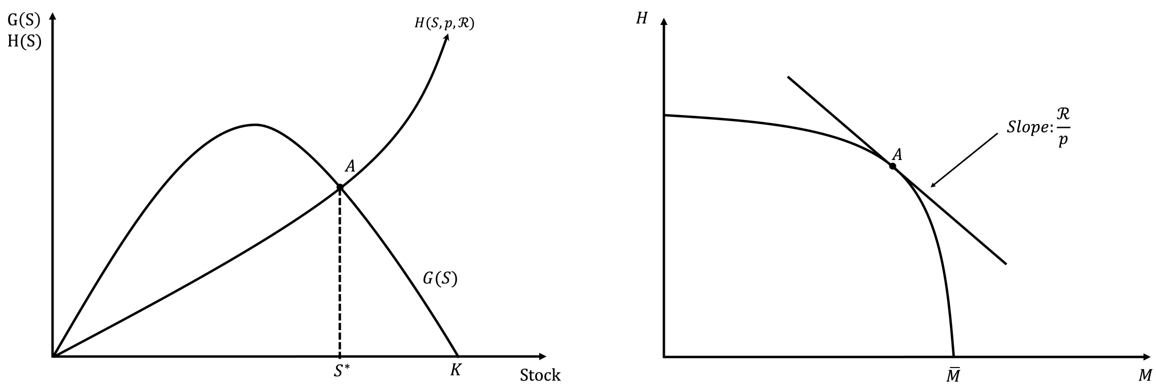
The key assumptions embodied in the growth function are that growth is positive even when an infinitesimal amount of stock remains, and this growth, in percentage terms, is, in fact, highest when the resource stock is its lowest. This implies that nature compensates for stock losses by growing more rapidly making catastrophic outcomes unlikely.[7]

[7]See my Innis Lecture, Taylor (2009), on how to alter the basic BT model to generate a model of Environmental

The evolution of the resource stock over time is determined by natural growth minus the harvest:

$$\frac{dS}{dt} = rS\left[1 - \frac{S}{K}\right] - H \tag{14}$$

To solve for the steady state in our small open economy combine (12) and (13) in (14) and impose the steady state condition $dS/dt = 0$. Alternatively, we could use the graphical methods shown in the two panels of Figure 4.[8]



(a) (b)

Figure 4: Steady State Equilibrium in the SOE

Harvesting rises in panel a) from both a productivity boost to existing agents when the resource stock rises (an intensive margin effect) and from the entry of new, less skilled agents (along the extensive margin). When both margins adjust the harvest function is strictly convex. Although the convexity of H and the concavity of G certainly work towards an interior solution, an extinction steady state is possible in this model. Finding the conditions needed to guarantee a unique, interior steady state requires some work and to help in this effort, it is useful to introduce three new definitions which I will do shortly.

Turning to panel b), the same agent heterogeneity responsible for gradual entry in panel a) is responsible for the the smooth curvature of the PPF here. Because the Pareto distribution is

Crises.

[8]It is, of course, possible to add an assumption on tastes and then solve for the autarky temporary equilibria and associated autarky steady state using conventional methods. One example is in Brander and Taylor (1997).

unbounded above, the PPF becomes infinitely steep as $H \rightarrow 0$. This ensures the economy remains an active H producer at any positive p and S.

It is now simple to change prices, regulation, resource growth rates or the mass of agents and trace through their short and long run consequences using these figures. Changes in prices for example alter harvesting decisions in panel b), but shift the harvest function in panel a) setting in motion consequent changes to the ppf in b), etc.

Although perhaps not obvious, if we eliminate heterogeneity, the figure also represents the original BT model. For example, if we let $\gamma \rightarrow \infty$, then $\alpha^* = b$ and the PPF in panel b) becomes linear with slope $-\alpha S$. Similarly, with one productivity the harvest function is linear in effort identical to that in the original BT model.

III.II Average Productivity, Effective labor, and Over Capacity

Since raising p shifts the harvest function upwards, and lowering r makes the growth function less steep near $S = 0$, the two curves in panel a) may not intersect. To find the conditions under which an interior steady state exists start by finding the average productivity of labor in harvesting. This is simply:

$$\frac{H}{[1-T(\alpha^*)]N} = \frac{\delta N S(\alpha^*)^{1-\gamma}}{[1-T(\alpha^*)]N} = \left(\frac{\gamma}{\gamma-1}\right)\alpha^* S \tag{15}$$

where I have used $L_H = [1-T(\alpha^*)]N$ and properties of $T(\alpha^*)$.

Since this measure moves with the resource stock, it proves useful to go slightly further to define the average (technical) productivity of those harvesters currently active. This measure is independent of the resource stock and is defined by $\bar{\alpha}(\alpha^*)$. I can now use this definition to rewrite the harvest function as:

$$\bar{\alpha}(\alpha^*) \equiv \left(\frac{\gamma}{\gamma-1}\right)\alpha^* \qquad H = \bar{\alpha}(\alpha^*)[1-T(\alpha^*)]NS \tag{16}$$

$\bar{\alpha}(\alpha^*)$ is the expected value of draws from $T(\alpha)$ when truncated at the marginal harvester's productivity α^*. Therefore, $\bar{\alpha}$ is the average (α or technical) productivity of the $L_H = N[1 - T(\alpha^*)]$ agents active in harvesting.

Using this new definition, it follows that the interior steady state shown in Figure 4 must satisfy:

$$S = K\left[1 - \frac{\bar{\alpha}[1 - T(\alpha^*)]N}{r}\right] > 0 \tag{17}$$

where I have suppressed the reliance of $\bar{\alpha}$ on the marginal harvester. It is apparent from (17) that a necessary and sufficient condition for a positive resource stock is:

$$\bar{\alpha}[1 - T(\alpha^*)]N < r \tag{18}$$

To simplify, I introduce a second definition, which is a measure of the the *effective labor* in harvesting. This is simply the raw labor input times its average (technical) productivity; that is, the *effective harvesting labor*, ℓ, becomes $\ell = \ell(\alpha^*) \equiv \bar{\alpha}L_H$. Using the properties of the Pareto distribution this simplifies to:

$$\ell = \bar{\alpha}[1 - T(\alpha^*)]N = \delta N/\alpha^{*\gamma-1} \tag{19}$$

When the marginal harvester's cut-off rises, effective labor in harvesting falls; when the cut-off falls, effective labor in harvesting rises. Prices and the stringency of regulation determine this cut-off productivity. Under open access and very high prices, even the least able agent will enter harvesting. This maximal effort level represents the economy's capacity to harvest, and it is here where extinction and no interior solution is most likely. Making use of our previous definition of δ and setting $\alpha^* = b$ in (19), we can define our economy's capacity to harvest, κ, as $\kappa \equiv \bar{\alpha}(b)N$. Not surprisingly, an economy's capacity rises with its mass of agents and their average productivity in toto.

We can use this last definition to determine whether an interior steady state exists. Substituting κ into (18), we find that as long as $\kappa < r$ an interior steady state must exist. This is true because even with all agents employed in harvesting the resource cannot be driven to extinction. Extinction is only possible when $\kappa > r$ and we might think of this as a situation where the economy has over capacity. If an economy exhibits over capacity, if prices are sufficiently high, and if there is open access, then the interior steady state is replaced by an extinction outcome.[9]

III.III Revenues, Costs, and Resource Rents

Thus far I have focussed on the mechanics of the model, and said little about resource policy. With the steady conditions nailed down, I can now ask - How should a resource be managed? In the original BT model open access reigned the day, and in the long run all rents from the resource were dissipated. Policy, to the extent it was considered, consisted of moving to free trade or not.[10]

But if the goal is to raise revenues from the resource, then we need to identify the potential pay off from nature. Consider the possibility that government policy can determine who, and for how long, any agent can harvest. It should be clear that any efficient policy will limit harvesting to the most productive harvesters by choosing a marginal agent α^*. Those harvesters with this or higher productivity spend all of their time in harvesting; those with lower productivities specialize in manufacturing.

With this in mind, focus for the moment on rents that are sustainable in the very long run, i.e., steady state rents. In many cases, maximizing steady state rents leads to the same solution as that found by solving the full optimal control problem and letting the planner's discount rate approach zero.[11] If discount rates are very low all we care about is the long run so ignoring transition effects makes very good sense.

[9] The alert reader will see that as $\gamma \to \infty$, our κ vs r condition collapses to the same condition guaranteeing an interior solution in Brander and Taylor (1997).

[10] See, however, the trade policy analysis contained in Brander and Taylor (1998*b*), and the comparison of two countries with very different resource policies in Brander and Taylor (1998*a*).

[11] See Clark (1990) for a discussion and details within the Gordon-Schaefer model.

