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Abstract. This paper provides a micro foundation for analyzing the relationship between environmental quality and income, by stressing the importance of property rights. The existing literature is prominently represented by the studies on Environmental Kuznets Curve (EKC) and has not examined the manner in which property rights shape the relationship between environmental quality and income. The empirical literature on EKC has typically analyzed the effect of economic growth represented by per capita income on environmental quality represented by air and water pollution. The assumption of exogenously given or perfect enforcement of property rights and use of inadequate definitions of income and environmental quality for mapping their relationship are two of the main limitations of this literature this paper addresses. We develop a model in which property rights to a natural resource stock evolve from a state of open access to more efficient property regime as the price of the resource increases. In our framework, environmental quality is synonymous with the size of the resource stock (stock of clean air and water, groundwater aquifer, stock of trees in a forest, oil reserve in an oil pool) and resource rent is synonymous with income derived from the resource. We show that the relationship between environmental quality and resource rent can evolve in various ways and under certain specific conditions it can also follow a U-shape that is consistent with the EKC. Thus the paper provides an alternative theoretical explanation for EKC based on evolution of property rights without relying on macro growth theory models. We test the model implications using historical case studies of various natural resources.

JEL Codes: Q20, Q50, D23, N50, O13.

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I. Introduction

The relationship between economic growth and environmental quality has become one of contemporary societies' major global concerns, yet it is a relationship is not well understood. The literature on economic growth and environmental change is prominently represented by the Environmental Kuznets Curve (EKC) hypothesis that emerged as a result of the studies by Grossman and Krueger (1991) and Shafik and Bandyopadhyay (1992). The EKC hypothesis asserts a U-shaped relationship between environmental quality and per capita income (or an inverted U-shape with respect to environmental degradation). It is based on the conjecture that during the initial phases of economic development, environmental quality (EQ) deteriorates with rising per capita income (Y) but in the later phases of economic development, after a certain critical level of per capita income is achieved the demand for better environmental quality leads to rise in EQ. The EKC hypothesis led to a surge of empirical studies (see Panayotou, 2000, p.84-91, for a representative summary) as well as some theoretical studies (see for example, Lopez, 1994; Seldon and Song, 1995; Andreoni and Levinson, 2001; Dinda, 2005) that both attempted to test the hypothesis and rationalize the phenomenon. The focus of these studies was mostly on pollution (air and water).

The initial optimism about the EKC as the 'answer' to the question of how environmental degradation is related to economic growth has given way to skepticism about the EKC on both empirical and theoretical grounds. The earlier empirical findings in support of the EKC are now found to be not robust across time, space and different aspects of environmental quality. And the theoretical models focusing on just air pollution abatement technologies to rationalize the phenomenon cannot clearly explain the EKC in the context of all other aspects of environmental quality. Stern (2004) catalogs several limitations of the empirical as well as the theoretical frameworks used by the studies on EKC. Yet there remain several other limitations that can be addressed to improve our understanding of the *EQ-Y* relationship.

In this paper, we use a resource stock level micro-economic framework to analyze the relationship between resource rents, resource stocks and property rights. In our framework resource stock is synonymous with *EQ* and resource rent is synonymous with *Y*. Our framework thus examines the same issue as the EKC, namely the *EQ-Y* relationship. From our vantage point, both *EQ* (resource stock) and *Y* (resource rent) are highly intertwined with property rights, hence the model accounts for the role of an important institutional (property rights) structure in shaping the *EQ-Y* relationship. Our analysis carefully defines the relevant *EQ* and *Y* at a micro-level and since we use resource stock as a measure of *EQ*, it makes our model framework applicable to various aspects of environmental quality rather than just pollution, which has been the main focus of the EKC literature. We show that there can be several alternative forms of the *EQ-Y* relationship and only under very specific set of model assumptions will a U-shaped *EQ-Y* relationship emerge that is consistent with EKC. Thus our model provides an alternative explanation for the EKC based on property rights evolution and rationalizes a broader set of *EQ-Y* relationship patterns. We use this basic single resource framework to demonstrate that at an aggregated level, which can be represented by a nation with multiple resources, the likelihood of observing an EKC goes down even further.

Our framework addresses two main limitations of the EKC literature. First, we carefully define the appropriate measures of *EQ* and *Y* for better understanding of their relationship. Our measures of *EQ* (resource stock) and *Y* (resource rent) can be applied for a wide range of definitions of environmental quality including renewable and non-renewable resources. Indeed, simply defining the *EQ* and *Y* this way broadens the applicability of the model framework.

Second, the model provides an alternative, property rights based, explanation for the EKC, an aspect that has been ignored in the existing EKC literature. Our model framework also rationalizes a wide range of patterns of the *EQ-Y* relationship and thereby explains why EKC is not a universal regularity. The importance of addressing these issues for analyzing the *EQ-Y* relationship is elaborated below.

The EKC literature has ignored the role of property rights or at best assumes that property rights are exogenously given, are well defined, or both[1]. At a first glance, property rights may appear to be disconnected from the *EQ-Y* relationship analyzed by the EKC literature typically in a macro framework. Yet, it is well established that property rights influence the use and stocks size of natural resources (Gordon, 1954; Scott, 1955; Coase, 1960; Demsetz,1967; Libecap 1989; Bohn & Deacon, 2000). Since resource stocks like clean air, groundwater aquifers, trees in a forest, are, in fact, measures of environmental quality, it follows that property rights should have a significant impact on environmental quality. Property rights also play a crucial role in determining the rents obtained from a natural resource as property rights shape the incentive structure for resource extraction and investment. Hence property rights do affect the measures of *Y* as well. Even if one considers the aggregated national income, property rights affect that *Y*, as a nation's income is derived from its resource base, be it land, minerals, flora and fauna or human resources[2]. Hence in a world where property rights regimes of natural resources evolve over time in response to economic changes, assuming away the role of such an institutional change or assuming it to be exogenously given and constant can hinder adequate understanding of the *EQ-Y* relationship.

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[1] An exception to this is Copeland and Taylor (2004) who examine the role of property rights in a trade model. In contrast to their macro approach, our model provides a micro-foundation for analyzing the role of property rights in shaping EQ-Y.

[2] The effect of property rights on national income derived from a set of resources rather than one single resource is bound to be more complex. We provide one potential way to assess that impact in section III.

It is worth noting that while the relationship between property rights and *EQ* has largely been ignored in the EKC literature; two recent studies have taken into account the role of property rights in influencing the *EQ*, and are thus related to our study. Birdyshaw and Ellis (2005), using a dynamic model of resource exploitation, show that the *EQ* can evolve along a U-shaped path over time, with endogenous change in property rights from common property regime to increasingly private property regime and the evolution is independent of consumer preferences and production technology. Compared to Birdyshaw and Ellis, we not only provide a broader range of evolution paths of *EQ* over time, but we also analyze the EQ-Y relationship. Additionally, we show that production technology (capital intensity) can play a vital role in shaping the temporal path of *EQ*. Copeland and Taylor (2004) provide a macro-trade framework, which depicts that country specific characteristics can explain the heterogeneity in institutional outcomes, namely, property rights. They highlight the impact of open trade on resource valuation and institutional changes in a country. In contrast to their macro approach, we provide a micro foundation to explain the heterogeneity in the evolutionary paths of environmental quality and income from a resource, based on evolution pattern of property rights.

In addition to the lack of attention to property rights, there are several measurement issues in the EKC literature that warrant closer examination. The empirical EKC studies have mostly analyzed the effect of economic growth, represented by per capita GDP of a country (highly aggregated measure of *Y*), on a specific aspect of environmental quality, *EQ* (see for example, Shafik and Bandyopadhyay, 1992; Grossman and Krueger, 1995; Selden and Song, 1995). The typical focus is on air quality measured by concentration of chemicals like sulfur dioxide or nitrogen oxide. A random selection of an empirical EKC study is likely to depict a regression of an air pollution measure (based on certain monitoring points) on national per capita

GDP and the squared per capita GDP. The use of aggregated national income for analyzing its relationship with a specific measure of environmental quality has several limitations. First, the pollution levels measured at limited number of monitoring centers of a country are not adequate to infer about the environmental quality of a country as a whole. There can be tremendous spatial variations in the measure of environmental quality that cannot be represented by a few specific monitoring centers that are typically located in large urban centers. Second, national economic growth as represented by per capita GDP is an aggregate measure of income derived from many different resources of the country including natural resources. The national economic growth may not have any effect or have non-uniform effects on use of different types of natural resources and at different locations. These problems arise due to spatial inequalities in economic growth, institutional structures and natural resource endowments, and the distribution of the sources of income (for example, natural resources, human capital) within a nation-state. In the light of these problems, inferences about the *EQ-Y* relationship based on the above described aggregated approach of the empirical EKC studies may be very misleading.

