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The devil in the details: Non-convexities in ecosystem service provision

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ABSTRACT

Standard economic theory is built on key assumptions regarding concavity and convexity, particular with respect to the production possibility frontier. Non-convexity is readily demonstrated using a two species conventional model. Now that ecosystem services are growing in prominence it is important to confirm that typical natural resource production relations obey these conditions. If not, innocently prescribing price or allocation policies can lead to a minimum rather than a maximum or to wrong equilibrium solutions in general. This is a particular danger in decentralized pricing systems.

1. Introduction

Ecosystem services are broadly defined as those processes of ecosystems that support (directly or indirectly) human well-being (Costanza et al., 1997; Daily, 1997). Ecosystem services arise from complex interactions among ecological elements, and occur at multiple scales, from climate regulation and carbon sequestration at the global scale, to flood protection, soil formation, and nutrient cycling at the local and regional scales.

A fundamental feature of the ecosystem service concept is that it adheres to a strictly anthropocentric perspective. Intrinsic value (unless argued in terms of increasing the spiritual/cultural value of an area to a person) is categorically excluded. The distinction is clear-cut when

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referring to the goods and services that people directly experience. This is the case with the ecosystem services listed under provisioning, regulating and cultural service categories as described by the Millennium Ecosystem Assessment (MEA, 2005). However, the distinction becomes less clear when dealing with the supporting service category (for example when one species supports the presence of another), in which the (human) beneficiary may not experience or be otherwise aware of the myriad species supporting the 'direct' good or service.

The ecology literature is replete with examples of interdependence among species. One of the central features of biology is that there are food webs or food chains linking one species to another. More generally, there are many critically important causes of species interdependence, energetic, and biogeochemical linkages between ecosystem services. Yet in contrast, one of the central features of most all of the bioeconomics models in economics is the presence of only one species, or trade-offs weighed against a single ecosystem service.

The Beijer Institute has devoted substantial energy to study the topic of non-convexities, with annual meetings on the topic starting in 1998 and culminating in the publication of symposium papers in 2004 (Dasgupta and Mäler). The focus of the papers in this volume is inherent instability in the models studied, a problem not present in the models below. Their interest in non-convexities was stimulated by discovering that the quality of shallow lakes subject to polluting inflows – fertilizer residuals of agricultural land and human waste water – would jump from clear to turbid state (see Mäler et al., 2004 in Dasgupta and Mäler). In many circumstances, our mis-specification of the model structure is innocuous but there are other times when simplification leads to suboptimal decision making. More serious consequences have been demonstrated by Sterner (2007) who has shown that assuming one stock of fish, when there are more, leads to irreversible extinction of one species.

Creating markets for traditional non-market goods such as certain pollutants can be expected to achieve workably economically optimum solutions as long as the standard concavity–convexity assumptions economists make are, in fact, met in the real world. These assumptions often hold for the goods and services customarily traded in markets in our economy so our quarrel is not with the efficiency of typical markets. The purpose of this paper is to draw attention to the pitfalls of oversimplified models by developing a few models for ecosystem services. We show the comparative ease of creating non-convexities arising from the biological anatomy of models, or when the interaction among ecosystem services and conventional outputs are omitted. This, in turn, throws a monkey wrench into policy making, particularly when there is a taste for creating market prices for heretofore, non-market goods and services. This topic is particularly germane given the current and growing enthusiasm for bringing ecosystem services to the fore (MEA, 2005; Daily, 1997; EPA, 2006; de Groot and Wilson, 2002, among others).

We show that a non-convexity can arise whenever there is a sufficiently strong positive technical externality, between production functions producing two (or more) separate goods, given a fixed factor such as land. That is, when there is joint production with one technology favorably enhancing a second output directly or indirectly, again each sharing a fixed factor, a non-convexity in the production possibility frontier can arise. We further show that a standard predator–prey model can display a convex production possibility frontier.