Long-run rents are given by the difference between total revenues and total costs in steady state; that is:

$$\tilde{\Pi} = p_H H - wL_H \tag{20}$$

where the harvest, $H = \bar{\alpha} L_H S$, equals natural growth, $G(S) = rS(1 - S/K)$, and the labor employed is $L_H = [1 - T(\alpha^*)]N$. Taking these steady-state relationships into account, we can rewrite rents to obtain:

$$\tilde{\Pi} = p_H \bar{\alpha} L_H K \left[1 - \frac{\bar{\alpha} L_H}{r}\right] - wL_H \tag{21}$$

Recalling that both $\bar{\alpha}$ and L_H are functions of our marginal harvester α^*, it proves useful to simplify further by rewriting in terms of effective labor. Using the definition $\ell = \bar{\alpha} L_H$ and dividing both sides by p_H to measure resource rents in physical units of the harvest good, I find resource rents in units of the harvest good $\Pi = \tilde{\Pi}/p_H$, can be written as:

$$\Pi = TR(\ell) - TC(\ell) \tag{22}$$

where $TR(\ell) = K(1 - \ell/r)\ell$, and $TC(\ell) = \ell/p\bar{\alpha}$. Note $\bar{\alpha}$ is a function of ℓ via (19), and I have replaced the wage with the price of manufactures, and then p, given diversified production.

This new measure of rents, Π, is simple enough to use for analysis. For example, if we divide total revenues in (22) by ℓ, its easy to see that average revenue starts at K and fall to zero when $\ell = r$. Marginal revenues also start at K but fall twice as fast reaching zero when $\ell = r/2$. These are shown in Figure 5 along with average and marginal costs in steady state. On the cost side, we know that marginal costs must rise when we increase employment in harvesting because this requires the use of lower and lower skilled harvesters. If marginal costs are rising, so too must average costs as shown.

To go further, rewrite total costs by exploiting the definition of average productivity to obtain:

$$TC = \frac{\ell}{p\bar{\alpha}} = \left(\frac{\gamma - 1}{\gamma}\right)\left(\frac{\ell}{p\alpha^*}\right) \tag{23}$$

which makes it very clear that costs are a function of ℓ directly and indirectly via α^* (our two margins again). Differentiating (23) with respect to ℓ and using (19), we find:

$$MC = \frac{dTC}{d\ell} = \frac{1}{p\alpha^*} > 0 \quad \text{and} \quad AC = \left(\frac{\gamma - 1}{\gamma}\right)\frac{1}{p\alpha^*} > 0 \tag{24}$$

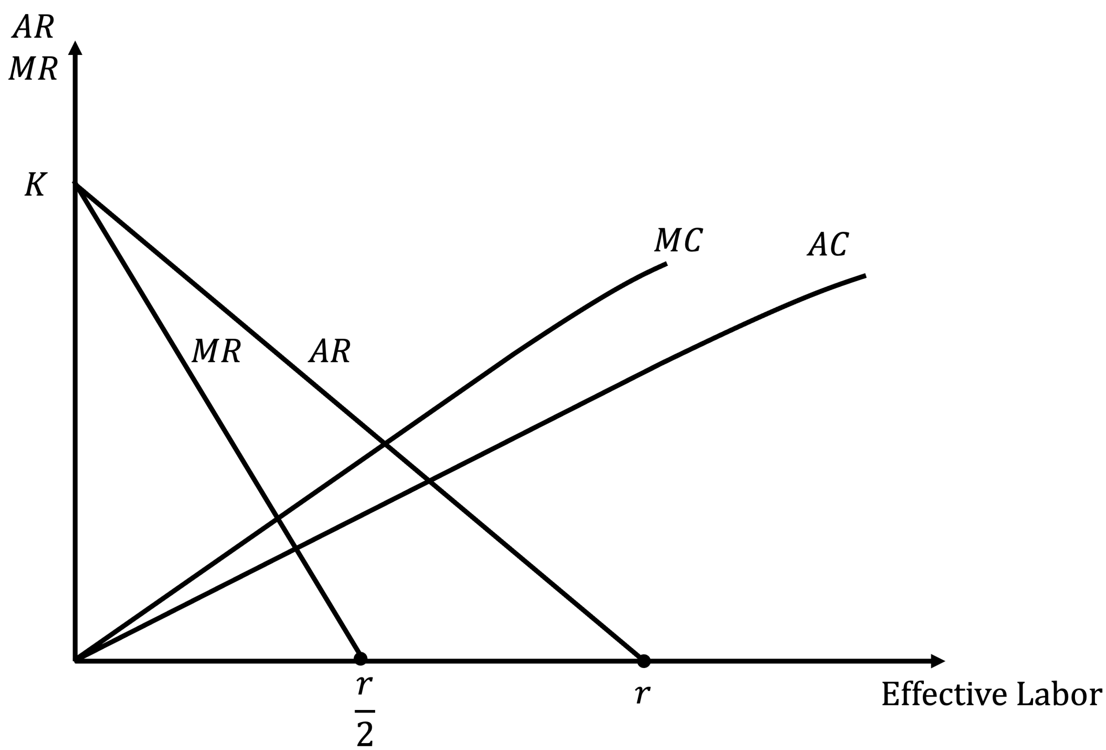


Figure 5: Revenues and Costs in Steady State

These cost functions have several useful properties. First, average costs are always $(\gamma - 1)/\gamma < 1$ below marginal costs at any labor input. Since marginal costs often dictate decision points, while AC determine the size of rents at these same points, this proportionality result can be quite helpful in finding rents. It is also handy to notice that the difference between marginal and average costs is at its largest when $\gamma = 2$, and disappears completely when $\gamma \to \infty$.

Second, both marginal and average costs are concave in ℓ, but the degree of concavity depends on the shape of the distribution. Concavity is a bit surprising, but less so when we recognize that increasing effective labor requires drawing agents from lower and lower parts of the productivity distribution. But the Pareto distribution has increasing mass as we approach b from above. Therefore, while MC rises, its rate of increase slows, and this is why costs are concave in effort.

Here again, our two limiting cases are insightful. If we let the productivity distribution become increasingly fat-tailed, then less of the mass is concentrated near b. Consequently, when we draw more workers into harvesting, they are less efficient, but the rate at which they are made available hardly changes. MC and AC become less and less concave. In the limit as $\gamma \to 2$ they become linear functions through the origin with slopes $1/[p\delta N]$ and $1/2[p\delta N]$, respectively. This linear case lends itself to closed-form solutions.

Our other limiting case $\gamma \to \infty$ pushes the probability mass towards b, meaning MC and AC become increasingly concave. Eventually, as γ approaches infinity, there are no high-ability workers left. Marginal and average costs become horizontal straight lines at the level $1/bp$. This zero variance case also leads to closed form solutions and mimics the results in the original BT model.

With this simple representation of revenues and costs in hand, I can now discuss how policy choices affect steady-state outcomes in our small, open economy. I focus on the gains from trade, but the model can of course be used to study the impacts of trade and resource policy in a many country framework or to discuss the determinants of comparative advantage.

III.IV The Open Access Steady State $\mathcal{R} = 1$

It is easy to depict the open-access steady state in a graph which I do below in Figure 6. The open access level of labor input is given by ℓ^O, and the shaded area gives the rents earned in this open access equilibrium. There are two ways to discover this result. One is to recognize that at the margin, the last entrant has costs equal to marginal costs at the current level of labor input. This marginal entrant also earns revenues equal to the average available to agents. Therefore, entry stops when average revenues fall and marginal costs rise to meet at point O in the figure. Agents with higher productivity receive the same revenues, but have lower costs. Average cost for any level of input is given by the AC curve, and hence the rents earned by all of these inframarginal agents is represented by the area of the shaded box. This is the intuition of free entry with open access.

We can confirm this result analytically. To do so, notice that the vertical height of the average revenue curve at any point is given by $S(\ell)$ where $S(\ell)$ is the steady state stock that would occur if ℓ was employed. That is $AR = K[1 - \ell/r] = S(\ell)$. Therefore, the intersection of AR and MC at point O represents the equality of:

$$S(\ell) = \frac{1}{\alpha^*(\ell)p} \tag{25}$$

where I have been explicit about the relationship between the level of effective labor and the marginal harvester. Rearranging slightly and recalling the definition of p, we find this implies $\alpha^*(\ell)p_H S(\ell) = p_M$ and hence the ℓ that satisfies this equality is by definition the open access level $\ell = \ell^O$ because rents are zero for the marginal agent:

$$\alpha^*(\ell^O)p_H S(\ell^O) = \alpha_O p_H S = p_M \tag{26}$$

Therefore, the open access equilibrium level of effective labor is found directly below point O and labeled ℓ^O.

One nice feature of this figure is that changes in relative prices only affect the cost curves, which simplifies comparative steady-state analysis tremendously.[12] Both MC and AC shift downwards with an increase in p, because this represents a reduction in the real (product) wage paid to workers. They shift upwards when the real wage is higher.

It is now easy to verify that the BT Redux model also generates the same, somewhat counter-

[12]Not everyone thinks this is a nice feature and would prefer that I write revenues in terms of p_H and costs in terms of w so that revenues could shift with product prices and costs with wages. I leave this to the interested reader. It may be easier for some to understand especially if you are used to partial equilibrium analysis. In the end outcomes are only a function of the relative price $p_H/w = p_H/p_M = p$ so I prefer this depiction.