We argue instead that the 'local' economic and institutional factors have the strongest effects on the resource use and the resulting environmental quality. In other words, the income from a specific natural resource for the users whose resource use decisions determines the stock of the resource is the most appropriate level of (dis)aggregation for such an analysis. We recognize that the appropriate level of aggregation depends on the nature of a resource and the institutional structure[3]. For example, the 'local' agents affecting the stock of trees in a forested area under common property regime in a rural area of a developing country might be appropriately represented by the villagers who manage the resource. In the case of the stock of

[3] We acknowledge that in some cases there can be interdependencies in resource extraction that can warrant analysis by aggregating multiple resource stocks and rents. Our micro framework provides the foundation for such analysis as is depicted in section III.

trees in a privately owned forest, the individual owner of the forest will be the appropriate level of analysis. Or in the case of flow of clean water in an open access river, all the users of the water resources (which might span large regions and populations) will represent the set of 'local' agents. Hence the measure of *EQ* and *Y* should be constructed with caution. Our model provides a micro-foundation for analyzing the *EQ-Y* relationship based on evolution of property rights and the above-mentioned definition of local agents and institutions.

II. Models of Environmental Quality (*EQ*) and Income (*Y*)

In this section we develop a framework to examine the relationship between environmental quality (*EQ*) and income *(Y*) derived from the resource. This micro-framework focuses on a specific resource and the extraction behavior of the local resource users.[4] We equate environmental quality (*EQ*) with the size of the resource stock (*s*) and equate income (*Y*) with the rent obtained from the resource extraction (*r*). The stock could be water in an aquifer, trees in a forest, oil and gas in a hydrocarbon reservoir, clean air in an air shed, or a wildlife population. The resource use (*x)* decisions of local agents with access to the resource, determine the stock of a resource (*s*). We assume that the value of the resource (or the products derived from the resource) evolves over time exogenously. The value of a resource can be the market price in case of a marketable resource like fish or oil. In case of a non-marketable resource, like watershed and forest, the value of the resource is determined by the market price of the marketable output it helps in producing or as the shadow value of the existence of the stock. We assume that the resource-extracting agents in our model have access to the local resource only and cannot

[4] Our case can be viewed as a macro model in which there is a small open economy in which all income is derived from a single natural resource.

influence the national or world prices of the resource or the prices of the output for which the resource is an input.

A. Evolution of Property Rights

The evolution of property rights to natural resources stocks have been shown to depend on the value of the resource and its implied outputs and the cost of establishment and enforcement of potentially 'more efficient' regimes (Demsetz, 1967; Anderson and Hill 1975, Umbeck 1977). According to Demsetz (1967), as a resource (or its output) gets more valuable, it generates incentive to establish a more well-defined property rights regime for the resource. However, even with rising valuation of a resource, property rights may not evolve towards more efficient regimes if the cost of transition to a new property rights regime outweighs the benefits.[5] Factors like number and heterogeneity of agents can increase the costs significantly enough to delay or completely deter change in a property rights regime.

We consider two broad patterns of evolution of property rights. The first evolution path is based on the Demsetz' (1967) theory that property rights evolve toward more efficient regimes as the value of a resource increases. We assume that the value of a resource in our model is rising over time. Hence, we expect the property rights evolution to be an increasing monotonic function of resource value. We have labeled this property-rights evolution pattern as monotonic.

The second property rights evolution path could emerge if an increasing resource price increases the establishment and enforcement costs of more well-defined property rights (Umbeck, 1977). In this case the costs can outweigh the potential benefits of transition to a new property rights regime, so there is no longer a monotonic relationship between resource valuation and property. We have labeled this evolution pattern as non-monotonic, where property rights do

[5] Lueck and Miceli (2007) discuss the development of this literature.

not move towards more well-defined regimes even in the face of rising resource values due to high costs of transition or enforcement.[6]

We utilize the above-mentioned property rights evolution patterns to trace out the relationship between environmental quality (*EQ*) and income from the resource (*Y*)[7]. In analyzing the impact of change in property rights on resource use and resource rent, we borrow results from the existing literature that under open access regime rents from a resource is completely dissipated while under the ideal private property regime, the first best rent maximization outcome is achieved (Scott 1955, Clark 1990).

Under any property right regime, the objective of a resource extracting agent is to maximize their own rent, $r = p\, f(l) - wl$ where r denotes individual rent, p is the price of the output of the resource, l is the input (labor), w is the market price of the input (wage) and $f()$ is the production function. Note that the price of the resource output, p, enters as an exogenous parameter in the rent function in our model. In the optimization framework, the constraints vary according to the nature of the resource and the property rights regime. Note that in our model framework the resource rent (r) is synonymous with income (*Y*).

Following traditional works like Gordon (1954) and Cheung (1970), under open access regime, if n individuals are exploiting a resource, then each individual solves the following optimization problem: $\max_{l_i} r_i = pf^i(l_i) - w_i l_i$ subject to $f^i = \left[l_i / \sum_{i=1}^{n} l_i \right] f\left(\sum_{i=1}^{n} l_i \right)$ where, l_i denotes the effort put in by individual i in resource extraction, w_i is the market wage

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[6] Political forces are often attributed to hindering institutional changes (Libecap 1989, Lueck and Miceli 2007). The heterogeneity of the agents can also be interpreted as different interest groups, which can exercise their political influence to further their self interest as is reflected by the usual clash of political interests of different groups for bringing about any institutional change. Hence heterogeneity of agents can account for this feature as well.

[7] Our measure of income, *Y,* is synonymous with the resource rent from a resource, in contrast to the aggregated measure of per capita income of a country that is used by the empirical EKC literature. The national income is derived from a large set of resources and the EKC literature uses it to analyze its effect on a specific resource (air or water pollution). We our micro-framework the resource rent, *r*, drives the resource use and stock rather than the national income.

(opportunity cost of effort), $f\left(\sum_{i=1}^{n} l_i\right)$ is the total output from the resource, $f'(.)>0$ and $f''(.)>0$. If all the agents are homogenous ($w_i = w_j$ for all $i \neq j$), the Nash open access equilibrium, $l = l^{oa}(n, w_1, ..., w_n)$, satisfies the first order condition:

(1) $\left(n-1/n\right)\left(f\left(\sum_{i=1}^{n} l_i\right) / \sum_{i=1}^{n} l_i\right) = \left(1/n\right) f' \sum_{i=1}^{n} l_i = w_i / p_i$, i=1,…,n.

As $n \longrightarrow \infty$, the above condition becomes $\left(f\left(\sum_{i=1}^{n} l_i\right) / \sum_{i=1}^{n} l_i\right) = w$, which implies complete rent dissipation as $\sum_{i=1}^{n} r_i = \sum_{i=1}^{n}\left[f^i\left(l^{oa}\right) - wl^{oa}\right] = 0$. Note that the total amount of resource extracted, x, is a result of the total effort, $\sum_{i=1}^{n} l_i$, put in by the agents determines the stock of the resource, s.

The above result of complete rent dissipation is based on the assumption of homogeneous agents. If agents are heterogeneous ($w_i \neq w_j$ for $i \neq j$), then the more efficient agents can earn positive rents and the rent dissipation is incomplete (Libecap, 1989). In contrast, private property rights regime bestows the ownership of a resource to an individual agent that provides incentive for optimal resource use, resource maintenance and investment. In this case the agent solves the following optimization problem: $\max_{l_i} r_i = f^i(l_i) - w_i l_i$ and obtains the first best outcome $l^* < l^{oa}$ and $r^* > r^{oa} = 0$.

The nature of the resource, renewable or non-renewable imposes different types of constraint for dynamic optimization. In case of renewable resource the constraint is in the form of natural growth function of the resource (Gordon-Schaeffer model for fisheries is a classic model framework). While in case of a non-renewable resource, the available initial stock imposes the constraint (Conrad and Clark, 1987).

We represent the equilibrium level of resource use under open access regime as x^{oa} that leads to complete dissipation of rent. We represent the corresponding level of resource stock as s^{oa}. Similarly, under an efficient property rights regime (private property regime or efficiently managed common property or state ownership regime) the resource use that corresponds to the optimal outcome from the rent maximization exercise is represented in our model as x^* and the associated level of resource stock and rent is represented as s^* and r^* respectively.

B. Model Framework

We use a simple three period model to analyze the relationship between resource stock (*EQ*) and resource rent (*Y*) and also the temporal paths of these two outcomes variables. In period 0, the resource is unexplored. Let the unexplored resource stock be s^u. In period 1, the resource is discovered and is accessible as an open access resource. The resource extraction under open access regime results in resource rent and resource stock of r^{oa} and s^{oa}. In period 2, in case of the monotonic pattern of property rights evolution, more efficient (secure) property rights are established for the resource. The resource extraction under the efficient property rights regime provides the rent, r^*, and results in a stock of s^*. However in the non-monotonic case, property rights remain in the open access regime even in period 2. To simplify our model we use discrete time periods of equal lengths for each regime[8]. The time period under each regime is most likely to be unequal in the real world and the time periods can be translated into months, years, decades or centuries depending upon the context.

