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Natural Resource Rents: Theoretical Clarification

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ABSTRACT

The concept of natural resource rents is much used in the natural resource economics literature. It is therefore somewhat surprising that in this same literature it is difficult to find a clear definition of the concept. Possibly as a result, the concept is often loosely employed and in some texts it appears to be taken to be virtually synonymous with profits.

The paper provides a definition of the concept of natural resource rents that is both unambiguous and in conformance with the more traditional concept of economic. A general expression for natural resource rents is derived as a function of the resource stock level, the rate of resource use and, its properties explored.

Keywords: Economic rents, natural resource rents, natural resource rents and profits

INTRODUCTION

The concept of economic rents has a long history in economic theory. A. Smith used it in his value theory as one component of profits (see Smith 1776). D. Ricardo (1817) further developed the concept and applied it in his theory of diminishing returns to agriculture. Hence the well known concept of land rents. Later classical economists including J.S. Mill and K. Marx employed the concept in similar ways (see e.g. Samuels et al. 2003). Following the tradition in the field I will often refer to rents in this classical sense as Ricardian rents.

The label natural resource rents, is much used in the natural resource economics literature in various contexts. These include the contribution of natural resource rents to economic growth (see e.g. Sachs and Warner 1991 and the references therein), the amount of rents as a measure of economic efficiency (see e.g. Homans and Wilen 2003), rents as a source of inequality (see e.g. Samuelson 1974), rents as a subject for taxation (see e.g. Grafton 1996) and so on. In spite of this widespread use of the term, it is difficult to find a clear definition of either natural resource rents or fisheries rents in the literature. What most authors seem to have in mind is some variant of the Ricardian land rents discussed above. However, the concept is often loosely employed and in some texts appears to be virtually synonymous with profits.

In the well known textbook on fisheries economics by Lee Anderson (1977), there are, according to the index, seven page references to the concept but no definition. On the other hand in the textbook on mathematical bioeconomics by Colin Clark (1976) there is no use of the term. In the textbook by Cunningham, Dunn and Witmarsh (1985) there are 24 page references to the concept but again no definition. In the influential volume Rights Based Fishing by Neher et al, there are eight references to the term but, once again, no definition. In Dasgupta and Heal's (1979) famous book on natural resource economics there are ? references to the term and no definition. Hanley, Shogren and White (1997) refer to the term ? times but offer no definition. In Hannesson's textbook of 1993, there are 40 page references to the term. Unlike the previous authors, Hannesson offers what amounts to a definition of the term (p.10). More precisely, he identifies the concept with the price an owner of the fishery could extract from the users. This is in accordance with the classical use of the term discussed above. However, Hannesson goes on to assert that this would be equal to the profits the buyers could gain from using the resource (p.10). This, however, would only be true in very special cases as explained in this paper.

The remainder of the paper is organized as follows: In the first section, the general concept of economic rents is defined and explained. The paper then goes on to consider natural resource rents specifically and discusses their properties. This is followed by a discussion of the relationship between rents and profits, or rather the lack of one. The final section summarizes the main results of the paper.

ECONOMIC RENTS

The concept of economic rents is reviewed by Armen Alchian in the New Palgrave Dictionary of Economics (1987). According to him, economic rents are:

> "the payment (imputed or otherwise) to a factor in fixed supply".