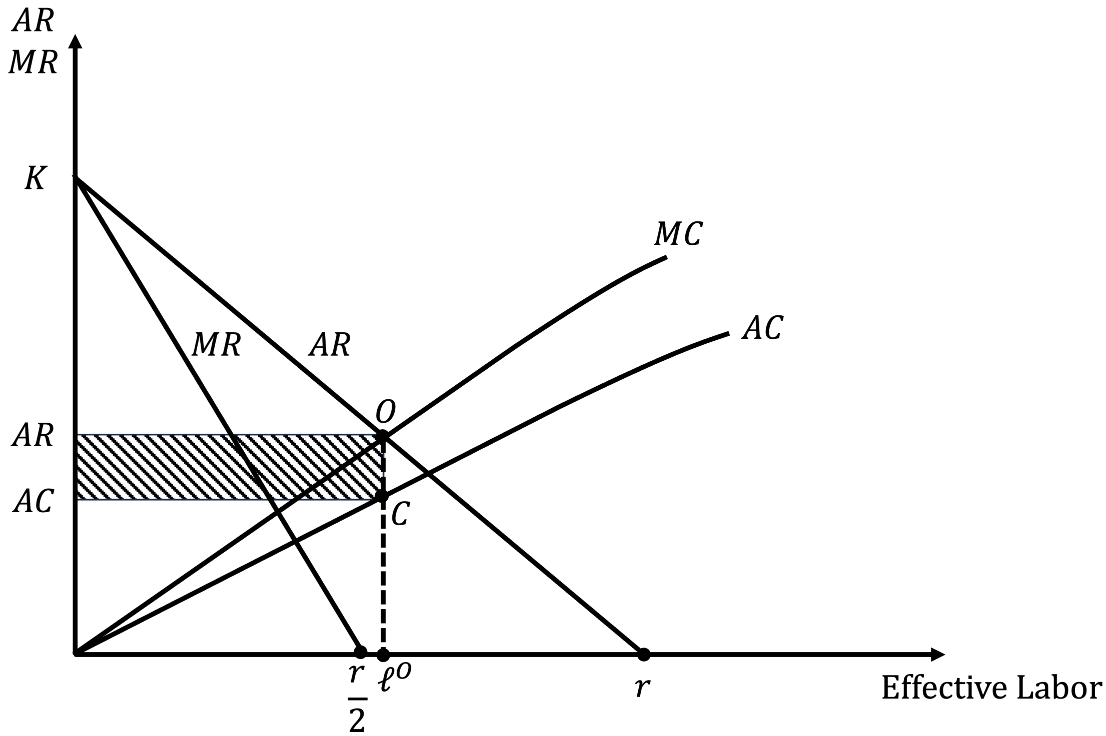


Figure 6: Open Access Revenues and Costs in Steady State

intuitive result that the production of both goods can fall when the economy responds to higher prices, p. To verify, notice that whether ℓ^O lies to the right or left of the point $r/2$ on the horizontal axis depends on prices. When prices are low, both cost curves will be relatively high, and effective labor in harvesting is below $r/2$. This implies the corresponding steady-state stock is greater than $K/2$, which implies that a marginal increase in price from this point will raise ℓ^O, lower S, and increase the supply of the harvest good. Recall $G(S) = H$ in steady state. Manufacturing contracts because it takes more labor to lower the resource stock so less less labor is available for M production. Over this range of prices, harvest output rises and manufacturing contracts when p rises.

But now suppose prices are much higher so that the cost curves in the figure are much lower, and the equilibrium ℓ^O exceeds $r/2$ as it does in the figure. This implies the steady state stock is below $K/2$, and marginal increases in price from this point will lower the resource stock and lead to less of the harvest good being produced. Because this requires more labor in harvesting, less manufacturing is produced.

Therefore, somewhat perversely, higher resource prices can lead to less of both goods being produced. This follows because the inefficiencies created by open access are, in some sense, worse when prices are high and the resource is already over-exploited.[13] For very high prices, ℓ_O could approach r but this depends on the relationship between κ and r. If $\kappa < r$, then extinction can never result, and the economy will eventually specialize in producing the harvest good.

III.V The Rent Maximizing Solution

Maximizing (22) requires we choose an ℓ where marginal costs are equal to marginal revenues. Let ℓ^B denote the rent maximizing level of effective labor, then the first order condition defining the first best becomes:

$$K\left[1 - \frac{2\ell^B}{r}\right] = \frac{1}{\alpha^*(\ell^B)p} \tag{27}$$

The solution for ℓ^B is shown in Figure 7 by the intersection point A.

At this optimum, average costs are given by the vertical height to point *C* and average revenues are measured by the vertical height to point *D*. Therefore, total rents are equal to the rectangular shaded area. If we interpret our rent maximizing solution as the work of a social planner with a discount rate that approaches zero, then this steady state is also the first-best allocation.

One important feature of this solution is that the first best labor allocation will never exceed $r/2$, implying the first best stock is always greater than $K/2$. Higher prices of the harvest good make the planner harvest more, but this process has a limit.[14]

[13] Consequently, this model generates a backward bending supply curve much like that in Brander and Taylor (1998*a*) and Copes (1970).

[14] This is not a generic feature of the problem; if the planner's discount rate was positive then optimal solutions can call for a lower than $K/2$ stock.

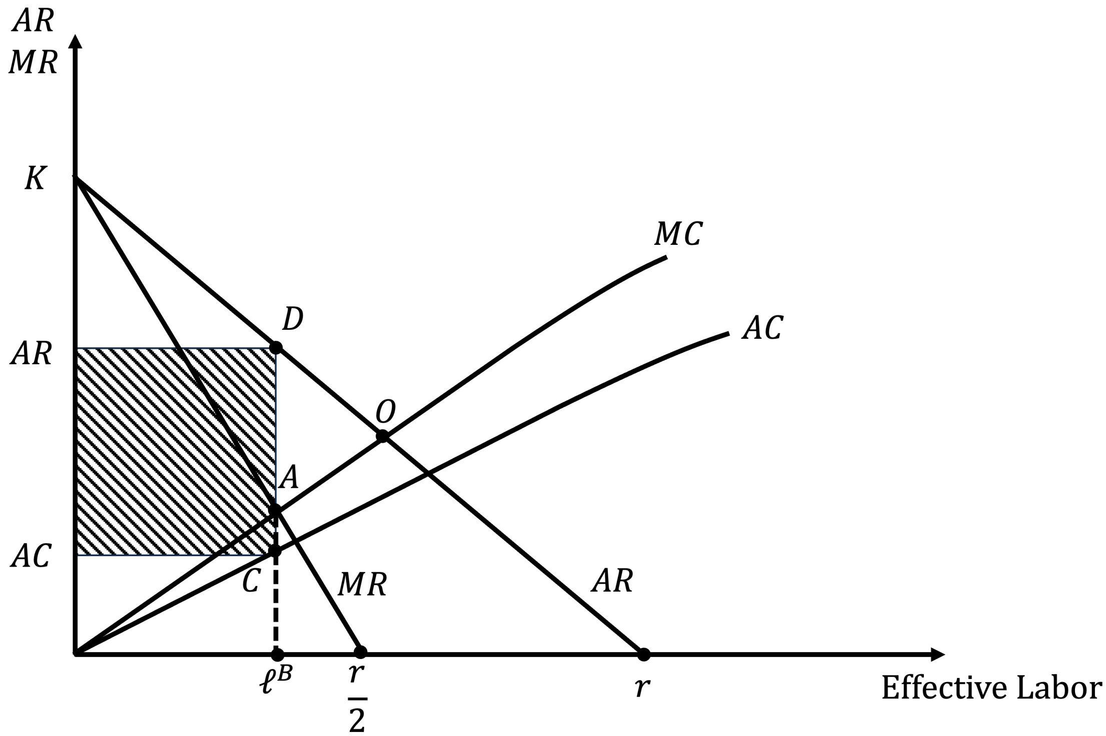


Figure 7: The Rent Maximizing Solution for ℓ^B

III.VI Gains or Losses from Trade?

Since the rent-maximizing solution just described represents the first best solution for an infinitely patient planner, this first-best economy cannot lose from trade. In contrast, in the open access case, Brander and Taylor (1997) provided two provocative results. A resource good exporter who diversifies in trade has to suffer long-run or steady-state reductions in consumption possibilities.[15] Surprisingly, these losses are increasing in a country's terms of trade!

The driving force behind these two results is excessive entry into the resource sector. When liberalized trade makes harvesting more profitable, it creates new entrants whose harvesting, in the long run, lowers the resource stock and industry productivity. If these productivity losses are large enough, they will completely undo the initial benefit of a higher price for their export good.

[15] If agents' discount rate is sufficiently low, then the economy's temporary gains from trade will not offset the long-run losses the economy suffers in steady state. An appropriately discounted stream of utility will be lower in trade than in autarky. All statements in this section about gains and losses assume a low enough discount rate to make the steady-state comparisons pivotal.