In addition to making distinctions about the property rights regime, we account for the characteristics of resource (renewable vs. non-renewable), the nature of agents under open access regime (homogenous vs. heterogeneous skills/costs in resource extraction) and the resource extraction technology (labor intensive vs. capital intensive), which can play a vital role in

[8] This is a simplifying assumption that does not alter the analysis.

shaping the *EQ-Y* relationship. The distinguishing impacts of the three sets of characteristics are described below.

Renewable vs. non-renewable resource: In case of renewable resources (such as forests, fisheries, water and air[9]) the natural replenishment of the resource can allow the stock of a resource to increase under more efficient property regime due to lower extraction rates relative to open access regime[10]. In contrast, the stock of non-renewable resource (like oil, coal and other minerals, rock formations) keeps declining over time with use, as there is no natural growth of the resource. Hence the size of resource stock, our measure of *EQ*, can never increase for a non-renewable resource[11], while *EQ* for a renewable resource can improve over time. It is also true that most resource stocks that would be considered as generating environmental quality are renewable resources[12], though scenic views and geological formations (such as the Grand Canyon) are largely nonrenewable.

The nature of agents: The distribution of the resource extraction skills of the agents under open access regime is an important determinant of the stock size, or level of environmental quality. In the case of agents with homogenous resource extraction skills the resource rents are driven to zero, as is depicted by the classic open access problem. Alternatively, in the case of agents with heterogeneous resource extraction skills, positive rents ($r^{oa} > 0$) can accrue under open access regime due to higher innate resource extraction abilities of the highly skilled agents (Libecap 1989).

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[9] Stocks of water and clean air are renewable though they do not have a biological growth.
[10] Renewable resources can also be driven to extinction if the open access regime persists.
[11] We recognize that even some of the mineral resources like coal and oil that are labeled as non-renewable can be replenished if we consider a time frame of several thousand years. For practical purposes we usually focus only on frequently observable replenishments, like within an annual time frame, for making the distinction between renewable and non-renewable resources.
[12] The idea of existence value is predominantly applied to renewable resource stocks, though there is no reason why it could not be applied to nonrenewable resources such as coal and oil.

Heterogeneity of agents can also increase the costs of a transition from open access to more well-defined property regimes. The contracting process for establishing more efficient property regime can get delayed or become completely impossible due to heterogeneity of agents (Libecap, 1989). As a result even with increasing price of a resource, the property right regimes may not move towards the more efficient ones. Hence heterogeneity of agents can lead to what we have termed as non-Monotonic evolution of property rights.

Resource extraction technology: The traditional analysis of rent dissipation under open access regime (Gordon 1954, Cheung 1970) relies on the implicit assumption that the resource extraction technology is labor intensive, where agents can extract the resource without committing to capital investments.[13] In case of capital-intensive resource extraction technology, significant upfront investment is required (for example, large scale logging, and crude oil extraction). Usually in case of capital-intensive production processes, there is a lag between the investment in capital and the actual production. If capital is required for extracting an open access resource there is no payoff from the investment as the resource rents are driven to zero, hence it dampens the incentive for individual agents to invest (Bohn and Deacon, 2000; Lueck and Miceli, 2007).[14] Hence with capital-intensive extraction process, under open access regime, the resource can remain under exploited or even unexploited due to no or sub-optimal investment. If the resource remains unexploited, it will imply $s^{oa} = s^{u}$ and $r^{oa} = 0$. The nature of agents (homogeneity or heterogeneity in resource extraction capabilities) does not affect the resource use or rent in this scenario, as we assume that there is no incentive to invest for any type

[13] To be more precise, the implicit assumption in the standard model is that production is instantaneous with the application of labor effort.

[14] Bohn and Deacon (2000) portray the investment problem arising due to insecure property rights that arises because of positive probability of government expropriation of the resource and/or the capital. Even in the absence of risk of expropriation, the open access regime does create disincentive for investment in capital-intensive production process.

of agent under open access regime. Investment and resource extraction occurs under the more efficient property regime that leads to decline of the resource stock to s^* and generate optimal rents r^*.

Under-utilization of resource and under-investment can occur not only because of insecure property rights (Bohn and Deacon, 2000), it can also arise in case of 'anti-commons', a property rights regime where a resource is owned by multiple agents and permission or agreement is required from each agent for the resource use (Buchanan and Yoon, 2000; Heller, 1998). As the number of owners increases the cost of achieving unanimous agreement (for permission) increases. The increased cost results in under-utilization and under-investment in the resource. Transition from anti-commons (multiple owners) regime to single owner property regime will lead to the same pattern of relationship between resource stock and resource rent (see Figures 1 and 2, models R4 or NR4).

Below we derive the temporal *EQ-Y* relationships from various combinations of the resource characteristics, agent skill distributions, production characteristics, and property rights evolution paths. We assume that extraction technology and nature of agents remain the same over time.[15] Tables 1 and 2 summarize all the cases that we examine, which arise due to different combinations of the resource, agent, production and property rights evolution characteristics. For all models we assume that the price of the output of the resource is rising over time[16].

For each of these models, the resource stock and rent outcomes in each period are derived based on the established results in the literature and the analysis of the impact of the different

[15] In the real world, technological innovations are constantly changing the extraction processes leading toward more capital-intensive technologies. Also, natural population growth and migration are changing the composition of resource extracting agents. For analyzing such a case where these characteristics have changed, one can still utilize our framework to analyze the *EQ-Y* relationship by switching to the appropriate sub-case by appropriately assigning the structural breaks to demarcate the structurally different time frames.

[16] We have focused on one specific pattern of price path where price is rising over time. The price of the resource might evolve differently than $p(t)$, $p' > 0$ that can have different effect on the *EQ-Y* relationship. Indeed with a non-monotonic path of prices, then EQ-Y relationship could take on any shape.

characteristics put forward in the model framework above. An exhaustive description of the derivation of these results and graphical representation of the *EQ* time path, *Y* time path and the *EQ*-*Y* relationships are provided in the appendix.

Table 1 - Model Structures and *EQ,Y* Evolution for Renewable Resources

Model	*Production technique*	*Nature of agents under open access regime*	*Evolution of Property Rights*	*Resource Stock Evolution*	*Resource Rent Evolution*
R1	Labor Intensive extraction	Homogenous	Monotonic	$s^1 = s^{oa}$ $s^2 = s^*$	$r^1=0$ $r^2=r^*$
R2	Labor Intensive extraction	Heterogeneous	Monotonic	$s^1 = s^{oa}$ $s^2 = s^*$	$r^*>r^1>0$ $r^2=r^*$
R3	Labor Intensive extraction	Heterogeneous	Non-Monotonic	$s^1=s^{oa}=s^2$	$r^*>r^1=r^2>0$
R4	Capital Intensive extraction	Homogenous / Heterogeneous	Monotonic	$s^1 = s^u$ $s^2 = s^*$	$r^1=0$ $r^2=r^*$
R5	Capital Intensive extraction	Homogenous / Heterogeneous	Non-Monotonic	$s^1 = s^u$ $s^2 = s^u$	$r^1=0$ $r^2=0$

Table 2 - Model Structures and *EQ,Y* Evolution for Non-Renewable Resources

Model	*Production technique*	*Nature of agents under open access regime*	*Evolution of Property Rights*	*Resource Stock Evolution*	*Resource Rent Evolution*
NR1	Labor Intensive extraction	Homogenous	Monotonic	$s^1 = s^{oa}$ $s^2 = s^*$	$r^1=0$ $r^2=r^*$
NR2	Labor Intensive extraction	Heterogeneous	Monotonic	$s^1 = s^{oa}$ $s^2 = s^*$	$r^*>r^1>0$ $r^2=r^*$
NR3	Labor Intensive extraction	Heterogeneous	Non-Monotonic	$s^1 = s^{oa}$ $s^2 < s^1$	$r^*>r^1=r^2>0$
NR4	Capital Intensive extraction	Homogenous / Heterogeneous	Monotonic	$s^1 = s^u$ $s^2 = s^*$	$r^1=0$ $r^2=r^*$
NR5	Capital Intensive extraction	Homogenous / Heterogeneous	Non-Monotonic	$s^1 = s^u$ $s^2 = s^u$	$r^1=0$ $r^2=0$

A graphical summary of the *EQ-Y* relationships under the different model structures is presented in the figures below. We have not presented the graphical results for the models R5 and NR5, the models with capital-intensive extraction and non-monotonic property rights evolution because there is no change in *EQ* and *Y* over time in these cases for both renewable and non-renewable.