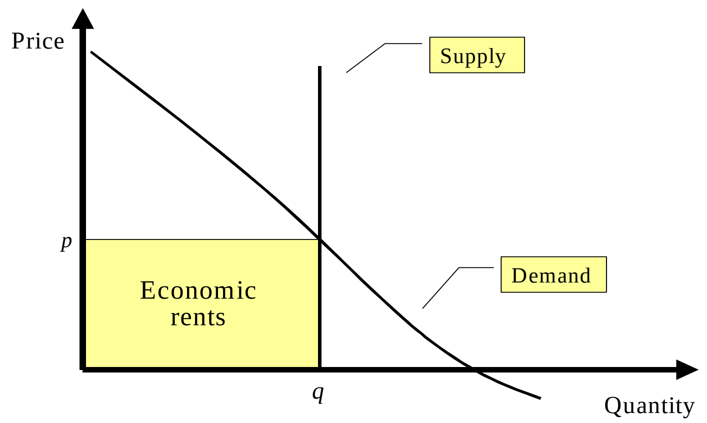
This definition is formulated in terms of a factor of production. However, quite clearly, is can be extended to cover any restricted variable including output in the profit function. An extended definition in same spirit would read:

"the payment (imputed or otherwise) to a variable in fixed quantity".

In what follows, this variable will be interchangeably referred to as a resource or a factor.

Alchian illustrates his definition with the familiar diagram in Figure 1 often used to illustrate Ricardo's theory of land rents. In this diagram, there is a demand curve and a supply curve. The market-clearing price is *p*. However, since the quantity of the factor is assumed fixed, the corresponding supply, *q*, would be forthcoming even if the price were zero. Hence, the entire price, *p*, may be regarded as a surplus per unit of quantity. The total surplus attributable to the limited factor is the rectangle $p \cdot q$. This quantity is seen by Alchian and the classical authors as economic rents. It is rents in the sense that the owner of the quantity q could rent it out for this amount.

Figure 1
Economic Rents



Note that as far as the concept of economic rents is concerned it is immaterial why or how the supply is fixed. It may be fixed because of limited natural resource availability as Ricardo's land of quality, or it may be fixed for economic reasons by suppliers enjoying some monopolistic position. In the latter situation the rents are sometimes referred to as monopoly rents (Varian 1984). What is crucial for the existence of economic rents is that the marginal cost of supplying a certain quantity is less than the demand price at that quantity. The difference constitutes rents per unit of quantity. If, as in Figure 1 and Ricardo's theory of land rents, the marginal cost of supply is actually zero, the rent per unit of quantity is the demand price.

It is important to realize that the economic rents depicted in Figure 1 also represent profits[1] to the owner of the resource. It doesn't, however, represent the total economic benefits of the supply *q*. This is measured by the sum of economic rents and the demanders' surplus represented by the upper triangle in the diagram. Thus, if the demanders are producers, their profits would be the demanders' surplus. Total profits from the supply *q*, would be sum of economic rents and the demanders' surplus. Thus, in this case, profits would be greater than economic rents. Some authors refer to the demanders' surplus in Figure 1 as intra-marginal rents (see e.g. Coglan and Pascoe 1999 for fisheries and Blaug 2000 more generally).

The concept of economic rents as defined above presupposes a factor in fixed supply. Obviously, the empirical relevance of factors in fixed supply may be questioned. After all it is in the nature of the economic activity to find ways to adjust supply to demand, particularly when profits can be made doing it. Even, Ricardo's (1817) argument in terms of the "original and indestructible powers of the soil" does not ring true. Surely, modern technology has enabled us

[1] Since the factor is by assumption in fixed supply, there can be no opportunity costs associated with its supply.

to both reduce and enhance these powers. Thus, it turns out to not to be easy to find examples of factors of production that are truly in fixed supply especially in the long run. Indeed, the most likely candidates for such factors seem to be natural resources which cannot be augmented. Unique natural geological phenomena seem to belong to that category. In the very short run, on the other hand, many factors are in fixed supply and, consequently capable of earning economic rents. To represent this phenomenon of transient or temporary economic rents, Marshall (according to Achian 1987) initiated the concept of quasi-rents.

If there is no fixed factor, economic rents in the traditional (Alchian 1987) sense are not really defined. However, as we have seen, what is crucial for the existence of a surplus or rents is not fixed supply (i.e, that the marginal cost of supply jumps from zero to infinity at some given quantity) but that the marginal cost of supply be less than the demand price. This observation motivates the following generalized definition of economic rents which includes Alchian's definition of rents, and hence Ricardo's land rents, as well as monopoly rents as special cases.