The surprise is that the negative impacts of trade - lowered industry productivity - always more than offset the positive impacts of trade - the ability to receive higher world prices for your export good.[16]

The key to these results is the free entry condition in harvesting, which in the BT model is simply:

$$p_H \alpha S^A = p_M = w, \; \Rightarrow p^A \alpha S^A = 1 \tag{28}$$

where superscript A refers to autarky values just as T refers to a trade values. Workers in manufacturing earn their value of marginal product $p_M = w$, but with free entry this is also equal to the return earned in harvesting. Consequently, workers in harvesting earn their opportunity cost of w and there are no rents earned on the resource. National income in this economy is simply wage income wN because resource rents, when (28) holds, are zero.

In the BT model when trade raises relative prices to $p^T > p^A$, workers move into harvesting because of the short term rents it provides. The economy specializes in H. This entry raises harvesting above its sustainable level, and the stock starts to fall. It continues to fall until either one of two things happen. One possibility is that the stock reaches a steady state $S > 0$ despite everyone working in harvesting. This is a fully specialized steady state with all labor in harvesting. In this case, at least some of the new rents created by trade remain in the long run. Rents remain because the economy doesn't have enough capacity to exhaust them. Workers wages equal their value of marginal product $p^T \alpha S^T > 1$. Workers' real income in terms of the manufacturing good is higher in trade than in autarky (divide their wage by 1 and compare to 1 in autarky) but lower in terms of the harvest good (divide their wage by the free trade relative price and recognize the stock is lower in trade). Therefore, whether agents gain or lose from trade now depends on our assumptions about preferences. If preferences place a large enough weight on the manufacturing good, or are such that

[16]A common belief amongst many economists is that while there may exist environmental costs of trade, the conventional gains from liberalized trade are so large they surely swamp whatever these environmental costs may be. This may well be true in some cases; for example, see Shapiro (2016).

agents' are willing to substitute towards the now relatively cheaper manufacturing good readily, then gains from trade will be assured. If not, trade will make agents worse off.

The second possibility is diversification. In this case, the stock falls until it reaches a point where all of the rents created by higher world prices are dissipated. This occurs in equilibria featuring $p^T \alpha S^T = 1$ because production is diversified. In this case, national income is no higher than before at wN, but agents' real income in terms of the harvest good is now lower because $wN/p_H = N/p^T < N/p^A$. Agents' real income in terms of the manufacturing good is unchanged from autarky because $wN/p_M = N$ in both cases. Therefore, agents' steady state consumption possibility set is smaller in the trading steady state than it was in autarky. There are losses from trade.

It also follows that the higher a country's terms of trade, p^T, the smaller its eventual consumption possibility set, and the greater these losses are.

Putting these results for the BT model together we see that if full rent dissipation occurs, then the structure of preferences is irrelevant and losses from trade have to occur. If only some of the new rents created by higher world prices are dissipated, then it is unclear whether there are losses or not. It depends on how willing agents are to substitute towards the now cheaper manufacturing good. The same basic logic holds in the BT Redux model, although complete rent dissipation never occurs.

To see why, consider Figure 8 where I have shown several possible outcomes arising from an opening to trade for an economy with $\mathcal{R} = 1$. The economy starts at point A in an autarkic steady state. The autarky steady state stock (not shown) determines the location of the outermost PPF containing A. There is also an associated autarky price of p_A that equates demand and supply for both goods. The Harvest at point A is sustainable and balances natural growth making this a steady-state.

If our economy is a harvest good exporter, then a trade liberalization is associated with a higher price for the harvest good. This is given by p_T. On impact, the economy moves to point T. The higher harvest at T starts a process of stock reduction which continues until a new steady state is reached. Exactly where this steady state lands depends on parameter values, but we do know some things in general. We know the new steady-state resource stock must be lower than in autarky, and by implication manufacturing output must also be lower than it was at A. The new steady-state harvest could however be higher or lower than in autarky (recall our discussion of the location of ℓ^O vs. $r/2$). Therefore, depending on parameter values this new trading steady state could be at points like T', T'', or T'''.

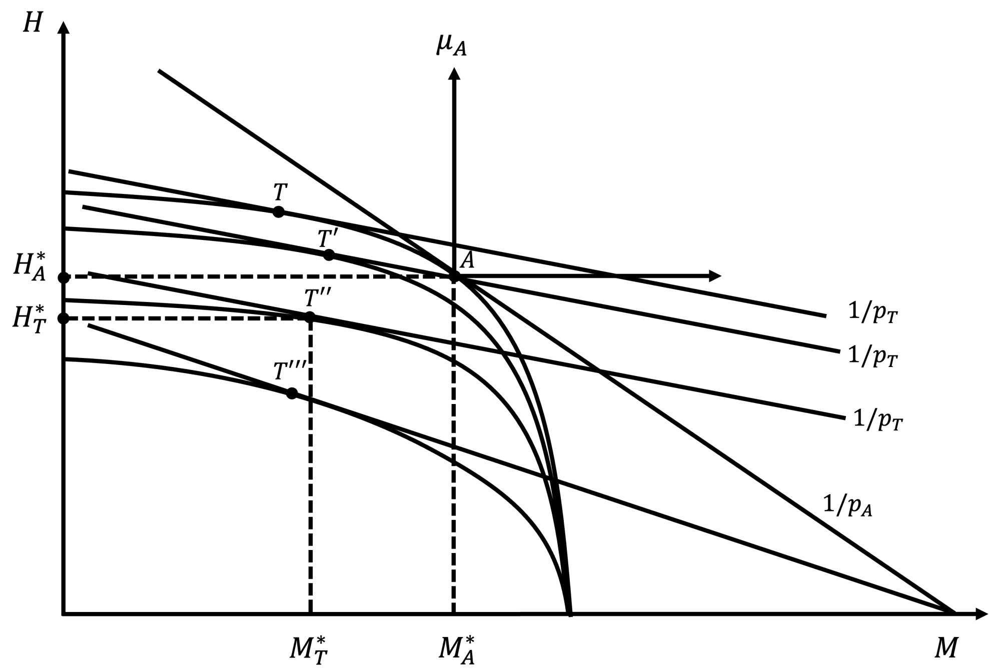


Figure 8: Losses from Trade

Point T' exhibits more harvest production than in autarky, and at free trade prices, this economy can still purchase its old consumption bundle at A. This economy has to gain from trade independent of its preference structure. Notice that for agents to be able to consume their old consumption bundle, the steady state harvest had to rise with trade. But using Figure 6 and our knowledge of the growth function $G(S)$, this is only possible if the autarky steady state has a labor allocation $\ell^O < r/2$ and the movement to free trade prices was *small*. Therefore, a necessary condition for gains from trade independent of the agent's preference structure, is that the resource is not severely over-used in autarky, so that $S^A > K/2$, and the movement to free trade represents a small change in prices.

Things are quite different at point T'' where less of the harvest good is produced in the new trading steady state, and the economy cannot purchase its old consumption bundle at A. This economy can still gain from trade, but it will now depend on agents willingness to substitute towards the now relatively cheaper manufacturing good. To see this I have drawn in a Leontief indifference curve through A with a zero elasticity of substitution across goods. Even though the free trade budget line allows for an increase in consumption of M well beyond that in autarky, agents are unwilling to make that trade-off and lose from trade. The alternative extreme is also shown. If agents treated the goods as perfect substitutes, then the indifference curve in the autarky steady state would have to be coincident with the autarky budget line through A. All points to the right of this line represent higher utility. Since production at T'' allows for consumption choices far to the right of this autarky indifference curve, this economy must gain from trade.

Finally consider point T'''. If the new steady state was at T''', then the free trade consumption possibility set is a subset of what it would have been had the economy remained in autarky. Notice that in this case, national income in terms of manufacturing is the same in autarky and in trade. To see what this requires, let $\bar{I}$ be national income in terms of manufacturing. Then, as shown in the appendix, this implies:

$$\bar{I} = N + L_H^O(\frac{1}{\gamma - 1}) \tag{29}$$

In general (29) rises with the movement to trade for a resource exporter because L_H^O rises with p. This means the horizontal intercept for the world price line would lie to right of the autarky intercept and a point like T''' would not exist. In one special case, it does exist. This is the situation where inframarginal rents are zero. This corresponds to the limiting case where $\gamma \to \infty$. In the limit we have $\bar{I} = N$ with complete rent dissipation. This is exactly the original BT case.[17]

What this discussion clarifies is that losses from trade depend on the relative strength of substitution along two different margins. If the pool of harvesters is heterogeneous and, therefore, poor substitutes for one another, then higher world prices brought about by trade will always generate inframarginal rents. These rents allow for greater consumption of (at least) the manufacturing good. And if goods are very good substitutes, agents will happily consume more of the manufacturing good and gain from trade. Alternatively, if the pool of harvesters is homogenous and, therefore, good substitutes for one another, then the higher rents brought about by trade can be completely dissipated by free entry. In this case, even if consumption goods are very good substitutes, agents will lose from trade.