Just as one swallow does not guarantee a summer, a few non-convex ecosystem structures do not guarantee widespread failure in the attempt to bring about a socially efficient allocation in a decentralized economy for heretofore non-market services or products arising from non-market resources. However, we believe that the biological conditions which bring about a perverse production possibility frontier (PPF) are sufficiently innocuous and pervasive that caution surely is in order.

As policy makers attempt to limit undesirable practices, economists often estimate the particular point that will describe the equilibrium price (quantity) for the policy-limited quantity (price). In the negotiations surrounding cap-and-trade policies in the fisheries and global climate change arena, for example, policy makers have to acknowledge that the effectiveness of these tools is only as good as our ability to "get the prices (quantities) right," holding constant assumptions about the underlying functions; i.e., the deeper dynamics of the system. Despite heroic efforts to estimate a given point along a function (or points in the case of multiple equilibria), and critical scrutiny of the actual function itself, we often fail to acknowledge factors that contribute to the dynamics of a function and thus the change of its shape over time. Current policy outcomes are enormously dependent on the expectation

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that we have these points (and thus functions and thus their dynamics) right. This paper gives us reason to be more cautious or meticulous than normal in our analysis because ecosystem service systems often do not obey our standard assumptions necessary for a unique set of equilibrium prices. The devil in the details may lie at one layer deeper in the system than the one that is subject to current debate.

2. Background

Since the 1970s, the focus on natural resource production has evolved over time from producing resource outputs themselves to an increasing ability to associate ecological health, sustainable harvest, restoration to the products themselves. In the 1960s and early 1970s, pioneering work by Krutilla (1967), Hammack and Brown (1974), and Fisher and Krutilla (1975), among others, greatly expanded the set of "goods and services" generated by natural systems considered by economists to be of value to humans. Krutilla (1967) changed the way resource economists think about dealing with the issue of "providing for the present and future amenities associated with unspoiled natural environments, for which the market fails to make adequate provision" (p. 778). This resulted in a major efforts in the 1970s and 1980s to quantify the non-market resource services and values (now referred to as ecosystem services) being produced on public and private lands, and provided some of the first impetus to place economic values on the non-market products.

Numerous authors, writing on ecosystem services have brought about recognition that economic activities are embedded in and dependent upon the biosphere (Daily, 1997; Costanza et al., 1997). Thus, with help of natural scientists, attention was focused on the value of explicit ecological processes that ultimately improve (service) the condition of the human environment such as water filtration, carbon sequestration, pollination, soil formation, nutrient cycling and the like. The Millennium Ecosystem Assessment painted a stark picture of declines in ecosystem services worldwide (MEA, 2005), raising attention for growing economic systems, populations, impacts and trade-offs associated with land use decisions, material and energy consumption.

2.1. Production possibility frontiers

For our purposes, a production possibility frontier shows the combination of two (or more) goods/services that can be produced with a *fixed* factor. Large conservation organizations, private companies, and non-governmental organizations have organized and often heavily funded major ecosystem service efforts, using the concept to assist the formation, functioning, and support of markets, institutions, and management that more effectively optimize management of market and non-market resources. Through incorporation and use of information on these ecosystem services and their shadow price values, production possibilities frontiers are increasingly seen as a tool to help capture trade-offs in planning processes. There is a small cottage industry in the policy arena where the author's have exploited the idea of the production possibility frontier (PPF) to discuss the trade-off between two goods or services available in a given ecosystem. However, detailed ecological information is often only available for a single ecosystem service.

Production possibility frontiers have been used to examine whether willingness to supply non-marketed ecosystem services (*ES*) is influenced by whether or not the non-marketed *ES* are produced jointly with agricultural products (Wossink and Swinton, 2007), to calculate shadow prices of social and biological outputs of forest management in India (Misra and Kant, 2005), and in other systems to model how production of marketed commodities and protection of natural systems conflict (Nalle et al., 2004). Yet attention for non-convexities in these systems is not common, with only a few studies examining non-convexities in electricity resources (Bjørndal and Jörnsten, 2008) and McCoy's (2003) examination of human-wildlife conflicts. Further, the applications of production possibility frontiers apply to static analysis where it is assumed that ecosystem services can be instantly increased without investment, and have no threshold below which they collapse (Norgaard and Jin, 2008). These two assumptions often don't hold upon closer examination of ecosystem service data and information.