> "Economic rents are payments (imputed or otherwise) to a variable above the marginal costs of supplying that variable."

Adopting this definition, denote the quantity of the variable by q. Let other relevant variables (such as other prices, natural resources stocks, expectations and so on) be represented by the vector $\boldsymbol{z}$. Then we can write the (inverse) demand function for the factor as:

$$p=D(q,\boldsymbol{z}).$$

It is useful to note in this context that in competitive markets if the factor resource is used for production purposes, $D(q)$ represents the marginal profits of using the factor. In other words, $D(q)=\Pi_q(q)$, $\Pi(q,z)$ represents the profit function (Varian 1984). When, on the other hand, the resources is used directly for consumption $D(q)$ would be proportional to the marginal utility of consuming the factor, $U_q(q,z)$ (Varian 1984). Without loss of generality let the marginal cost of supplying the variable be zero (Alchian's definition of rents). Given this, rents might be expressed in any of the following three ways:

$$R(q,\boldsymbol{z})=D(q,\boldsymbol{z})\cdot q=\Pi_q(q,x)\cdot q=U_q(q,z)\cdot q\,.$$

Of course the benefits of resource use may involve more than one independent variable. The above expression for economic rents generalizes to the case of many variables in a straight-forward manner. Let $\Pi(\boldsymbol{q},\boldsymbol{z})$ be the profit function with the quantity (inputs and outputs) vector $\boldsymbol{q}$. Then rents from all these variables are defined as:

$$R(\boldsymbol{q},\boldsymbol{z})=\Pi_{\boldsymbol{q}}(\boldsymbol{q},\boldsymbol{z})\cdot\boldsymbol{q}\equiv\sum_{i=1}^{I}\Pi_{q_i}(\boldsymbol{q},\boldsymbol{z})\cdot q_i\,.$$

Note that when there is more then one variable in the objective function, economic rents from each of them depends in general on the amount of all the others.

NATURAL RESOURCE RENTS

Consider a natural source use activity (e.g. industry) characterized by the instantaneous benefit function:

(1) $\Pi(q,x)$, defined for $q,x \geq 0$,

where q denotes the volume of resource use (e.g. extraction) and x the stock of the resource both at time t. The benefit function is taken to have the usual properties. More precisely: $\Pi(0,x)=\Pi(q,0)\leq 0$, $\Pi_x(q,x)>0$ and $\Pi_q(q,x)>0$ for $q<q°>0$. For analytical convenience it is, moreover, assumed that the benefit function is differentiable as needed and concave. In what follows, we will normally refer to $\Pi(q,x)$ as applying to the use activity as a whole. In that case $\Pi(q,x)$ must be some aggregate of individual benefit functions.

The resource evolves according to the differential equation:

(2) $\dot{x}=G(x)-q$, defined for $x\geq 0$,

where $G(x)$ is the renewal function of the natural resource having the usual properties (Clark 1976). More specifically, $G(0)=0$ and if the resource is renewable there will be an interval over which $G(x)>0$. As the $\Pi(q,x)$ function, the function $G(x)$ is assumed to be as differentiable as needed.

Optimal use

To understand the nature of natural resource rents it is convenient to consider first benefit maximizing behaviour. All the key results concerning natural resource rents in the case of optimal use carry over to suboptimal use.

Individual users and, consequently, the use activity as a whole, are assumed to seek to maximize the present value of profits. For this purpose they can decide to be active and, if active, select the path of extraction, $\{q\}$. Formally this problem can be expressed as:

(I) $$\underset{\{q\}}{Maximize}\ V=\int_0^{\infty}\Pi(q,x)\cdot e^{-r\cdot t}dt,$$

Subject to: $\dot{x} = G(x)-q$
$x(0) = x_0$
$x, q \geq 0$.