The earlier BT analysis obscured this horse race. It obscured it because incomplete rent dissipation only occurred with specialization and complete rent dissipation only occurred with diversification. It appeared that these production patterns determined outcomes when, in fact, it was the extent of rent dissipation. The BT Redux model puts these results in context. It tells us the key to gains or losses from trade lies in a comparison of the extent of rent dissipation vs. the degree to which consumers are willing to substitute across goods. When the extent of rent dissipation is high (low), and substitution low (high), there are losses (gains) from trade.

What is less clear is whether, or to what extent, these results carry over to a world where some policy is in place, $\mathcal{R} > 1$, or perhaps more realistically, to a world where $\mathcal{R}$ changes with trade policy. One of the original critiques of the Brander-Taylor model was that it assumed open access conditions were exogenous and unaffected by the price changes trade would bring. I address this critique below.

[17] The PPF would be linear in this case and not that shown.

IV Is Free Trade Good for Renewable Resources?

This question has no single answer. Some countries will undoubtedly do well liberalizing trade while others will not, and theory alone cannot resolve this issue. Theory can however help us develop an empirical strategy designed to distinguish likely winners from likely losers, and perhaps pinpoint reasons for failure and success when they occur.

One important limitation of the analysis thus far is the assumed rigidity of resource policy. It is reasonable to think that resource management may improve if a natural resource becomes more valuable. If this did occur, then it becomes far more likely that free trade at higher world prices would bring benefits to our small open economy. This basic idea is sometimes attributed to Harold Demsetz who articulated a theory of endogenous property rights in Demsetz (1967). Demsetz's idea is very intuitive and in Copeland and Taylor (2009) we addressed this possibility by developing a theory of endogenous regulation which established *de facto* property rights over a renewable resource by building on the original BT model.[18] This theory showed we could divide the parameter space defining countries into three sets. These sets defined an associated three categories of countries which we named: Hardin, Ostrom and Clark economies.

Before I discuss how these categories are relevant to the BT Redux model, it is useful to examine the relationship between the stringency of regulation imposed under open access vs that imposed by our rent maximizing social planner. The key observation is that our previously parametric $\mathcal{R}$ needs to be replaced by a policy stringency function $\mathcal{R}(p)$ because the social planner adjusts resource policy when world prices change.

IV.I Endogenous Resource Regulation

To characterize $\mathcal{R}$ as a function of p start by recognizing that labor allocations at points A and O in Figure 7 imply $\alpha_O^* < \alpha_B$. More labor under open access implies a lower cut-off, and not sur-

[18]See also Hotte, Van Long and Tian (2000) and McCarthy, Sadoulet and de Janvry (2001)

prisingly, with our rent maximizing social planner determining policy, $\mathcal{R} > 1$ at these given prices. But $\mathcal{R}$ is in fact endogenous. To make this crystal clear use $\ell = \delta N \alpha^{1-\gamma}$ to replace the productivity cut-offs that define $\mathcal{R}$ with their associated labor allocations. Making these substitutions, I find:

$$\mathcal{R}(p) = (\ell^O/\ell^B)^{1/(\gamma-1)} \tag{30}$$

where labor allocations are functions of p, *à la* Figure 7.

Our analysis shows that when resource prices are relatively low, rents are small, and open access effort levels are correspondingly small. At these same low prices the planner has to fatten the resource stock to raise productivity in order to create resource rents. To do so, the planner also employs very few workers. Therefore, when prices are low, ℓ^O and ℓ^B are very similar and $\mathcal{R}(p)$ approaches 1. Graphically, when the relative price of the harvest good is very low in relation to the price of manufactures, the MC of drawing labor from manufacturing is very high, and the gap between where AR and MR intersect MC is therefore very small.

Conversely, when resource prices are very high, the planner harvests more but the first best labor allocation can never exceed $r/2$. These same high prices attract entrants under open access, and open access labor is much higher. It cannot however exceed the level that drives the resource to extinction which is r. Therefore the gap between these two allocations grows and is at its largest when prices are very high. As $p \to \infty$, $\mathcal{R}$ has a finite bound above unity.[19] Less obvious is that the policy function $\mathcal{R}(p)$ has an elasticity less than 1, which implies the shadow price rises with p but less than proportionately.[20]

In a world with endogenous regulation, there are additional possibilities, but these possibilities are spanned by our two extreme cases. To illustrate, I graph $R(p)$ for our rent maximizing planner and the corresponding $R(p) = 1$ for an economy that exhibits open access at all prices in Figure 9.[21]

[19] The maximum value of $\mathcal{R}$ is $\mathcal{R}(\infty) = 2^{[1/[\gamma-1]]}$.

[20] See the Appendix for a proof.

[21] In some cases, I can solve for the policy function explicitly. For example, if $\gamma \to 2$, the policy function and its derivatives are given by: $\mathcal{R}(p) = 2 - \frac{1}{1+\varphi p}$, $\mathcal{R}'(p) = \frac{\varphi}{(1+\varphi p)^2} > 0$, and $\mathcal{R}''(p) = -\frac{2\varphi^2}{(1+\varphi p)^3} < 0$, where

As shown, the policy function under open access is a simple horizontal line at one, while that for our planner starts at one but rises at a decreasing rate towards its maximum value. Also shown are three policy functions labelled Clark, Ostrom or Hardin in the figure. These three types of economies are distinguished by their economies' extent of excess capacity in their resource sector, their ability to catch and punish cheaters determined by their enforcement power, and their incentive to extinguish the resource which compares the planner's rate of time preference to the intrinsic growth rate of the resource.[22]

Returning to the figure, Hardin economies represent a set of countries, which at any world price, cannot regulate their resource effectively. Their policy function is coincident with $\mathcal{R} = 1$ at all prices. In terms of primitives, Hardin economies are countries with significant over-capacity in the resource sector, and relatively poor monitoring and punishment options, leading to low enforcement power.

Countries with a slightly more favorable set of these same conditions can stem over-harvesting to some extent but can never deliver the first best outcome. These are *Ostrom* economies. At very low prices, an Ostrom country exhibits open access because, at low prices, a social planner needs to fatten the resource stock to create rents, but this requires a draconian reduction in effort which is just not credible. Agents facing these restrictions would cheat, and the planner is powerless to restrict entry. Consequently, the policy function for an Ostrom economy is coincident with the $\mathcal{R} = 1$ function over the initial range of prices given by the segment AC. Eventually, at high enough prices, the reduction in effort the planner can enforce is consistent with positive rents. The Ostrom economy now limits entry to the resource sector. This price is shown as point p^{++}. Limiting entry requires fixing a cut-off productivity, and hence the ratio of labor allocations (open access to the constrained planner solution) continues to grow with prices. The Ostrom policy function rises rapidly but never reaches the restrictiveness of the first best - because this economy is, by definition, Ostrom.

$\varphi = (\delta NK)/r$. In this case if we now let p go to infinity, $\mathcal{R}(\infty) = 2$ which is just r divided by r/2 as mentioned above.

[22] See Copeland and Taylor (2009) for details.

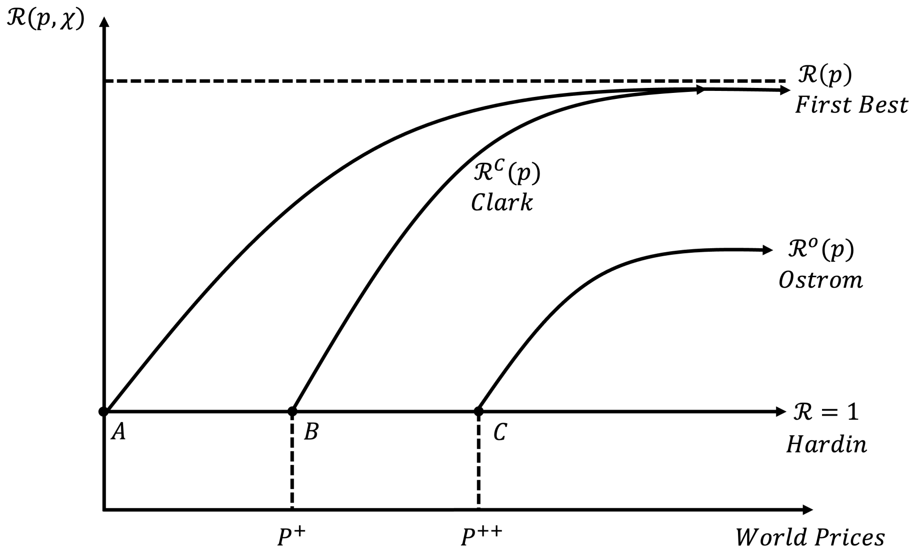


Figure 9: Hardin, Ostrom, and Clark

Finally, there is a set of economies with even more favorable primitives. Their resources grow faster, their overcapacity is smaller, or their enforcement power is higher. These are Clark economies. Their policy function also starts with an initial segment AB where open access cannot be eliminated for exactly the same reasons given previously. But now at a relatively low price, some enforcement is possible and the policy function rises rapidly. Eventually the Clark policy function matches that of the unconstrained first best as shown.