A few tendencies have deviled the application of PPFs in addressing ecosystem services or non-market resources. First is that often studies are not explicit about what is being held constant (a necessary criterion for effective PPF application). A second tendency is to assign the troublesome character to the presence of humans or human interaction in the system, rather than an inherent problem of joint production or technical externalities (McCoy, 2003). A third tendency is to weigh trade-offs between one marketed good, and one non-marketed good, for example timber vs hunting (Nanang and Hauer, 2008). Yet joint production is a typical problem for ecosystem service accounting (Boyd and Banzhaf, 2007), and the human element is not possible to remove from an ecosystem service perspective, thus we propose that more care be taken to assure that the system treated with PPFs is not subject to non-convexity.

How common is non-convexity? That is, of course, difficult to know unless one has a grip on the nature of the population and all its elements. In our paper, we show that a standard predator–prey model creates a non-convexity in production. Technological externalities or joint production in one output sector can have the same effect. Dasgupta and Mäler (2004a,b) point out that economists frequently assume fishery growth functions that often have a convex–concave structure (and conclude that ‘‘the price system is therefore generally not viable for implementing the optimum program.’’). One way the convex–concave structure arises is when there is a critical population threshold below which the population inescapably marches to extinction. Scholes demonstrates that in the African savannah, tree cover (basal area) and grass production PPF in mixed tree–grass ecosystems is convex rather than exhibiting the desired concavity over most of its range. Crepin (2004) analyzes a model of boreal forest where pine, birch and moose interact in a convex rather than in the ‘‘desired’’ concave manner.

In the next two sections, we set out a well-behaved model with two standard independent, dynamic population equations, each sharing a common fixed factor. We then introduce a predator–prey relation and the PPF becomes irregular or bowl shaped. In Section 5, the PPF for a fixed factor, static model is derived that is also irregular when there is a positive externality, or one output sector that produces a joint product. A concluding section follows.

3. The model

Since we are celebrating Tom Crocker's retirement, it is imperative to note his very early concern about non-convexities (Crocker and Forster (1981) in the context of water quality close to three decades ago. We will only sketch the model to establish its relevance. A renewable natural resource such as fish follows a conventional Lotka (1925) population dynamics where acid rain precipitation acts as a predator in a river system. Harvest is proportional to stock as in the standard Schaefer model (effort fixed). In their empirical analysis, Crocker and his co-author find that the sufficient condition or the second order condition for a maximum may not be met and a naïve solution could produce a *minimum* not a *maximum*, as our paper below will make more clear.

The PPF (and the supporting product price ratio and indifference curve) is the locus of where want to derive the existence of non-convexities and the ensuing consequences. To avoid ambiguity, Fig. 1 is

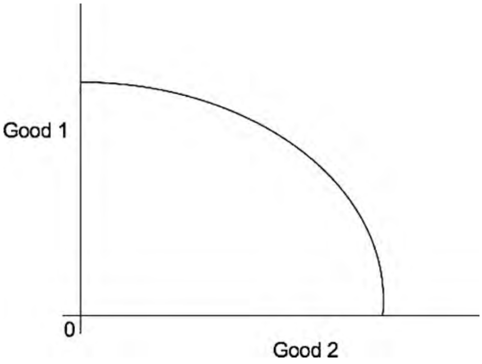

Fig. 1. Production possibilities frontier (PPF).