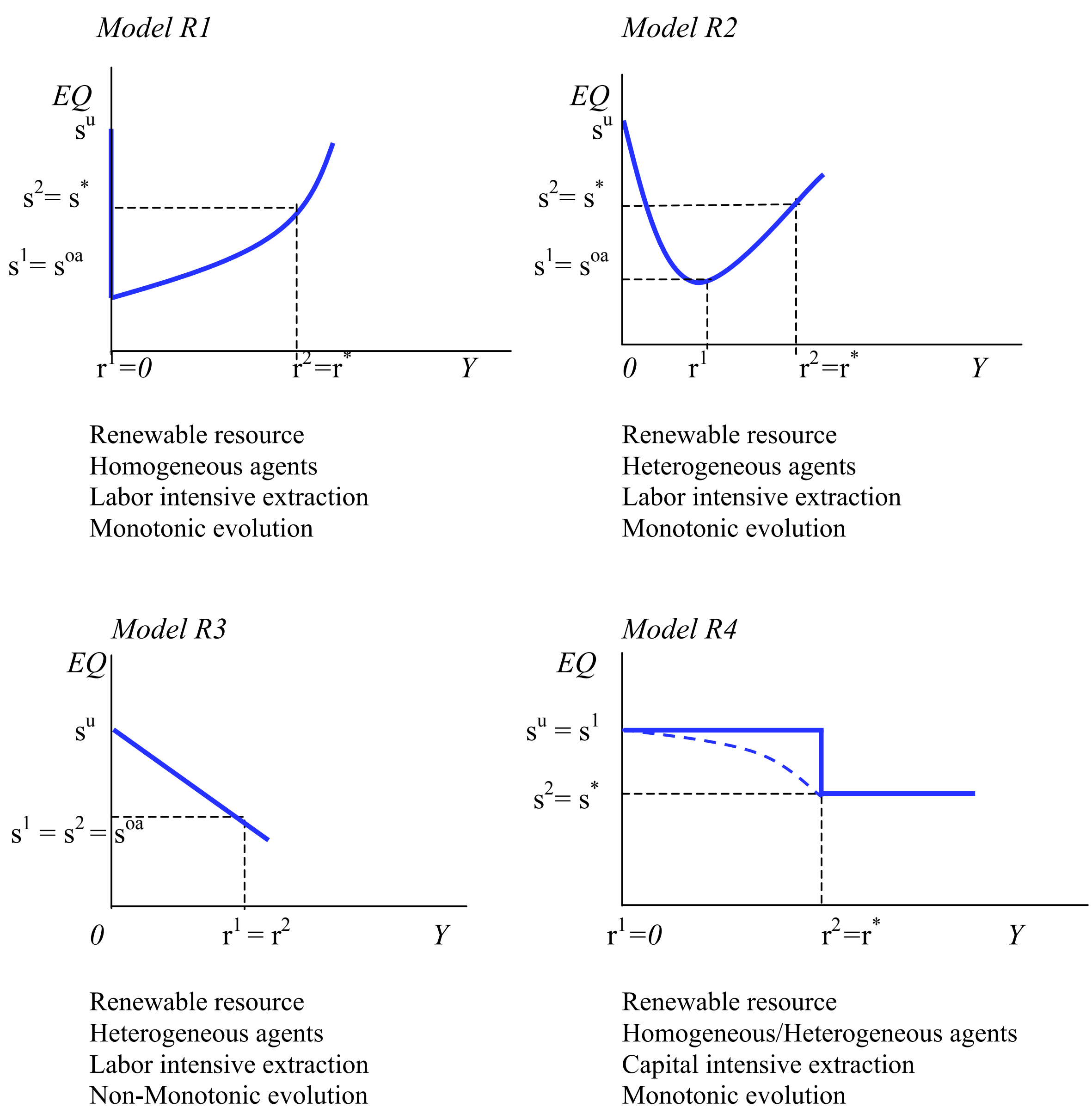

Figure 1 -- Models for Renewable Resources

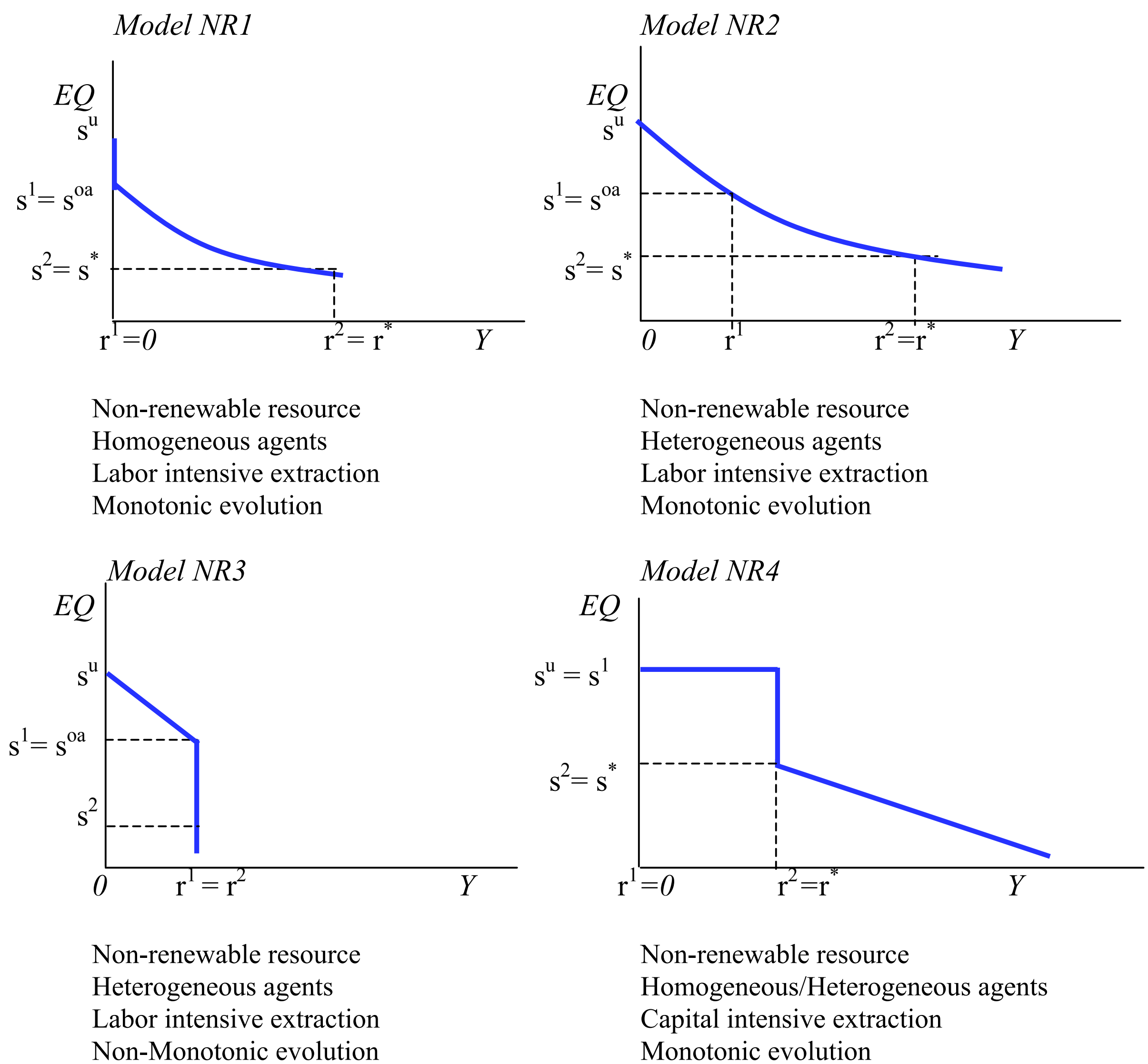

Figure 2 -- Models for Non-Renewable Resources

Since we are especially interested in obtaining the cases where the *EQ*-*Y* relationship has the U-shape like the EKC, we start by eliminating the cases where such a pattern is not feasible. It is clear by the definition of the non-renewable resources that the *EQ* cannot increase over time for these resources. Hence, the U-shaped EKC pattern can never emerge in the *EQ*-*Y* relationship in case of non-renewable resources, as is depicted by models NR1-NR4. We find that the *EQ*-*Y* relationship does not follow the EKC pattern in most of the cases even for renewable resources either. The only exception is the case of a renewable resource with labor intensive extraction process and heterogeneous agents in the open access regime following a monotonic pattern of property rights evolution (model R2), where the *EQ-Y* relationship does follow a U-shaped pattern that is consistent with the EKC hypothesis.

It is worth noting why only very specific model features generate the U-shaped *EQ-Y* relationship. Note that the model of a renewable resource with labor intensive extraction process and homogeneous agents in the open access regime following monotonic pattern of property rights evolution (model R1) is the second closest model to the U-shape. In case of the model represented in model R1, the homogeneity of the agents under period 1 (open access regime) drives the rent to zero as a result the rent in period 1 is same as period 0 (unexploited resource), while the resource stock declines due to open access resource extraction in period 1. This explains the vertical segment of *EQ-Y* relationship in case R1, which makes it different from the U-shape of model R2. Thus in model R2, heterogeneity of agents under open access regime that results in positive rent in period 1, plays a crucial role in generating the U-shape. Now if we turn to model R3, in spite of the presence of heterogeneous agents in period 1, we do not find the U-shape because the heterogeneity of agents in this case is associated with the non-monotonic pattern of property rights evolution that keeps the institutional set up locked up in an inefficient state of open access even in period 2. As a result the resource *EQ* cannot rebound, as is the case with monotonic evolution that leads to an efficient property rights regime in period 2. Hence monotonic pattern of evolution is also important for generating the U-shape.