While this analysis is suggestive, strictly speaking, Copeland and Taylor (2009) only applies to our model in the limiting $\gamma \to \infty$ case.[23] Morevoer, even the simple - *Hardin*, *Ostrom*, and *Clark* - country divisions need adjustment when we move to a world with investments in monitoring or alternative fine structures. Despite these complications, one general observation stays true: policy functions should be country-specific because they are tied to deep primitives capturing enforcement power, over-capacity, and national time preference measures. And we could write the set of policy functions for a broad range of countries as $\mathcal{R}(p,\chi)$ where χ is a vector of country characteristics.

[23]The key complication carrying these results forward in the BT Redux model is that as prices rise, there is an expanding set of harvesters to deter from over-harvesting and this makes enforcement harder. It is possible to extend the analysis to take this new feature into account but doing so takes us well beyond the scope of this paper.

With this in mind, we can now consider the causal connection between these deep parameters and the likelihood of gains from trade.

IV.II The Causal Connection

Figure 10 contrasts the impact of trade liberalization for two economies, alike in all respects, except resource regulation in one economy improves with the price of the harvest good while in the other it does not. Both economies start at point A in the two panels with a relatively low domestic price (world price plus trade frictions) of p. As shown by the right panel, A is also a steady state. The resource stock given by S_A is determined by the countries' common harvesting and growth functions. Despite their differences, both economies start with open-access solution and $\mathcal{R} = 1$.

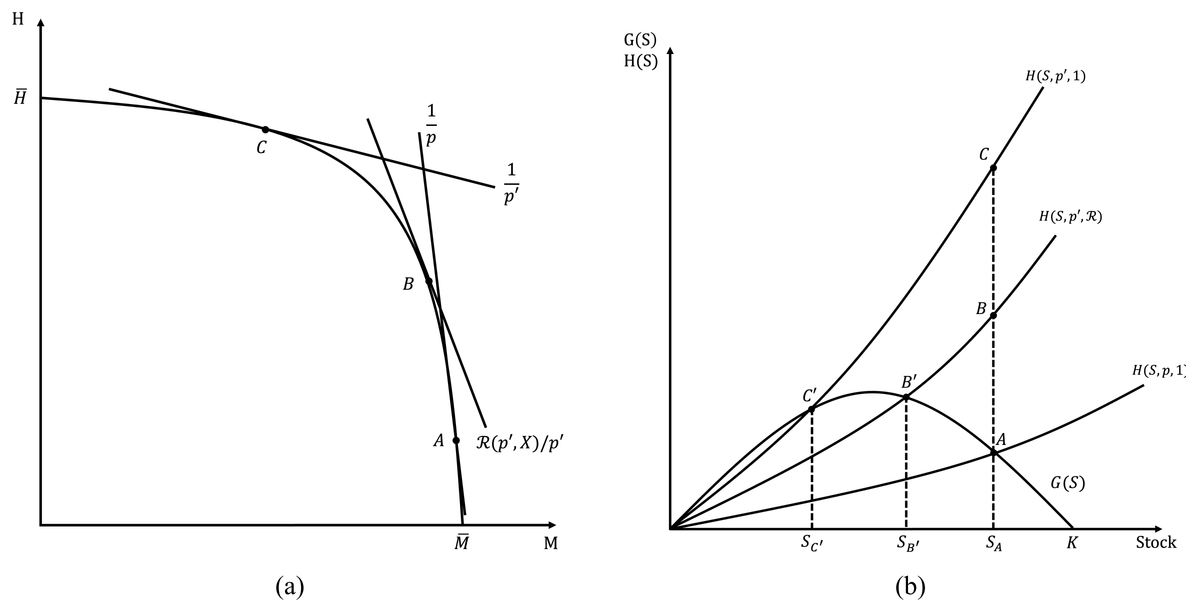


Figure 10: A Fall in Trade Frictions

A decline in trade frictions - from either lowered transport costs or reduced barriers to trade - is captured by the movement to the higher domestic price p'. For a Hardin economy with no ability to regulate its resources, $\mathcal{R}(p, \chi) = 1$ throughout and the temporary equilibrium moves to point C in both panels. Harvesting effort explodes with the trade liberalization.

For an Ostrom or Clark economy with the ability to regulate, regulation responds and $\mathcal{R}(p,\chi)$ increases with p.[24] The temporary equilibrium moves to points like B in both panels. Harvesting effort still rises but the increase to B is tempered by the simultaneous change in the restriveness of policy. As a result, the change in the steady-state resource stocks is much smaller.

The key observation is that both short run (movements to B or C) and long-run impacts (movements to B' and C') of trade liberalization are conditional on a country's ability to alter its resource regulation in response to changed conditions. Therefore, any empirical strategy hoping to link an opening to trade with resulting changes in resource stocks will need to condition on those country characteristics affecting this flexibility.

IV.III Estimation Strategies

While our theory shows freer trade creates both very short run and very long run changes, neither impact is likely observable. Instead, we will observe an economy along its transition path from one steady state to another over many years if not decades. Therefore, it is useful to investigate how differences across countries in their deep parameters affects their response to trade liberalization by focusing on this transition period. We do so using (12) and (14) to write:

$$\dot{S} = rS[1 - S/K] - \delta NS[pS/\mathcal{R}]^{\gamma-1} \tag{31}$$

where $\dot{S} = dS/dt$. Rewriting equation (31) in percentage change terms, we have:

$$\dot{S}/S = r[1 - S/K] - \delta N[pS/\mathcal{R}]^{\gamma-1} \tag{32}$$

Since the left-hand side of equation (32) is the time derivative of $\ln S(t)$, it might be fruitful to represent the right-hand side with a log-linear approximation around the economy's steady state. Call the right-hand side of (32) $F(S)$, and recall that a log-linear approximation of $F(S)$ near the

[24] This requires the price increase be large enough, so that $p' > p++ > p$.

steady state where $S = S^*$ is simply $F(S^*)[1 + \eta\hat{S}]$ where η is the elasticity of F w.r.t. S, and $\hat{S} = \ln S(t) - \ln S^*$. Using the fact that $F(S^*) = 0$, we can employ this approximation to simplify and rewrite equation (32) as a linear differential equation in $\ln S(t)$:

$$\frac{d}{dt} \ln S(t) = -\lambda \ln S(t) + \lambda \ln S^* \tag{33}$$

$$\lambda = \left[\frac{G(S^*)}{S^*}\right] \left[\left[\frac{S^*}{[K - S^*]}\right] + (\gamma - 1)\right] > 0 \tag{34}$$

where λ measures the speed of convergence towards the steady state.

Solving (34) and letting $S(0)$ be the stock level at $t = 0$, yields an equation guiding the evolution of the resource over time:

$$\ln S(t) = e^{-\lambda t} \ln S(0) + \left[1 - e^{-\lambda t}\right] \ln S^* \tag{35}$$

The stock starts at $S(0)$ and converges to S^* as $t \to \infty$.

There are various ways to exploit the relationship in (35) to generate testable implications of the BT Redux theory. Below I outline three possible methods. All three exploit an expression linking the growth rate of the resource over a given period of time to primitives of the system and the stock's initial value. It is also possible to develop similar methods if the unit of observation is harvests rather than resource stocks, but this is left to the interested reader.

To find an expression in growth rates, consider two periods, T and $T - Z$. In period T we observe $S(T)$ somewhere along its transition path towards the steady state S^*, and in period $T - Z$ we also observe an initial value of $S(T - Z)$. Using this information, evaluate (35) at T, subtract $S(T - Z)$, and divide the resulting difference by Z, to find:

$$\frac{\ln S(T) - \ln S(T - Z)}{Z} = -\frac{[1 - e^{-\lambda Z}]}{Z} \ln S(T - Z) + \frac{[1 - e^{-\lambda Z}]}{Z} \ln S^* \tag{36}$$

The left-hand side of equation (36) is the average log change in the resource stock between $T - Z$ and T. The right-hand side relates this change negatively to the initial stock size $S(T - Z)$ and positively to the eventual steady state S^*. This equation is similar to that used to justify conditional convergence style regressions often employed in empirical growth theory. In those applications, Z would typically be 20 or more years, and measures of income per capita would replace our measures of the resource stock.

IV.III.1 Method 1: Long Differences

One way to evaluate the implications of our theory is to use *long differences*. The benefits of a long difference approach are that it requires very little data, can capture trends in slow-moving stock variables, and may reduce the impact of measurement error made worse in higher frequency fixed effects analyses. As will become apparent, the cost of adopting this approach is more of the burden of identification falls on theory.

To proceed, set (32) to zero to solve for the steady state. The solution is a function of only three things. First, the steady state stock is a function of the ratio $\delta N/r$. If this ratio is greater than 1, the country has sufficient capacity to drive the resource to extinction. It is, therefore, a measure of overcapacity, and the steady state stock falls with increases in this measure. Second, the stock is falling in the ratio $p/\mathcal{R}(p, \chi)$ which is our shadow price. An increase in world prices drives the shadow price up, drives harvests up, and initiates a long-run reduction in the stock. Alternatively, holding prices constant, but increasing policy stringency via a salutary increase in χ lowers the shadow price, limits entry, lowers harvests and leads to stock rebuilding. Finally, the resource stock is increasing in its carrying capacity K. Increases in K imply growth rates are higher at any stock, and this generates stock rebuilding.