According to the maximum principle (Pontryagin et al. 1962, Leonard and Long 1992). The necessary (and in this case sufficient) conditions for solving problem (I) include:

(3.1) $\Pi_q - \lambda \leq 0$, $q \geq 0$, $(\Pi_q - \lambda)\cdot q = 0$,

(3.2) $\dot{\lambda} - r\cdot\lambda = -\Pi_x - \lambda\cdot G_x$,

(3.3) $\dot{x} = G(x)-q$,

(3.4) Appropriate transversality conditions (for infinite time).

Expressions (3.1)-(3.4) describe the behaviour of a profit maximizing natural resource users. If the users take prices as exogenous and these prices are "true" as is usually assumed, conditions (3.1)-(3.4) also represent a socially optimal behaviour.

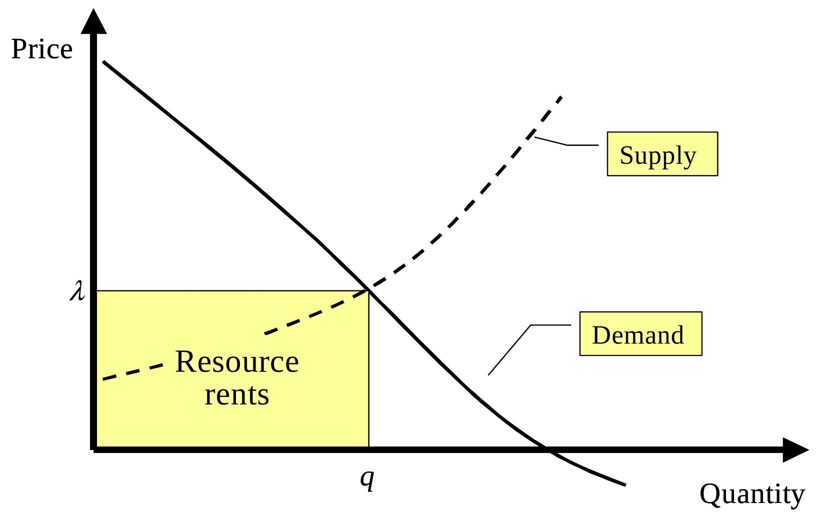
Now, as discussed in the previous section, economic rents are defined as $D(q)\cdot q$, where $D(q)$ represents the demand for the factor in fixed supply. In the context of natural resources the demand is the demand for natural resource use, i.e. $D(q)=\Pi_q(q,x)$. Hence, adopting Alchian's definition of economic rents, natural resource rents are defined as

(4) $R(q,x) = D(q) \cdot q = \Pi_q(q,x) \cdot q$.

Note that these are instantaneous rents. They refer to a point in time. Resource rents for the harvesting programme as a whole would be given by the present value of the complete time path of rents.

In the resource use activity defined above, the supply price of the resource at quantity q is given by the co-state variable, λ. This supply function is implicitly defined by conditions (3.2)-(3.4) above (for further details see the appendix). It depends in general on the state of the resource, x, and the level of extraction, q as well as exogenous variables such as prices. The demand for resource use, however, is given by condition (3.1). The demand price (i.e. λ) depends also on the state of the resource the level of extraction, q as well as exogenous variables. Thus, if the optimal extraction at a point of time is positive, there exists a supply/demand equilibrium defined by conditions (3.1) to (3.4). It follows that for the resource use activity we may draw a resource rent diagram corresponding to the conventional one in Figure 1.