The next question is: why the model with renewable resource with heterogeneous agents and capital-intensive resource extraction process following monotonic evolution (model R4) does not generate the U-shape? The answer lies in the capital-intensive resource extraction process. The capital intensity of the extraction process keeps the resource unexploited (or under exploited) in open access regime (period 1), which generates to the flat (or downward) segment of the *EQ-Y* relationship in model R4. Thus, we find that all the following characteristics - renewable nature of the resource, labor intensive resource extraction process, heterogeneity of the agents under open access regime and monotonic evolution of property rights are essential for generating the U-shaped *EQ-Y* relationship. Hence, it implies that EKC is unlikely to be a very general phenomenon, rather it is a likely outcome only for very specific set of 'resource', 'economic' (agents, extraction process), and 'institutional' (property rights) characteristics.

III. Implications for the Environmental Kuznets Curve

The single resource micro-framework developed in the previous section has implications for the Environmental Kuznets Curve as well. One can generalize the framework from a single resource economy to a multi-resource economy and derive the relationship between aggregated measures of income and environmental quality. For this purpose, we propose the following aggregated measures of environmental quality and income carefully in order to address the limitations of the existing EKC literature.

Assume that an economy derives its total output Y from N resources.

(2) $$Y = \sum_{i=1}^{n} p_i y_i (s_i, p_i, e_i)$$

where s_i is the stock of resource i, e_i is the resource extraction effort put in by agents for resource i, y_i is the output produced from resource i and p_i is the price of output produced from resource i.

We recognize that the environmental quality of a real economy is composed of different natural resources. Hence we construct a weighted resource stock index to depict the environmental quality of the economy.

(3) $$EQ = \sum_{i=1}^{N} w_i . s_i$$

The weights (w_i) represent the relative contribution of a resource in the income generation of the economy[17], which implies $w_i = p_i \; y_i()/Y$. Hence this measure of environmental quality represents a biological measure, resource stocks, weighted by an economic measure. The environmental quality, *EQ*, is determined by weighted average of stock of various resources. Hence it is a better representation of the environmental quality than that of a measure based on a single resource of an economy, as is the case in the EKC literature.

The property rights regime that governs a resource depends on its value relative to other resources in the economy[18], *or* $PR_i = f(p_i)$. As depicted in our micro-framework, property rights drive the extraction rate and hence the stock, and the income from the resource. Different property right regimes for different resources will result in varied impact on the aggregate measures of *EQ*[19] and *Y*. A simple illustrative example demonstrates that below.

Consider a simple economy with just two resources where each of the resource can possibly follow one of the ten possible models depicted in Tables 1 and 2. Even in this simple case, the aggregated *EQ-Y* relationship can evolve in 100 alternative ways depending upon the

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[17] We recognize that there can be several alternative ways of constructing the weighing function. This is one plausible case for illustrating the argument that economic weights of the resources are important.

[18] In our basic micro- framework we have considered a discrete version of this function as we consider only two types of property rights, open access and an efficient property rights regime, for simplicity. The continuous function presented here is a generalized version that can represent increasing efficiency of property rights with rising resource value, which can ideally be continuous.

[19] We recognize that two or more stocks might be related in use and depletion (e.g. mining coal and water pollution, or mining/smelting copper and air pollution). Our framework does not explicitly take into account such interdependence.

model for each of the two resources. The only set of feasible cases where one can expect to find a U-shaped relationship between the aggregated *EQ* and *Y* are as follows. The simplest case is the one in which there is a renewable resource exploited by heterogeneous agents, using labor intensive extraction and facing monotonic property rights evolution. Since both the resources have the U-shaped the aggregated measures will also follow the same path by construction, irrespective of their weights in the economy. However when, one of the resources follows the U-shaped pattern and the other does not, the relative weights of the resources play an important role in determining the aggregate EQ-Y relationship. In case of equal weights of each of the two resources, the aggregate EQ-Y relationship will not follow the U shape if one of the resources deviates from the EKC (U-shape) pattern. However in case on unequal weights of the resources, there are 18 other possible scenarios under which it is possible to obtain the EKC. These are the cases where only one of the resources fits the EKC pattern and the share of that resource in economy's income is high enough to offset the non-EKC pattern of the other resource. The requirement of the relative weights of the two resources that can generate the EKC in this set of cases depends on the model of the non-EKC resource.

This demonstrates that even for a simple two-resource economy the EKC pattern can arise for the aggregated *EQ-Y* relationship only in 1 out of the 100 stylized scenarios if we assume equal weights for each of the resources and at best in 19 cases if we allow for unequal weights of the resources. It is possible to generalize this for an economy with N resources. The purpose of this simple example is to illustrate that the U-shaped EKC pattern can arise in the aggregated context as well, but only under very specific model conditions. It thereby provides an explanation for the argument that EKC is not a universal phenomenon and it depends on economy specific characteristics. This suggests that much of the empirical EKC literature, which relies on data aggregated to the country level, is not useful for inferring a relationship between environmental quality and income (or other measures of economic growth).

IV. Some Historical Evidence

Our model framework provides ample opportunity to test its implications using formal econometric methods. An ideal data set for such an analysis would be a panel data set with a measure for the stock of a resource (e.g., forest, fisheries, groundwater, cattle), the income derived from that resource and the property rights evolution. Due to lack of adequate data availability, we have relied on the case studies from the existing literature to draw evidence in support of our model.

In this section we examine economic history case studies of natural resources in the light of our model framework. We use these histories to examine the path of property rights, the size of the resources stock (EQ), and the generation of income (Y). In each case we begin by explaining the property rights evolution and then examine resource use and incomes over time. We identify the relevant characteristics in our various models and attempt to test the model by looking at the evidence on resource and incomes. In general we find that our framework is supported by these histories and offers insightful interpretations (see table 3 for a summary).

A. Timber in the Great Lakes region of USA

The history of timber extraction in the Great Lakes states illustrates the relationship between ownership, resource stocks and incomes. Johnson and Libecap (1980) (J&L hence forth) present the history of property rights evolution and timber extraction along with the movement of timber prices in the Great Lakes area in the 19^{th} century. J&L's focus was to show that the private forest owners extracted the timber in an optimal way, in contrast to the popular belief that the old growth forest was over extracted during that time. We reinterpret the evidence presented by J&L in the light of our model framework and find that this case satisfies the assumptions and predictions of the model for a non-renewable resource with capital-intensive extraction technology with monotonic property rights evolution (model NR4).

First recall the features that provide evidence for the model assumptions. Old growth forests are treated as non-renewable resources hence we will focus on models of non-renewable resources here. According to J&L, the filing of claims for establishing private property rights to the forest land, which was public land, was negligible in the Great Lake states until the logging techniques became capital-intensive and competition for timberland increased due to rising price of timber in the second half of the 19th century. This evidence of establishment more efficient property right in response to rising timber prices is consistent with our definition of Monotonic evolution of property rights. The capital intensity of the timber extraction process implies that this case satisfies the assumptions for the model of a non-renewable resource with capital-intensive extraction technology with monotonic property rights evolution.

Now we turn to the model implications. J&L note that timber theft from public lands (analogous to open access regime) was low as a proportion of total timber production in the region. This feature can be attributed to the capital-intensity of the production process that diminishes the incentive to invest and extract in an open access regime as was argued in our model framework in Section II. Though, the public property regime did not provided adequate incentive for harvesters to invest in the capital-intensive logging, the transition to private property regime took care of the incentive problem and extraction went up, which implies declining stock of old growth forests. Hence, the evidence of initial increase in harvest rate of timber upon the major transition to private property regime in J&L's study is consistent with our model NR4's *EQ* path (see Appendix). One can also infer that with rising prices and increased extraction the rent from timber, our measure of *Y*, also went up after the establishment of private property rights. Hence, the case of 19th century timber harvest in the Great Lakes region is clearly consistent with our model of a non-renewable resource with capital-intensive extraction technology with monotonic property rights evolution depicted in model NR4.