In most cases, an explicit solution for the steady state does not exist, and in *lieux* I assume lnS^*

can be written:[25]

$$\ln S^* = a_0 ln(\delta N/r) + a_1 ln(p/\mathcal{R}(p,\chi)) + a_2 ln K \tag{37}$$

To investigate the relationship using long differences, suppose we have data from several countries $j = 1, ...M$ for just two periods separated by a lengthy interval of Z periods. Over the interval Z, some countries have undertaken major trade liberalizations while others have liberalized trade very little or perhaps not at all. There is data on resource stocks, domestic prices, and other country characteristics from today's period T and the distant T-Z period. Let period T variables be denoted with a $'$, and assume the economy was in a steady state in the distant past, then we can substitute for both $S(T-Z)$ and S^* on the right-hand side of (36) to obtain:

$$\left(\frac{\ln(S'/S)}{Z}\right)_j = \beta_0 \ln\left(\frac{(\delta N/r)'}{(\delta N/r)}\right)_j + \beta_1 \ln\left(\frac{p'/\mathcal{R}(p',\chi)}{p/\mathcal{R}(p,\chi)}\right)_j + \beta_3 \ln\left(\frac{K'}{K}\right)_j + \epsilon_j \tag{38}$$

where the β_i coefficients are the product of their corresponding a_i from (37) with the common term $(1-e^{-\lambda Z})/Z$, and ϵ_j is an error term.[26].

Equation (38) is a simple long-differences regression model that captures the essence of our theory. For example, if habitat loss occurred over the period, $K'/K < 1$ and β_3 should be positive; growth in the economy's ability to take from nature is captured in the first term, telling us that such growth should lower stocks with $\beta_0 < 0$, etc. Finally, when domestic prices rise towards world prices with trade liberalization, we know $p'/\mathcal{R}(p',\chi) > p/\mathcal{R}(p,\chi)$. The shadow price of the harvest good rises with trade liberalization, and the resource stock should fall as a consequence.

[25] I am assuming $S^* = [\delta N/r]^{a_0}[p/\mathcal{R}(p,\chi)]^{a_1}K^{a_2}$. The interested reader can compare the properties of this approximate solution to the actual solution in our two limiting cases. For example, when $\gamma \to 2$, I find that the steady state stock is given by: $S^* = \left[\frac{1}{K} + \frac{\delta N}{r}\frac{p}{\mathcal{R}}\right]^{-1}$ which nicely identifies the three determinants mentioned above. Alternatively, in the original BT model with $\mathcal{R}(p) = 1$ everywhere, the equivalent expression when the economy is specialized is $S^* = K[1-\delta N/r]$, provided $p\alpha S^* > 1$, which is again similar to what I have assumed.

[26] The close reader will notice that β_i coefficients contain λ, which is an endogenous variable, and therefore, strictly speaking, the regression is non-linear. It is typical to ignore this complication in the growth econometrics literature, as I will here. For empirical guidance in this area, see the excellent Handbook chapter by Durlauf, Johnson and Temple (2005)

Going forward to estimation, we face two problems. The first is that χ is embedded in the policy functions. In a world with many countries and therefore many policy functions, we need to condition on the set of χ determinants. One straightforward solution is via an interaction so that the coefficient β_1 would represent the impact of trade liberalization on its resource stock for an ”average” country. This coefficient should be negative. The coefficient on an interaction of χ determinants with β_1 captures the impact of ”better” country characteristics on stock adjustment. If we measure χ so that higher values represent better governance and enforcement power, then a positive signed interaction coefficient suggests a smaller stock adjustment in countries that manage their resources well.[27]. This would be evidence that some economies in our sample operate like Ostrom or Clark economies, and we know that these economies typically gain from trade liberalization. In contrast, finding that the determinants of χ have no effect on stock depletion is consistent with a policy function that depends solely only on prices. It is strong evidence that harvesting decisions are governed exclusively by market opportunities; that the economy is currently in an open access regime; and that losses from trade may occur.

The second problem we face is finding exogenous variation in world prices that in turn drives changes in harvesting and stocks. Thus far I have associated this variation with trade liberalization, but there are many other possibilities. To be useful this variation has to be unrelated to the country's characteristics embedded in its policy function and unrelated to the other economic determinants in (38). While difficult, this is not impossible. For example, a change in world prices brought about by a unilateral trade liberalization undertaken by a very large third country excluded from the analysis would suffice. Another source of variation could be price changes created by wars, insurrections or natural disasters. Finally, and less spectacularly, improvements in transportation networks that are either binary - a canal opening or closing - or continuous - ongoing technological progress in shipping - would also affect domestic prices by making all trading economies more integrated with

[27] The idea that the environmental impact of trade liberalization depends on country characteristics is not new. It was for example, key to the identification strategy employed early on by Antweiler, Copeland and Taylor (2001). More recently it was employed in the resource and trade context by Erhardt (2018)

world markets.

An alternative to long differences is to exploit the built-in conditional convergence framework the model generates. If Z is very long, perhaps 30 or more years, then a long-differences specification has some appeal. But if Z is much shorter, say 10 or 20 years, then it becomes less likely that $S(T-Z)$ represents a steady state from the distant past. Instead $S(T-Z)$ may well be a point along the path to the steady state we are converging to today, and our assumption of a movement from one steady state to another might be a bridge too far.

IV.III.2 Method 2: Conditional Convergence

The benefit of rewriting the model's predictions in the form of standard conditional convergence specifications is that there exists a very large empirical literature to guide estimation.[28] Another benefit is that even less data is required to evaluate the simplest of these specifications.

To generate a conditional convergence specification, return to (36) and assume our initial observation S is not a steady state. In this case, use (37) to write a standard conditional convergence regression as:

$$\frac{\ln(S'/S)_j}{Z} = \beta_0 \ln S_j + \beta_1 \ln(\delta N/r)'_j + \beta_2 \ln(p'/\mathcal{R}(p',\chi))_j + \beta_3 \ln K'_j + \epsilon_j$$

where variables with a $'$ are those determining the new steady state the economy is converging towards. Here again we would need to condition the impact of prices on country attributes χ, as well as ensuring the variation in prices driving the change in steady states is exogenous to other determinants. The literature on estimating conditional convergence type relationships is both large and controversial, and includes many other techniques to investigate the underlying dynamic relationship. One very useful starting point to this large literature is Durlauf, Johnson and Temple (2005). A more recent worthwhile application is Durlauf, Johnson and Temple (2009).

[28] See for example, the Handbook chapter Durlauf, Johnson and Temple (2005)

IV.III.3 Method 3: Panel Estimation

If data is plentiful and the period between observations short, then a natural alternative is panel data estimation. We can think of each year (or each x year increment) in this panel as representing a movement from some S to S'. We could then stack a series of short run changes inspired by (36) across the time dimension to obtain a panel of observations for our j countries.

Given the frequency of the data, it would be natural to think of countries in terms of types. Limiting ourselves to countries which are resource good exporters, we could categorize countries into those where little or no trade liberalization took place during the sample period and those who experienced a major trade liberalization.[29] Under the strong assumption that these policy choices are randomly assigned conditional on other economic determinants, we can sort countries into treatment and control groups. Our previous use of conditioning to capture country specific responses would now be reflected in methods to estimate heterogeneous treatment effects. One way to make this idea precise is as follows:

$$\Delta S_{jt} = \beta_0 + \beta_1 D_{jt} + \beta_2 \chi_j D_{jt} + \pi_j + \pi_t + \epsilon_{jt} \tag{39}$$

where ΔS_{jt}, the log change in the resource stock over a small increment of time, is related to a country specific fixed effects, π_j, a common to all countries time effect, π_t, treatment variables reflecting policy changes, D_{jt}, and an error term. In the simplest specification, D_{jt} would be a binary treatment equalling 1 over periods of trade liberalization in country j in year t and zero otherwise. To capture heterogenoue effects across countries, χ_j would need to reflect primitive differences across countries in their political/governance/legal characteristics specific to country j that affect their policy responsiveness function. If these primitives are very slow-moving and perhaps constant over the period, then their level effects are swept into the country-specific π_j.

[29] If our sample includes exporters and importers, then we need to account for this difference in our estimation. Trade liberalization should raise the relative price for an exporter, but lower it for an importer. This can be dealt with mechanically via a further set of interactions, or by using theory to predict importers and exporters on the basis of their fundamentals. See Antweiler, Copeland and Taylor (2001) for an example using the latter approach.

Common shocks to world prices or transport options would be captured by π_t.