Figure 2
A Resource Use Activity: Resource Rents



As the supply curve of q is drawn in Figure 2, the area referred to as "Resource rents" does not appear to be economic rents at all, although parts of it may represent the suppliers' surplus. Note, however, that λ is merely an imputed or notional price. It represents the opportunity cost of reducing the size of the resource, sometimes referred to as a user cost (Scott 1955, Dasgupta and Heal 1979). This user cost is the result of the maximization of the present value of profits and is generated by the concern that "oversupply" now might hurt future profits. Thus, it is similar to the user costs a monopolist might calculate for his own current supply. The difference is that in the natural resource context, the imputed user costs stem from the scarcity of the resource, while in the traditional monopolist situation it comes from the perceived downward slope of the demand curve – scarcity of demand. In any case, the resource user cost does not represent outlays of money. Thus, in a certain sense it is not cost at all. It is certainly not a cost in the sense of Ricardo and the definition of economic rents discussed in the previous section.

We conclude that the multiple $\lambda \cdot q$ appears to represent economic rents in the traditional (Ricardian) sense as defined by Alchian above. In any case, this multiple seems the closest parallel to economic rents that can be found in natural resource use activities.

An important message of equation (4) is that resource rents are a function of both the extraction rate and the level of the resource as well as of other variables entering but not explicit in the profit function. We refer to this as result 1.

Result 1

Natural resource rents depend in general on use rates, the level of the resource and the exogenous variables of the situation including prices.

Given that some level of harvest is profitable (i.e. the optimal action is not to select q=0) resource rents must be nonnegative. We refer to this result as result 2.

Result 2

Assuming that resource use is beneficial, resource rents as defined by (1) and (2) are nonnegative.

Proof:
If resource use is beneficial, the optimal use is $q^*>0$. Therefore, $\Pi_q(q^*,x)=\lambda$ according to (3.1). It is well known (see e.g. Leonard and Long 1992) that along the optimal path, the shadow value of the resource, $\lambda^*=\partial V^*/\partial x$, where V^* refers to the optimal value of the programme. If resource use is beneficial $\partial V^*/\partial x$ cannot be negative. It follows that $R(q^*,x) = \Pi_q(q^*,x)\cdot q^* = \lambda^*\cdot q^*\geq 0$.

Non-optimal harvesting

The above theory of natural resource rents applies equally to non-optimal as to optimal resource use. This is easily seen by noting that for any given level of resource, x, resource rents according to (4) will be defined by the use level, i.e., q, irrespective of how that may be determined.

It is informative to explore this a bit more formally. Consider for instance a resource extraction industry whose firms maximize current profits. For concreteness this industry can be imagined to be a common property fishery. Now, let an upper bound on the harvest $q°$ be imposed. This can be seen as a fisheries management device. By altering this upper bound, the harvest can be made to cover any range from zero to the open access harvest level. Since this range includes the profit maximizing harvest level (for any existing biomass), the optimal fishery is included in this formulation as a special case. Under these conditions, the firms in the industry will attempt to solve the following problem:

$$\underset{q}{Maximize}\ \Pi(q,x) \text{ subject to } q \le q^\circ,$$

where as mentioned $q°$ is the restricted quantity. A necessary condition for solving this problem is:

$$\text{(3.1b)} \qquad \Pi_q - \mu \le 0,\ q \ge 0,\ (\Pi_q - \mu)\cdot q = 0,$$

where μ is the shadow value of the constraint. Now, (3.1b) is formally identical to (3.1). Therefore the theory of resource rents as derived for optimal resource use above applies to the suboptimal case as well. The point is that it doesn't really make any difference for the theory of economic rents how q is constrained as long as it is constrained.

If the use constraint is not binding, as in the case of common property fisheries, μ will be zero[2] and therefore, by (3.1b), $\Pi_q=0$! So, in this case, rents will be zero. We state this as Result 3.

Result **3**

In a common property resource use, if there are no use constraints, equilibrium resource rents will be zero.

Note, however, that even if natural resource rents are zero, there may be rents associated with some other restricted inputs (or outputs). Thus, for instance there may be rents associated with limited outputs (e.g. output quotas), capital restrictions, monopolistic behaviour etc. Thus, there may be rents in a natural resource use industry although they are not natural resource rents in the above sense or that of expression (4). Whether such rents would be sustainable or transient is another matter.