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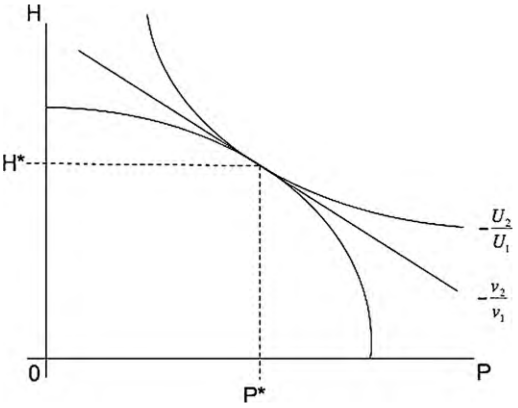

Fig. 2. Market equilibrium.

an illustration of a well-behaved PPF. The function is concave and the set of possible production combinations is convex. The figure is hat shaped we will say if the function is concave.[1]

Policy makers assume there are two species of value, H and P. For concreteness, imagine that hyenas (*H*) are competing for some given antelope species (*K*), the fixed factor, along with lions (*P*). It is assumed that we can control the access of each species to antelope.

Initially, the population dynamics equation for each of the two species is of the standard logistic form (Clark, 1976),

$$\frac{dH}{dt} = r_1 H\left(1 - \frac{H}{\sqrt{K}}\right) = f(H,K) \quad 0 < K < 1, \tag{1.1}$$

$$\frac{dP}{dt} = r_2 P\left(1 - \frac{P}{\sqrt{1-K}}\right), \tag{1.2}$$

where the fixed factor, *K*, plays the natural role of carrying capacity. dH/dt and dP/dt are the time rates of growth for *H* and *P*, respectively. The parameters r_1 and r_2 are the intrinsic rates of growth for *H* and *P*, respectively. We abstract from non-steady states. Therefore, in equilibrium, $dH/dt = dP/dt = 0$. Construction of the PPF is straightforward. From (1.2),

$$K = 1 - P^2$$

Substituted into (1.1) yields the PPF,

$$H = \sqrt{1 - P^2} = W(P), W' < 0, W'' < 0, P < 1, \tag{2}$$

illustrated in Fig. 1.

The standard equilibrium optimum solution for H^*, P^* is derived from the consumer maximizing utility subject to a budget constraint with fixed unit prices v_1 and v_2 for *H* and *P*, respectively, illustrated in Fig. 2.[2] Formally the utility maximization problem is: Max. $U(H, P) + V(M - v_1 H - v_2 P)$, where *M* is money income, *V* is the Lagrange multiplier, and the utility function is assumed to be well behaved. From the first order conditions,

$$\frac{U_1}{U_2} = \frac{v_1}{v_2},$$

The indifference curve, U_1/U_2, and the price ratio, v_1/v_2 are illustrated in Fig. 2.

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[1] More formally, a function *f*(*x*, *y*) is concave if it lies above (or on) the chord joining any two points, see Silberberg (1990).

[2] We make the strong assumption that the natural resource stocks have unit prices or rental rates in order to finesse the further relationship between ecosystem flow services such as harvest and the stock. The rental rate for the resource is just the price of the flow service, if it exists, less its marginal cost of production, see (Brown, 1974). Moreover, the conventional treatment of equilibrium takes product prices as given to both the consumer and producer, thereby producing a fixed price ratio. We wanted to stick to the basic story before venturing into the world of non-convexities.

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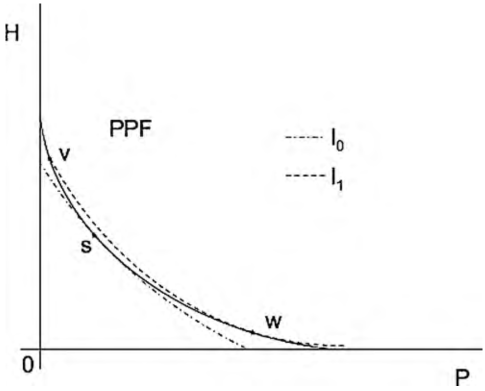

Fig. 3. Multiple equilibria.

4. The true model

A natural error to make in a bioeconomics model is to omit a third or more species which interacts in some fashion with the first two species. It is easy to construct non-convexities in this case but it carries the extra baggage of a third differential equation. It seems more straightforward to allow interaction between the two species as we do below:

$$\frac{dH}{dt} = r_1 H\left(1 - \frac{H}{\sqrt{K}}\right) - aH^2P = f(H,K) - aH^2P, 0 < a < 1 \tag{3.1}$$

$$\frac{dP}{dt} = r_2 P\left(1 - \frac{P}{\sqrt{1-K}}\right) = G(H,K) \tag{3.2}$$

In this special case of the Gause model (Clark, 1976), lions are the predators of hyenas, illustratively. The parameter "*a*" captures the ability of hyenas to be transformed into lions.