B. Fisheries in North America

The North Pacific halibut fishery is an interesting case for our framework as it has undergone a series of regulatory (property rights) changes. Studies by Homans and Wilen (1997) and Grafton, Squires and Fox (2000) have illustrated the regulatory changes and their effects on efficiency. Due to the recognition of over fishing of halibut, in the 1980's regulations were imposed by limiting the fishing season that aimed to maintain a certain level of fish stock. In an effort to do so the season length reduced to as low as 6 days in case of British Columbia halibut fishery. But season length restrictions attracted increased fishing efforts within the short time span of the fishing season and the increased competition amongst the fishermen that led to over-investment in equipments as well as increase in the loss of fishing gear and fish and risk for fishermen fishing even in bad weather. Catching and processing the entire annual catch in a short time span led to decline in the fish quality. Hence, individual vessel quotas (IVQs) were introduced in 1990's and subsequently transferability of the IVQs was also allowed. IVQs allowed longer fishing season without affecting the targeted total allowable catch and thereby solved the problems associated with the short fishing season. IVQs increased efficiency as is reflected by improved product quality, a proxy for *EQ*[20], and increased revenue, *Y*. Since fisheries are renewable resources and the fishermen are heterogeneous in their fishing abilities

[20] Biological assessment of the total fish stock is a direct measure of *EQ* that would fit our model framework. From these case studies *EQ* can be inferred indirectly from the quantity and quality of the output that improved over time with more efficient regulatory regime.

whose labor input plays a significant role in the fishing catch, we can classify fishing as a labor-intensive process. Thus all the assumptions of model R2 are satisfied in this case. The evidence that *EQ* and *Y* improved with move towards more efficient regulatory regime this case study supports R2's prediction as well.

C. Rangelands in the Western United States

The rangelands of the American West are an interesting case because the property rights regimes evolved in more or less a monotonic fashion from open access to common property to government managed or private property rights over the last two centuries as is depicted in Libecap's (1981) study. Rangelands are a renewable resource and ranching is a labor intensive activity, this case satisfies the model characteristics of renewable resource with labor intensive production process following monotonic evolution.

Prior to the large increases in cattle populations and the introduction of agriculture open access range was not severely depleted. Ultimately, however, the open access ranges were overgrazed and two responses ensued. In some cases, ranchers were able to establish private property rights to land and invested in fencing and wells and adjusted their stocks to maximize returns. In other cases, ranchers used informal local agreements to restrict entry and use of the ranges in form of livestock associations in mid 1800's (Anderson and Hill, 1975). The associations were able to increase ranch earnings (*Y*) in several cases. If we focus on this specific feature of transition from open access to more efficient common property regime during the early phase of the property rights evolution to draw an analogy to our model framework, we can probably infer that it fits the model for renewable resource with labor intensive production process with homogeneous agents following monotonic evolution (model R1). It is worth noting that we are relying on the assumption that the formation the livestock associations and the proper functioning of the informal regulations were facilitated by homogeneity of the ranchers. Since the ranch earnings (*Y*) increased as a result of the regulations and one can also infer that it would not have been feasible without improvement of the rangeland quality (*EQ*), hence we can infer that the implications of model R1 are supported as well by this example.

D. Crude Oil in the United States

The history of crude oil extraction in the US presents another case of non-renewable resource that can be analyzed with our framework. Libecap and Smith (2002) (L&S hence forth) present the evolution of property rights for crude oil (petroleum) extraction in the United States.

According to L&S, the US has witnessed four types of property rights regime for oil and gas over the last two centuries. Crude oil extraction started in US from an open access regime ('extractive anarchy' as per L&S) where the producers extracted oil from the same underground reservoir without any coordination plan in 19th century and it lasted until the petroleum price was low and the knowledge about the geological features of the oil pool was limited. With increase in price of petroleum and improvement in the scientific knowledge about the subsurface reservoirs, buy-outs and private negotiations started with the aim of controlling the common pool losses in the early 20th century that represents the second property rights regime. In many cases, however, the presence of multiple and heterogeneous stakeholders on a single oil reservoir increased the transaction costs of multilateral private agreements and private agreements could not reached to curb open access waste. Hence private negotiations gave way to state imposed conservation regulations that imposed restrictions on number and spacing of wells and production, which represents the third property rights regime. Although political lobbying resulted in policies favoring the small firms in many cases that weakened the ability of the policy to minimize the common pool losses, yet it reduced production externalities relative to competitive extraction under the prior regimes. By the 1950's, technological development made it possible to recover the trapped oil in a 'secondary recovery' phase by interjecting water and gas to partially depleted reservoirs to rebuild the subsurface pressure. However it required conversion of certain production wells into non-producing injection wells to increase production of the reservoir as a whole. Hence it led to the promotion of reservoir or field wide unitization, which represents the fourth regime. Unitization or consolidation implies maximization of the reservoir wide oil recovery and hence it is the most efficient solution. These four regimes represent increasing efficiency in terms of reservoir wide crude oil extraction and rent, which evolved along with rising prices of oil. Hence this case study provides evidence in support of the monotonic evolution pattern of property rights.

The crude oil case study provides several important insights for our framework. If we focus on the first regime, which was open access regime with labor-intensive extraction technique and heterogeneous agents, then the transition to the second regime would fit model NR2. If we focus on the secondary recovery, it fits in our model framework for the case of capital-intensive extraction process for non-renewable resources (model NR4) as the secondary recovery is most capital intensive and occurred only after unitization, the most efficient regime of the four. Hence the different phases of the evolution fit into different models, which again highlight the flexibility of our model framework.

Although it can be inferred from L&S's study that the overall crude oil history in the US depicts monotonic evolution of property rights, however there is enough evidence presented by Libecap and Wiggins (1985) which examines that the unitization process, the most efficient property rights regime, was delayed or deterred in the states where heterogeneity of resource extracting agents was higher. Thus there exists evidence in support of non-monotonic pattern of evolution at more micro-level while monotonic pattern appears to prevail at more macro level. This evidence further strengthens our micro approach for better understanding of *EQ-Y* relationship. It is worth noting that our model framework is flexible enough for explaining the aggregated trend but it is the micro-approach that provides its strength of explaining the spatial and/or temporal variations in the *EQ-Y* relationship.

E. Forest Policy in India

The evolution of forest policy in India presents another interesting case. The forests have predominantly government (public) property in independent (post 1947) India. Due inadequate monitoring, for practical purposes the government owned forest resources have been equivalent to open access resources. This led to severe degradation of the forests that raised serious concerns from ecological perspective as well as for the sustenance of the forest dwellers or villages near the forests. It resulted in the Indian government's order of Joint Forest Management (JFM) in 1990. This policy was aimed at regenerating forests by local community participation. In other words it changed the unofficial open access regime to a formal common property rights regime. According to the JFM policy the local village communities could manage the forest areas allocated under JFM under the guidance of forest departments. The communities have complete claim to the flow of non-timber forest products (NTFP) like such as leaves and fruits and they share the timber revenue with the forest department.

We can put this case in the framework of model R2, the case of a renewable resource with labor-intensive extraction for heterogeneous agents, following monotonic evolution of property rights because of the following reasons. The transition from open access (unofficial) to formal common property regime in the face of severe forest degradation represents a monotonic evolution of property rights as the price of forest products, especially timber, has been increasing all along the way. Forests in general can be classified as a renewable resource and the primary extraction for the village communities involve non-timber forest products (NTFP), which are renewable, unlike timber from old growth forests. The extraction of the NTFP is labor-intensive process. The composition of the village communities include people from different socio-economic groups, hence they represent a heterogeneous set of resource extractors.

The overall qualitative prediction of the model R2 is borne out by the studies conducted by Rao et al (2004) and Mishra et al (2004)[21]. These studies analyze the impact of JFM policy in the states of Andhra Pradesh and West Bengal respectively. The analysis reveals that JFM had positive impact on both the forest regeneration and the returns from forests. The forest areas that were in the worst states were put under the JFM policy. It is worth noting that the JFM policy was adopted selectively in varied scales in different regions and at different points in time. These analyses are based on the responses from the local communities managing the forests surveyed in the year 2001-2002. These studies depict that the forest cover, in terms of density of trees, had increased in most of the districts they surveyed and the number of species also increased in most cases. Hence overall, the environmental quality (EQ) as measured by forest biomass and biodiversity had improved as a result of the adoption of JFM. The increase in the flow of non-timber forest products and the improvement in grass productivity increased the forest-based incomes (Y) for the local communities as well. Hence, we can conclude that transition from open access to common property regime led to increase in both EQ and Y as depicted in model R2.

F. Forest Policy in Nepal

Forest policy in Nepal can also be used to illustrate our framework. Forests play a very important role in rural livelihoods in Nepal. People rely on forests for non-timber forest products

[21] It is worth noting that the implementation of the policy was not uniform across different states of India and the impact of JFM varies across as well as within a state (Rabindranath and Sudha, 2004).

as well as timber for their sustenance. Hence the management of forests is a critical socio-political issue for this country. Malla (2001) documents the history of the forest policy evolution in Nepal. The forestland ownership in Nepal shifted from the rulers prior to 1950s to the government through a nationalization of forests policy from the 1950's to 1970's. In the late 1970's with increasing emphasis on rural development and forest conservation, community (village level) forestry regulations were introduced. Though the condition of the forests improved under the community forestry regime, the socio-economic impact of the policy is a contentious issue due to the evidence of the poorest segments of rural population becoming worse off in several cases. In 1992 the Government of Nepal embarked on a new smaller scale forest management project by allowing lease holding of forestland for the poorest households. Under this policy small groups of poorest households can get 40 years lease to degraded forest land which they can rehabilitate and improve their income primarily through increased fodder production and it has been found to succeed in its objective (Malla, 2000). This new project can examined with model R1, which represents the case of a renewable resource with labor intensive extraction, homogeneous resource extractors and monotonic evolution of property rights. As mentioned earlier forest resources, especially for non-timber use can be classified as a renewable resource. The fodder production in Nepal is a labor-intensive activity and the lease managed by small groups of the poorest farmers represent homogeneous group of extractors. The evolution from village level community management of forests to lease holdings managed by small groups in for the most degraded forests represents a monotonic evolution of property rights. The improvement of the degraded forestland and earnings of the leaseholders support the predictions of model R1 as well.