The shape of the natural resource rents function

Given that we can use expression (4) for natural resource rents under any institutional structure, it is of some interest to derive the shape of the rents function, i.e. $R(q,x)$. Now, clearly $R_q(q,x)=D(q)\cdot(D_q(q)\cdot q/D(q)+1)$. So, the effect of increased extraction on rents is positive if the elasticity of demand[3] is less than unity and vice versa. By the same token, rents are maximized at the level where the elasticity of demand equals unity. Moreover, if $\Pi_{qqq}\leq 0$, $R(q,x)$ will be concave in q. Finally, $R_x(q,x)>0$ iff $\Pi_{qx}(q,x)>0$.

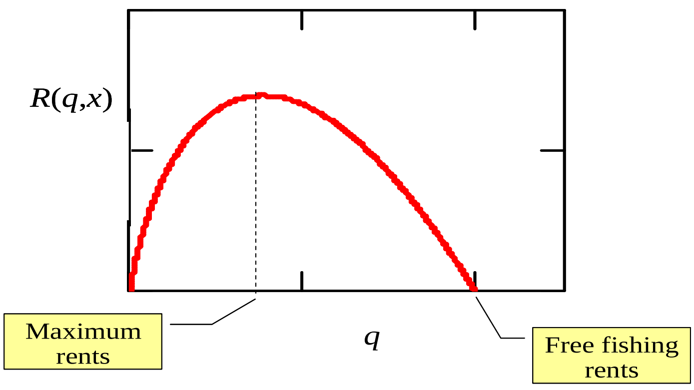
Figure 3 provides an example of a natural resource rents function for a very simple natural resource extraction model defined as:

$$\Pi(q,x)=p\cdot q-c\cdot\frac{q^b}{x}$$

where q and x represent the volume of extraction and resource as before. p denotes the price of extracted quantity and c and b are cost parameters. For this case natural resource rents are defined by the expression:

$$R(q,x)=p\cdot q-b\cdot c\cdot\frac{q^b}{x}.$$

Figure 3
Rents as a function of harvest quantity
($x=p=1$, $c=0.5$ and $b=1.1$)



2 This follows from the Kuhn-Tucker theorem.
3 Defined as $-(D_q(q)\cdot q/D(q))^{-1}$.

RELATIONSHIP BETWEEN RENTS AND PROFITS?

The key result concerning the quantitative relationship between natural resource rents or, for that matter, any rents and profits is that there is no such relationship. Rents can be greater, less or equal to profits. We now establish this formally.

Consider any economic activity using *q*. As previously mentioned, the activity may be either production activity, in which case *q* would be regarded as an input, or a consumption activity in which case, q would be a utility generating consumption good. For convenience, let's talk about profit in this section. Let *q* be constrained at $\bar{q}$. Then the overall profits (or utility) are:

$$\Pi(\bar{q},\boldsymbol{z}) = \int_0^{\bar{q}} \Pi_q(q,\boldsymbol{z})dq$$

This can obviously be rewritten as

$$\Pi(\bar{q},\boldsymbol{z}) = \int_0^{\bar{q}} \Pi_q(q,\boldsymbol{z}) - \Pi_q(\bar{q},\boldsymbol{z})dq + R(\bar{q},\boldsymbol{z}),$$

where $R(\bar{q},\boldsymbol{z}) \equiv \Pi_q(\bar{q},\boldsymbol{z})\cdot\bar{q}$; note that since $\bar{q}$ is fixed, $\Pi_q(\bar{q},\boldsymbol{z})$ is independent of *q*. But the integral on the RHS of this expression is simply the demanders' surplus or intra-marginal rents already discussed. Therefore, we have:

(5) $\Pi(\bar{q},\boldsymbol{z}) =$ demanders' surplus + rents.

Expression (5) is useful in many applications. The main point here, however, is that irrespective of the rents, the demanders' surplus can be of any sign.