The PPF for (3.1) and (3.2) is

$$H = r_1 \frac{\sqrt{1-P^2}}{aP + r_1}, H' < 0, H'' < 0. \tag{4}$$

For "*a*" small, the PPF is well behaved. As "*a*" increases, the PPF flattens out and the feasibility set becomes bowl shaped or non-convex, see Fig. 3. For those who like video versions, http://faculty.Washington.edu/gbrown/Model-Movie.mov which shows how the PPF varies as "*a*" goes from 0 to 1. The PPF is denoted by *H′P′*. Note in Fig. 3 that S, a possible solution (where the consumer's marginal rate of substitution between H and P equals the producer's marginal rate of transformation), produces a social minimum.

The problem arising from non-convex PPF's have been well described by Baumol and Oates (1975) and we paraphrase their analysis below.

(i) In Fig. 3, *S* is a point of minimum social welfare but is a possible solution with Pigouvian charges where the budget line passes through *S*.
(ii) *W* is a point of tangency between the indifference curve I_1 and the solid line PPF but indifference curves intersecting *H′P′* above *V* are superior options.
(iii) When the PPF is bowl shaped, there may be a point of local maximum value of output at either *H′* or *P′* but there is no guarantee that the social optimum exists either at *H′* or *P′*. Parenthetically, either of these solutions, if optimal, implies the extinction of a species.

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For the three above reasons, simply creating a decentralized markets for ecosystem services or other non-market goods dependent on biological production is not a sufficient guarantor of moving toward welfare improvement when the biota interact in natural ways that create ambiguous market equilibrium solutions. When biological production functions are in play, one must be more vigilant about testing the assumed functional forms against ground truth and making sure that the convexity–concavity assumptions for production and preferences necessary for unique, stable equilibrium are indeed met.

In the words of Baumol and Oates, in the presence of non-convexities, Pigouvian charges or subsidies "no longer can be depended on to give the right signals, . . ., [to] tell us whether we are at a welfare maximum or minimum, whether a maximum is local or global, or in which direction the economy should move to secure an increase in welfare." When charges or subsidies are unreliable policy instruments, then a quantity policy rule is the logical alternative assuming, of course, that both the PPF and preferences are empirically known. After all, in this primitive model there are *no* other choice variables. For those uncomfortable with the forced retreat to the "command and control" solution, they will have to introduce ad hoc mitigating assumptions or embellish the model with a strategic layer of political economy or some other structural innovation that provides an escape mechanism.

5. Timber vs other ecosystem services

Another example of non-convexities arises from positive externalities or spillovers. Curiously, most discussions of externalities that may or may not cause non-convexities are of the negative kind as when Baumol and Oates (1975) talk about the utility plant that generates pollutants that impose costs on a nearby laundry. All the cases in Dasgupta and Mäler feature negative non-convexities.

Imagine for a given amount of land, the producer can specialize in the production of timber or other ecosystem services and his/her choice is to choose the fraction of land to devote to each output. On the land which produces timber, other ecosystem services are produced. There is therefore a joint product on this land, not necessarily in fixed proportions.

An example of this case can be seen in areas where forest lands (subject to timber harvest or not) are compatible with providing wildlife habitat (Rohweder et al., 2000) or valuable hydrological benefits for the downstream urban areas (Kruutilla et al., 1983; McCarthy and Lindenmayer, 2007). Studies from the H.J. Andrews Forest Research data, where observations of both control and treated watersheds in a classic paired-basin study tracked timber harvest intensity and water production empirically in small watersheds. The studies involved a long time period of forest regrowth and hydrologic recovery, and demonstrated the joint production of water and timber on the harvested stands (Waichler et al., 2005; Grant et al., 1990; NRC, in press).