In this simple set up, the coefficient β_1 captures the average effect of trade liberalization on a resource exporter. This should be negative. The product $\beta_2\chi_j$ would measure the heterogeneous impact of trade liberalization on countries that differ in their specific characteristics χ_j. A finding that $\beta_2 = 0$ suggests treated economies are all Hardin - which of course carries with it the potential for negative welfare impacts from trade liberalization. Alternatively, a finding of $\beta_1 > 0$ is consistent with the treated economies being Ostrom or Clark economies which respond less aggressively to the trade liberalization and are likely to gain from it.[30]

This simple specification of course ignores several real complications. The binary treatment treats all liberalizations alike, when countries must differ in the depth of their liberalizations. It implicitly assumes all impacts are captured in one period, rather than spread out over time as it might be in an alternative Event Study formulation. And I have limited my example here to resource exporters with data available on resource stocks rather than harvests. None of these limitations are fatal, in fact very little of any generality can be said about appropriate methods without knowledge of the specific context, data availability, and precise research question being asked. My purpose here was to demonstrate how three very simple empirical techniques - long differences, conditional convergence, and difference-in-difference - are potentially useful methods for evaluating the impact of trade liberalization on resource use and country welfare within the BT Redux framework.

V Conclusion

This paper generalized the canonical Brander-Taylor model of open-access resource use and trade to address three critiques which limited its usefulness for policy guidance and empirical investigation.

First, I showed how introducing heterogeneity across agents in their harvesting productivity eliminated the model's extreme specialization patterns while maintaining its simple Ricardian struc-

[30] Erhardt (2018) employs a method very much like this to find countries vary in the impact of trade liberalization depending on their country specific attributes.

ture. Apart from its modeling benefit, heterogeneity across agents creates inframarginal rents that differ across agents even under open access. These differential rents are a common feature in many resource industries, and often lead to conflict over changes in trade and resource policy.

Second, I moved beyond open access to introduce a policy stringency function that allows for endogenous changes in resource policy. This function together with world prices determines output decisions in our small open economy. Under open access, a change in world prices is transmitted directly to producers; with a policy stringency function in place, endogenous changes in resource policy temper these output responses.

Third, using the continuity generated by the heterogeneous responses of agents and the insights provided by policy stringency function approach, I showed how the model's core predictions could be evaluated using empirical methods. The key insight is that differences across countries in their policy stringency functions, which are linked to their varying ability to monitor resource harvesters and credibly enforce regulations, determine whether any given trade liberalization is likely to lead to welfare gains. I presented three very simple empirical methods for evaluating this relationship, but many others are possible.

VI Appendix: Lengthy Calculations

VI.I National Income & Rents

Income is equal to the value of final output at world prices: $p_H H + p_M M = p_H H + wT(\alpha^*)N = p_H H - w[1 - T(\alpha^*)]N + wN$, which is just resource rents plus the value of wage income. If we divide this by p_H to put rents in terms of the harvest good, and substitute in the components of rents under open access using the notation of Figure 6 we obtain:

$$I = \frac{N}{p} + \ell_O \left(AR^O - AC^O\right) \tag{40}$$

At the open access level of effort, average revenues equal marginal costs. This implies:

$$I = \frac{N}{p} + \ell_O \left(MC^O - AC^O\right) \tag{41}$$

$$I = \frac{N}{p} + \ell_O \left(AC^O \left(\frac{MC^O}{AC^O} - 1\right)\right) \tag{42}$$

Substituting out for average costs and exploiting the fact that marginal costs are just a fixed multiple of average costs yields:

$$I = \frac{N}{p} + \frac{1}{p\alpha_O^*}\left(\frac{\gamma - 1}{\gamma}\right)\left(\frac{\gamma}{\gamma - 1} - 1\right)\ell_O \tag{43}$$

$$I = \frac{N}{p} + \frac{1}{p}\left(1 - \frac{\gamma - 1}{\gamma}\right)\frac{\ell_O}{\alpha_O^*} \tag{44}$$

Using the definition of effective labor and rearranging yields economy wide income in terms of the harvest good:

$$I = \frac{N}{p} + \frac{L_H^O}{p}\left(\frac{1}{\gamma - 1}\right) \tag{45}$$

If we multiply this by p we get income in terms of the manufacturing good which is simply: $N + L_H^O[1/[\gamma - 1]]$.

VI.II Cost Curve Calculations

Substituting in for α with an expression directly involving ℓ, total costs can be written as:

$$
\begin{aligned}
TC &= (\frac{\gamma - 1}{\gamma})(\frac{1}{p})\left(\frac{1}{\delta N}\right)^{\frac{1}{\gamma-1}} \ell^{\frac{\gamma}{\gamma-1}} \\
MC &= (\frac{1}{p})\left(\frac{\ell}{\delta N}\right)^{\frac{1}{\gamma-1}} \\
AC &= (\frac{\gamma - 1}{\gamma})(\frac{1}{p})\left(\frac{\ell}{\delta N}\right)^{\frac{1}{\gamma-1}} \\
\varepsilon_{MC} &= \frac{1}{\gamma - 1} \\
\varepsilon_{AC} &= \frac{1}{\gamma - 1}
\end{aligned}
$$

VI.III The elasticity of $\mathcal{R}(p)$ is < 1

Use the definition of $\mathcal{R}$ to rewrite its elasticity in terms of the elasticities of the different cut-off productivities.

$$
\begin{aligned}
\mathcal{R}(p) &= \frac{\alpha_B^*(p)}{\alpha_O(p)} \\
\mathcal{R}'(p) &= \left(\frac{\alpha_B^*(p)}{\alpha_O(p)}\right)\left(\frac{\alpha_B^{*'}(p)}{\alpha_B^*(p)} - \frac{\alpha_O'(p)}{\alpha_O(p)}\right) \\
\frac{\mathcal{R}'(p)p}{\mathcal{R}(p)} &= \frac{\alpha_B^{*'}(p)p}{\alpha_B^*(p)} - \frac{\alpha_O'(p)p}{\alpha_O(p)}
\end{aligned}
$$

Transform the cut-off elasticities into labor choice elasticities using their relationship.

$$
\varepsilon_{\mathcal{R}p} = \varepsilon_{\alpha_B^* p} - \varepsilon_{\alpha_O p} = \frac{1}{1-\gamma}\left(\varepsilon_{\ell_B p} - \varepsilon_{\ell_O p}\right)
$$

Recall how these labor allocations are determined, to solve for their responsiveness to price changes. Start by recalling.

$$\frac{1}{p\alpha_O^*} = MC(\ell_O) = AR(\ell_O)$$
$$\frac{1}{p\alpha_B^*} = MC(\ell_B) = MR(\ell_B)$$

Using the relationship between cut-off productivities and labor, these can be simplified to the following where $a = (\delta N)^{\frac{1}{1-\delta}}$:

$$a\ell_O^{\frac{1}{\gamma-1}} = pAR(\ell_O)$$
$$a\ell_B^{\frac{1}{\gamma-1}} = pMR(\ell_B)$$

If we totally differentiate both sides, and let $\hat{\ell_O} = \frac{d\ell_O}{\ell_O}$ and $\hat{p} = \frac{dp}{p}$, and rearrange we can solve for the elasticities of these labor choices to prices. Both cases are similar in form. In the open access case this produces, in particular, that:

$$\frac{1}{\gamma-1}\hat{\ell_O} = \hat{p} + \varepsilon_{AR}\hat{\ell_O}$$
$$\hat{p} = \left(\frac{1}{\gamma-1} - \varepsilon_{AR}\right)\hat{\ell_O}$$

The other case is similar, which implies we need to substitute for the elasticities of AR and MR which are easily found to be:

$$\varepsilon_{AR} = \frac{AR'(\ell_O)}{AR}\ell_O = -\left(\frac{K}{r}\right)\frac{\ell_O}{AR} < 0$$
$$\varepsilon_{MR} = \frac{MR'(\ell_B)}{MR}\ell_B = -\left(\frac{2K}{r}\right)\frac{\ell_B}{MR} < 0$$

Substituting in for the elasticities of AR and MR, we find:

$$\varepsilon_{\ell_O p} = \frac{\hat{\ell_O}}{\hat{p}} = \frac{1}{\left(\frac{1}{\gamma-1} - \varepsilon_{AR}\right)} = \frac{\gamma - 1}{1 - (\gamma - 1)\varepsilon_{AR}}$$

$$\varepsilon_{\ell_B p} = \frac{\hat{\ell_B}}{\hat{p}} = \frac{1}{\left(\frac{1}{\gamma-1} - \varepsilon_{MR}\right)} = \frac{\gamma - 1}{1 - (\gamma - 1)\varepsilon_{MR}}$$

Which then implies:

$$\begin{aligned}\varepsilon_{\mathcal{R}p} &= \frac{1}{1-\gamma}\left(\varepsilon_{\ell_B p} - \varepsilon_{\ell_O p}\right) \\ &= \left(\frac{1}{1 - (\gamma - 1)\varepsilon_{MR}} - \frac{1}{1 - (\gamma - 1)\varepsilon_{AR}}\right) < 1\end{aligned}$$

where the last inequality follows from simplifying $\left(\frac{1}{1-(\gamma-1)\varepsilon_{MR}} - \frac{1}{1-(\gamma-1)\varepsilon_{AR}}\right)$ to find it is less than 1 provided $(\gamma - 1)\varepsilon_{MR}\left(2 - (\gamma - 1)\varepsilon_{AR}\right) - 1 < 0$, which is true because $\varepsilon_{AR} < 0$ and $\varepsilon_{MR} < 0$.

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