Table 3 - Summary of the Case Studies

	Nature of resource	*Property rights evolution*	*Resource extraction technology*	*Nature of resource extracting agents*	*Model*
Timber in Great Lakes	Non-renewable	Monotonic	Capital intensive	Homogenous/ Heterogeneous	NR4
Halibuts in North Pacific	Renewable	Monotonic	Labor intensive	Heterogeneous	R2
Rangeland in Western US	Renewable	Monotonic	Labor intensive	Homogenous	R1
Crude Oil in US	Non-renewable	Monotonic	Labor to Capital intensive	Heterogeneous	NR2/NR4
Forest in India	Renewable	Monotonic	Labor intensive	Heterogeneous	R2
Forest in Nepal	Renewable	Monotonic	Labor intensive	Homogenous	R1

V. Summary and Conclusion

We have developed a microeconomic foundation for analyzing the relationship between environmental quality (*EQ*) and income (*Y*) by focusing on the role of property rights in shaping this relationship. We consider two types of property rights evolution patterns -- monotonic or non-monotonic. Monotonic evolution refers to the case where property rights to a natural resource evolves from a state of open access to more efficient property regime as the price of the resource increases and in the non-monotonic case the open access property rights persist even with rising resource price. In our framework, environmental quality (*EQ*) is synonymous with the size of the resource stock (stock of clean air and water, groundwater aquifer, stock of trees in a forest) and resource rent is synonymous with income (*Y*) derived from the resource. We show that the relationship between *EQ* and *Y* can evolve in various ways. We find that under very specific model assumptions the *EQ-Y* relationship can also follow a U-shape that is consistent with the Environmental Kuznets' Curve (EKC). Thus the paper provides an alternative theoretical explanation for EKC based on evolution of property rights and explains why it is not a universal phenomenon. We show that careful reinterpretation of historical case studies of various natural resources not only provides evidence in support of our model assumptions and implications but also demonstrates the wide applicability of the framework.

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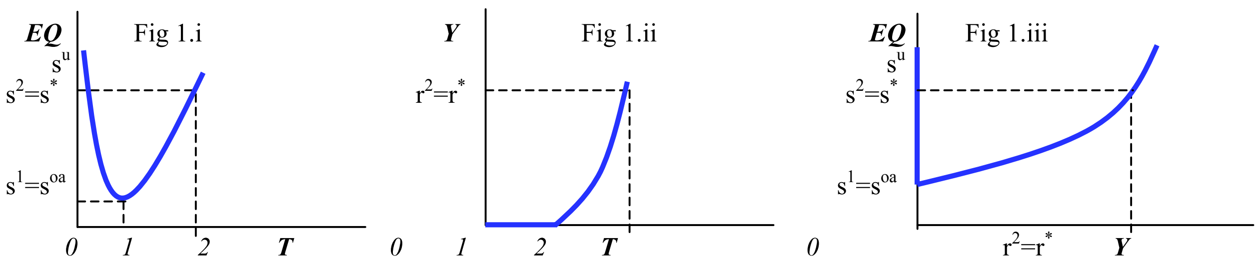
APPENDIX

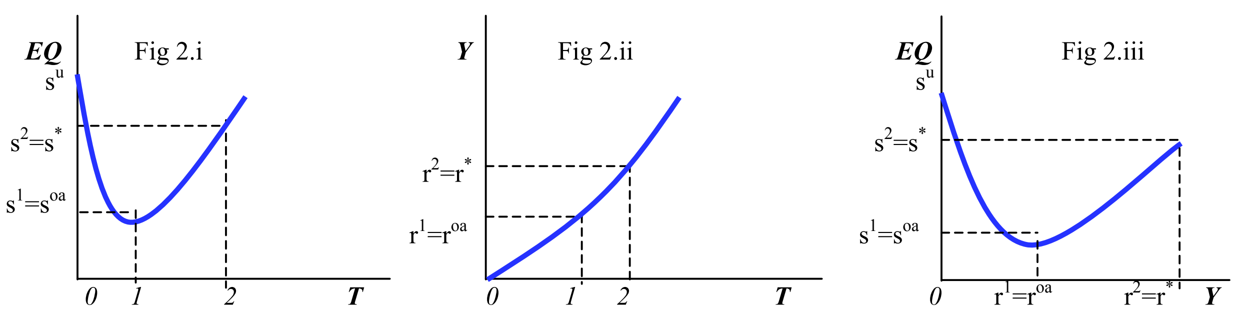
This appendix traces out the time paths for resource stock, our measure of *EQ* and resource rent, our measure of *Y* and then draw the *EQ*-*Y* relationship based on these two time paths. We present these evolution patterns for each of the models presented in Tables 1 and 2 in the main text except for the models with capital-intensive extraction and non-monotonic property rights evolution because there is no change in *EQ* and *Y* over time in these cases for both renewable and non-renewable resources. Note that *T* denotes the time period with 0 as the initial period followed by the open access regime in Period 1 and depending upon the evolution pattern open access or more efficient property right regime in period 2.

R1. Renewable resource, Labor intensive extraction, Homogenous agents in period1, Monotonic property rights evolution



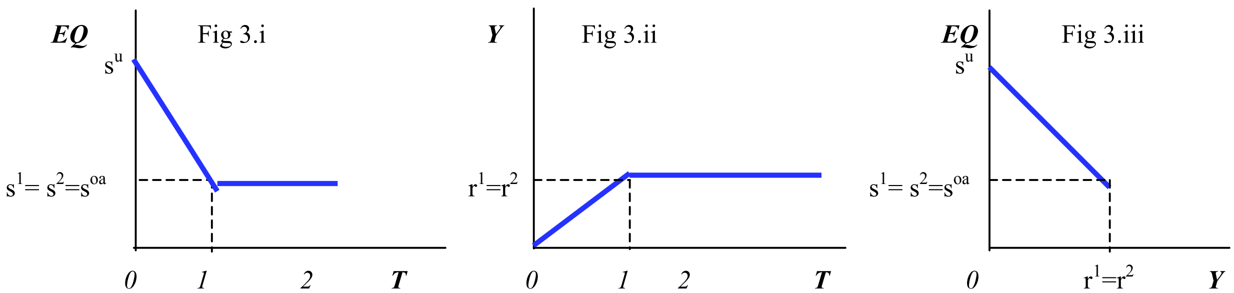
In this case, in period 1, under open access regime, since the agents are homogenous, the classic open access outcome occurs. The extraction takes place till average product equals the wage rate of labor, as the production process is labor intensive. The resulting stock is $s^1=s^{oa}$ corresponding to $x^1=x^{oa}$. The rents are zero, $r^1=0$, same as in case of an unexploited resource. The property rights evolve following the Monotonic evolution pattern. Hence, in period 2, more efficient property rights are established that provides optimal rent, $r^2=r^*>r^1$. Under the efficient property rights regime extraction takes place till marginal product equals marginal cost, $x^2=x^*<x^{oa}$. Since the resource is a renewable resource, the switch to the efficient property rights regime leads to increase in the resource stock, $s^2=s^{e*}> s^1$.

R2. Renewable resource, Labor intensive extraction, Heterogeneous agents in Period 1, Monotonic property rights evolution



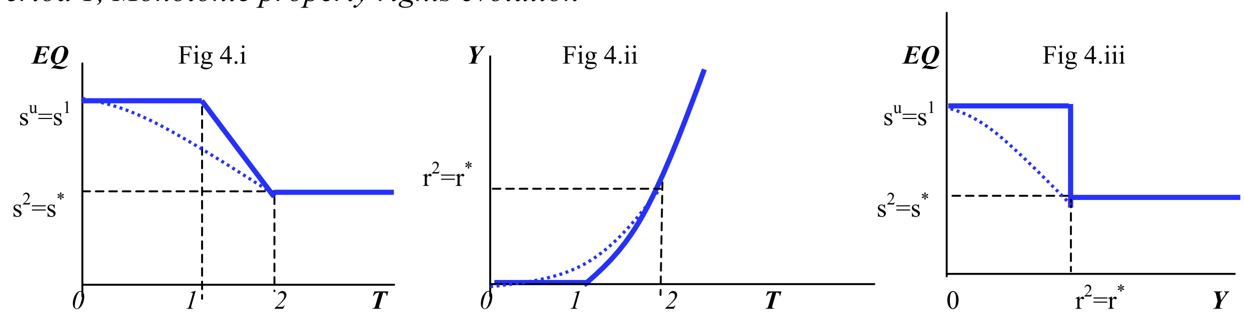
This case has the same features as Model R1 above, except for heterogeneous agents in period 1, under open access regime. The heterogeneity of agents results in positive rents in period 1, $r^1>0$. All the other outcomes are same as in case of model R1. Note that in this case we assume that the heterogeneity of agents may delay the transition towards the efficient regime but does not prevent the transition.