We can write out the timber production function generally to include a Ricardian element, where, as the fraction of land allocated to trees increases, the quantity of trees forthcoming is subject to diminishing returns because the quality of land diminishes in a continuous fashion. The model containing this case can produce non-convexities but assuming constant returns to scale produces the same qualitative result, has a simpler structure, the result is clearer and conforms to the Faustmann solution for determining the time of optimal rotation which generally is independent of the size of the plot.

Suppose there is a unit of land, a fraction, S of which can be devoted to growing trees for timber, tree units are normalized to accommodate the production relation,

$$T = S. \tag{5}$$

In the background, there is a decision maker who has solved the single or optimal rotation problem and the optimal rotation time is the same for each and every acre of identical quality land.

The remaining amount of land $(1-S)$ is used to produce non-timber ecosystem services, ES,

$$ES = (1-S)^b.$$

In addition, some ecosystem services such as water, recreation days or habitat for birds are produced on the tree growing property. Total ecosystem services produced is

$$ES = (1-S)^b + aS^d, \tag{6}$$

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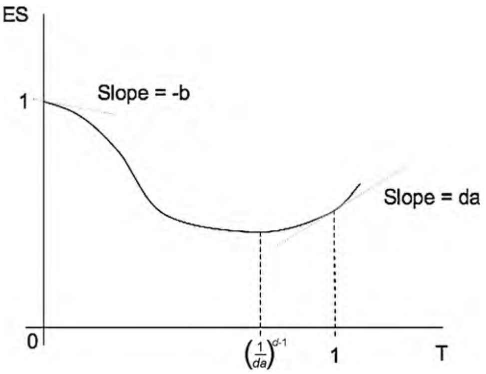

Fig. 4. PPF with positive externality.

where "a" equals a positive weight permitting the aggregation of the two different types of ecosystem services, if there is a difference.

Substituting (5) into (6) and taking the derivative yields,

$$\frac{dES}{dT} = -b(1-T)^{(b-1)} + daT^{(d-1)}. \tag{7}$$

The surface of dES/dT as S is varied is the PPF and conventionally has a negative slope. We can see from (7) that, for example, as the value of the ecosystem services produced on the land specializing in timber grows, particularly as "a" grows, in the positive second term on the r.h.s. of (7), it is quite possible for $dES/dT > 0$. When no land is in timber, $S=0=T$, $dES/dT=-b$, illustrated in Fig. 4; and when all land is in timber, $S=1=T$, $dES/dT=da$, illustrated in Fig. 4.[3] It can be shown that the optimal land devoted to timber grows as "a" increases because the positive externality is increasing.

It is apparent from the non-concave shape over part of the range of the PPF in Fig. 4 that if the unit values of timber and other ecosystem services were somehow known and there was a conventional market in these goods and services, we could not trust exchange in this unfettered market to bring about a social welfare maximum. The devil, as we called it in the title of the paper, is the positive externality or spillover that arises here when there is a technological (biological or physical) interdependence between two productive activities. The intent of this paper is to alert researchers and policy makers to the potential problem and not to elaborate on designs for solving the problem. However, a word of caution about unlikely solutions and difficulties is in order.

The PPF tool often is used when there is one firm trying to find the best combination of two or n goods to produce, subject to a fixed resource. In this setting one might be tempted to argue that the solution is straightforward. The firm merely "internalizes the externalities." Well, the fact is that there is enormous scientific uncertainty about how, for example, species or natural elements in a given ecosystem interact with species or other elements in that ecosystem.[4] Even within the straight jacket of the model here and even if the firm or many firms faced a linear price ratio, it or they do not know the product combination that maximizes utility.

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[3] Since the slope of the PPF is negative for small T and positive for large, it hits at least one minimum in between which occurs at $T=(1/da)^{1/(d-1)}$ assuming $b=1$, or constant returns on the land specializing in ES.