An <u>exact</u> Taylor expansion of the profit function around $\bar{q}$ yields:

$$\Pi(q) = \Pi(\bar{q}) + \Pi_q(\bar{q})\cdot(q-\bar{q}) + \Pi_{qq}(\hat{q})\cdot(q-\bar{q})^2/2, \text{ some } \hat{q}\in[0,\bar{q}].$$

This holds for any *q* and therefore also for *q*=0. I.e.,

$$\Pi(0) = \Pi(\bar{q}) + \Pi_q(\bar{q})\cdot(0-\bar{q}) + \Pi_{qq}(\hat{q})\cdot(0-\bar{q})^2/2, \text{ some } \hat{q}\in[0,\bar{q}].$$

Rearrangin*g* we find:

(5) $\Pi(\bar{q}) = \Pi(0) - \Delta + \Pi_q(\bar{q})\cdot\bar{q}$,

where $\Delta \equiv \Pi_{qq}(\hat{q})\cdot\bar{q}^2/2$ is the quadratic term.

For a weakly concave profit (or, more generally, benefit) function which is necessary for economic regularity (see e.g. Varian 1984), $\Delta \le 0$. Now, $\Pi(0)$ represents the benefits obtained when there is no resource use. This quantity, thus, equals the negative of what is usually called fixed costs. Thus, presumably $\Pi(0) \le 0$. With all this in hand, we can easily derive the relationship between profits and rents summarized in Table 1.

Table 1
Relationship between profits and rents

	Profit function	
Fixed costs	Linear, $\Pi_{qq} = 0$	Strictly concave, $\Pi_{qq} < 0$
Positive ($\Pi(0) < 0$)	$\Pi(q) < \Pi_q(q) \cdot q$	?
Zero ($\Pi(0) = 0$)	$\Pi(q) = \Pi_q(q) \cdot q$	$\Pi(q) > \Pi_q(q) \cdot q$

Thus we see that profits can be either grater or smaller than economic rents. In particular, in the most plausible situation, i.e., a strictly concave profit function and positive fixed costs, the relationship in indeterminate. More precisely it depends on the relative magnitudes of the fixed costs and the curvature of the profits function represented by Δ. Let Φ represent this difference, i.e. $\Phi = \Pi(0) - \Delta$. Then, if $\Phi>0$, $\Pi(q) > \Pi_q(q) \cdot q$, and vice versa.

The relationship between variable profits, i.e., $\Pi(q) - \Pi(0)$, and rents is much more straight-forward. Inspection of equation (5) shows that variable profit are always greater or equal to rents provided the profit function is at lest weakly concave. More formally

(6) $\Pi(q) - \Pi(0) \geq \Pi_q(q) \cdot q$

The equality applies when the profit function is linear, i.e. $\Delta=0$.

CONCLUSIONS

In the above a rigorous definition of concept of natural resource rents was forwarded. This definition is in conformance with the standard classical understanding of economic rents as discussed by A. Smith (1776) and D. Ricardo (1817) and formally stated by Alchian (1987). It was shown that using this definition natural, resource rents will be defined for any level of natural resource use (provided only that marginal benefits of resource use exist). Natural resource rents can be positive or negative. However, it was shown that if the resource user maximized his benefits and was not constrained to use too much of the resource (as in some cases of external pollution), natural resource rents could never be negative.

It was further shown that there is in general no relationship between the magnitude of natural resource rents and profits or, more generally, the total benefits of resource use. The same applies to economic rents in general. Thus, the thoughtless identification of economic rents with profits and vice versa is illegitimate. These are simply two different concepts. For instance, rents might be positive while profits were negative.