R3. Renewable resource, Labor intensive extraction, Heterogeneous agents in Period 1, non-Monotonic property rights evolution



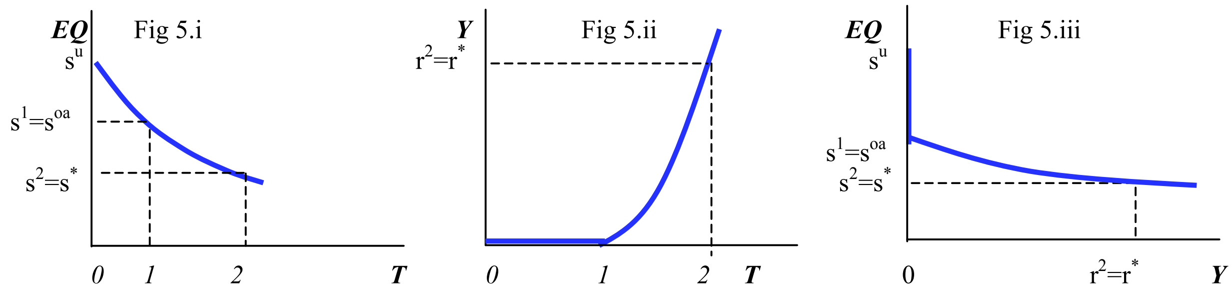
This case is same as model R2 above, except for the fact that in this case the heterogeneity of agents prevents the transition towards the efficient regime and the open access regime persists even in period 2. Hence the open access equilibrium persists in period 2 as well, implying $x^1 = x^2 = x^{oa}$. Due to heterogeneity of the agents, the rents are positive $r^1=r^2>0$ and the renewable nature of the resource can result in $s^1= s^2=s^{oa}$.

R4. Renewable resource, Capital intensive extraction, Homogenous or Heterogeneous agents in Period 1, Monotonic property rights evolution



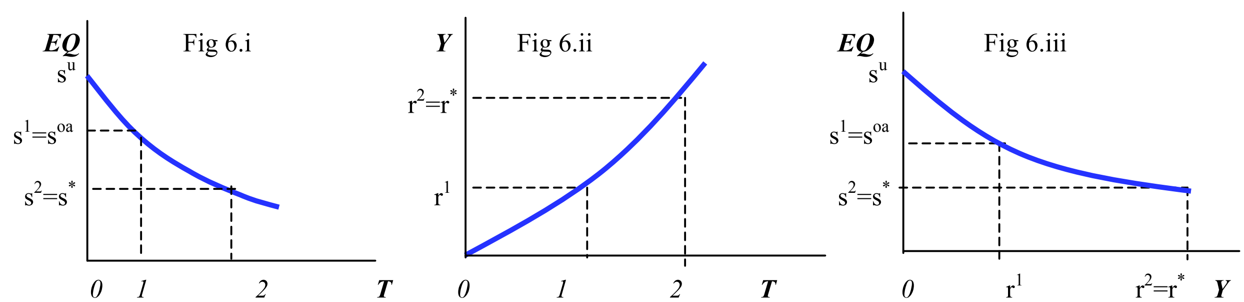
All the prior models had assumed labor intensive resource extraction technology. In this case the resource extraction is capital intensive. In period 1, the open access property rights regime does not provide any incentive to any agent to invest in the capital for resource extraction. Hence the resource remains unexploited. Hence $s^1=s^u$ and $r^1=0$. This represents an extreme case where the upfront investment is prohibitively high to induce any resource extraction efforts without secure property rights. However, at relatively lower levels of capital intensity, the resource is under-exploited (relative to efficient level of extraction) rather than unexploited. Hence it implies $s^u > s^1 > s^*$ and $0 < r^1 < r^*$. This scenario is depicted by the dashed blue line in the above set of figures. In period 2, efficient property rights regime is established and it has the usual efficient outcomes, $s^2=s^*$, $r^2=r^*$.

NR1. Non-renewable resource, Labor intensive extraction, Homogenous agents in Period 1, Monotonic property rights evolution



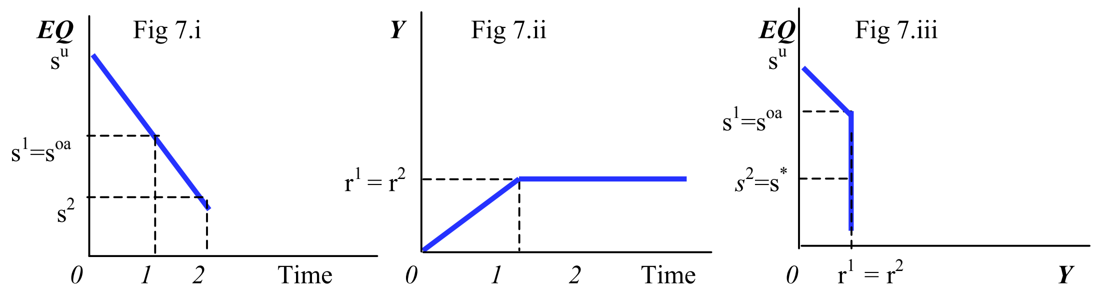
This model has the same features as that of model R1, except for the non-renewable nature of the resource. Hence in period 1 and 2, the outcomes for rents ($r^1=0$, and $r^2=r^* > r^1$) and extraction are similar ($x^1=x^{oa}$ and $x^2=x^* < x^{oa}$). However due to the non-renewable nature of the resource the effect on the stock is different ($s^1=s^{oa}$ and $s^2=s^* < s^1$). Non-renewability implies that the stock keeps declining even with lower extraction rate in period 2.

NR2. Non-renewable resource, Labor intensive extraction, Heterogeneous agents in Period1, Monotonic property rights evolution



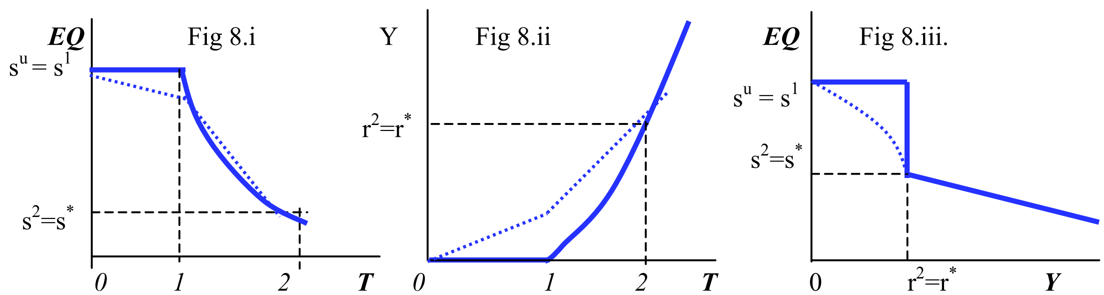
This case has the same features as Model NR1, except for heterogeneous agents in period 1, under open access regime. The heterogeneity of agents results in positive rents in period 1, $r^1>0$. All the other outcomes are same as in case of model NR1. As in model R2, in this case we assume that the heterogeneity of agents may delay the transition towards the efficient regime but does not prevent the transition.

NR3. Non-renewable resource, Labor intensive extraction, Heterogeneous agents in Period1, non-Monotonic property rights evolution



This case is same as model NR2 except for the fact that in this case the heterogeneity of agents prevents the transition towards the efficient regime and the open access regime persists even in period 2. Hence the open access equilibrium persists in period 2 as well, implying $x^1 = x^2 = x^{oa}$. Due to heterogeneity of the agents, the rents are positive $r^1 = r^2 > 0$ and the non-renewable nature of the resource implies $s^1 = s^{oa}$ and $s^2 < s^1$.

NR4. Non-renewable resource, Capital intensive extraction, Homogenous or heterogeneous agents in Period1, Monotonic property rights evolution



In this case the resource extraction is capital intensive. This model has the same features as that of model R4, except for the non-renewable nature of the resource. In period 1, the resource remains unexploited. Hence $s^1 = s^u$ and $r^1 = 0$. This represents an extreme case where the upfront investment is prohibitively high to induce any resource extraction efforts without secure property rights, like in case of oil exploration. However, at relatively lower levels of capital intensity, the resource is under-exploited (relative to efficient level of extraction) rather than unexploited. Hence it implies $s^u > s^1 > s^*$ and $0 < r^1 < r^*$. This scenario is depicted by the dashed blue line in the above set of figures. In period 2, efficient property rights regime is established and it has the usual efficient outcomes, $s^2 = s^*$, $r^2 = r^*$.