There is one noteworthy difference between the natural resource rents as defined in this paper and classical or Ricardian rents as the latter are sometimes presented. In simple statements of Ricardian rents the quantity of supply is taken (or suggested) to be exogenously fixed. In the definition of economic rents presented in this paper, the supply may just as well be endogenous, i.e. set by the supplier himself. From this perspective, there exists a supply function for the quantity in question defined by the suppliers utility (profit) maximization process. In the context of natural resources, this supply curve is essentially the suppliers perceived user cost of drawing down the resource. More technically it is given by his imputed shadow price of the resource. It is this supply combined with the demand which determines the actual level of resource use. It is important to realize that in spite of this, the two definitions are still fully compatible. What would be seen as rents according to the simple perception of Ricardian rents would also be rents according to the definition of this paper. The latter is simply a generalization of the former although perhaps not of the actual concept of rents Ricardo had in mind and probably not that which A. Smith discussed.

Having provided an explicit definition of natural resource rents, the question naturally arises as to how to obtain estimates of those rents in particular empirical cases. Fortunately, according to the definition, this task is quite straight-forward. Natural rents are defined simply as $R(q,x) = \Pi_q(q,x) \cdot q$, where q is the resource use, x the resource level and $\Pi(q,x)$ the benefit function. So, all that is needed to estimate natural resource rents in any setting is knowledge of (i) the benefit function, (ii) the current level of resource and (ii) the current level of resource use. Oc course, the empirical task of actually obtaining these estimates may be substantial.

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Appendix

Demand and supply of natural resource use

In the main text it was explained that (optimal) natural resource use — and, consequently, resource rents — could be seen to occur at the intersection between the demand and supply of natural resource use. Here we attempt to further clarify this idea.

In standard economics, supply and demand are associated with two separate parties, suppliers and demanders. In the context of natural resources use, the resource users may be seen as demanders and the resource owners as the suppliers. For analytical purposes it is irrelevant whether these two parties actually exist. In many cases, the resource user and the owner are one of the same. We merely imagine their existence here to show how the supply and demand curves naturally arise.

Let us now consider how resource use would proceed if these two parties, the resources users and the resource owners interacted in a perfect market.

Resource users, of course, try to maximize their benefits, i.e. the function $\Pi(q,x)$, where *q* is resource use *x* resource stock. In doing so they are constrained by market prices for the two goods. So their maximization problem is:

$$\underset{q,x}{Max}\ \Pi(q,x)-s\cdot q-v\cdot x\,,$$

where *s* and *v* are the prices of *q* and *x*, respectively. Obviously, necessary conditions for solving this problem are:

(A.1) $\Pi_q = s$, all *t*,

(A.2) $\Pi_x = v$, all *t*.

Obviously, (A.1) is the (inverse) demand function for resource use, in which we are particularly interested. (A.2) is the demand function for resource stock, which affects the benefits from fishing). It is interesting to note that these demand functions are static — they do not directly take the future stocks into account. This is as expected. The users are price takers and are not in a position to control the evolution of the resource.

The resource owners will want to maximize the present value of their monetary gain from the resource (remember that by the design of this example they are not users). This they can do by determining their supply of *q* as follows:

$$\underset{\{q\}}{Max}\ \int_0^\infty (s\cdot q+v\cdot x)\cdot e^{-r\cdot t}dt\,.$$

Subject to: $\dot{x}=G(x)-q$

$x(0)=x_0$, given.

Necessary conditions for solving this problem include:

(A.3) $\dot{x}=G(x)-q$

$$\dot{s}-r\cdot s=-v-\sigma\cdot G_x\,.$$

Now, by (A.2), $v = \Pi_x$, the second of these equations becomes:

(A.4) $\dot{s} - r \cdot s = -\Pi_x - \sigma \cdot G_x$.

Solving the two differential equations (A.3) and (A.4) subject to the initial condition, $x(0) = x_0$, and the appropriate transversality condition, yields the function:

(A.5) $S(q;r,x_0,t)$.

This function is the (inverse) supply function of harvest at all points of time. It is dynamic — it depends explicitly on time. In equilibrium, the time dependence disappears as illustrated in Figure 2 in the main text.

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