[4] For example, the first author and a colleague interviewed all the leading researchers whose research focus is Lake Victoria fisheries and although they recognized the important species biological interdependence between the two most commercially valuable species, none believed that they had credible estimates of the species interaction coefficients. The natural way for an economist to estimate the economic damages from an oil spill that causes losses of non-market fish species such as benthic organisms is to utilize the food web production function that connects the non-market species with species that have market value (and cost data). Despite the substantial research funds available on all sides for litigation, such research has never been done because the necessary data do not exist. One can go on and on with examples as any natural resource economist with inter-disciplinary experience with natural scientists well knows.

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The concept of the PPF is general and can just as well refer to two or more firms producing two or more goods subject to a fixed factor. Let us make the heroic assumption that there is no technical uncertainty. But before going on, it really is a heroic assumption because the ''uncertainty'' often is a key strategic point of the debate about natural resource use; are the Minke whales, in fact, threatened in the debate between Iceland and other nations in the International Whaling Commission? Surely ''uncertainty'' has been the crux argument that some administrations have used for years to stonewall attempts by other nations to galvanize the world to do something about global climate change. Having dispensed with technological uncertainty, there remains the problem with transaction costs to use a catchall term. Water, fish, fowl, air and mammals migrate. They do not obey political-economic boundaries. North Pacific Pollock and other fishery and mammal species even go into areas that are open access, not subject to any nation's jurisdiction, making them an open access, common property species. Transactions costs typically increase with the number of interested parties and costs increase even more when there are both gainers and losers associated with any given decision. This sort of problem arises when there are multiple equilibria, i.e. when there is no unique equilibrium because nature does not deliver up economically congenial production functions.[5]

To sum up this section then, the potential for inefficient solutions arises from non-convexities due to positive technical externalities between two or more ecosystems or between two (or more) uses of a given ecosystem. The probability of trouble increases with the magnitude of the technical externality. This conclusion is based on a specific example while the general conditions supporting it are developed in the Appendix A.

6. Conclusion

One acts at one's peril by treating ecosystem services as any other good or service. If one employs a standard economic model, make sure that the standard concavity assumptions are met before recommending policies. If not, policies based on these models can result in non-optimal decision making which results in social losses.

Creating markets for traditional non-market goods such as certain pollutants can be expected to achieve workably economically optimum solutions as long as the standard concavity–convexity assumptions we make are, in fact, met in the real world. These assumptions seem reasonable for many of the goods and services customarily traded in our economy.

In contrast, we do not know much about the structures of natural resource systems of production and in the face of this substantial ignorance we recommend that caution is advised when economists create models involving natural resources in order to inform policy makers. Our recommendation to be cautious is particularly appropriate now that substantial emphasis is being given to the provision of ecosystem services.

We think there is sufficient analytical and empirical evidence to suggest that economist's recommendations to policy makers to use particular pricing policies to achieve a better allocation of ecosystem resources should be vetted by respected natural scientists who confirm that the biological production functions have an acceptable credibility.[6] If non-convexities in the biological structure of a bioeconomic model are sufficient to make Pigouvian charges (taxes) or subsidies untenable, then the only other policies admissible.

are rules involving quantities; i.e., command and control. In the standard models we construct there are no other logical choices. For conventional economists, this is an unsettling conclusion one must draw to be avoided only by enriching our models with more complexity.

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[5] Once technical uncertainty is resolved there is the usual randomness in any set of natural relationships and then if the natural resource is non-private as most natural resources are, there is the question of whether a price or quantity policy is the best regime (Weitzman, 1974).

[6] We think it is empirically relevant to remark that model builders do not view the same world as researchers working ''on the ground.'' Those steeped in ''reality'' worry about many more variables than the model builders. We acknowledge that choosing who does the vetting about model relevance can be critical.

Appendix A

Suppose the tree production function is given by

$$T = h(S),\ h'(S) > 0.h''(S) = 0 \tag{A.1}$$

where T, trees and S, share of land allocated to trees. Recall, the standard assumption in the Faustmann treatment of the tree rotation problem is that it is independent of the size of the stand, the assumption made here.

From (A.1),

$$S = h - 1(T) = f(T),\ f'(T) > 0,\ f''(T) = 0. \tag{A.2}$$

The ecosystem service production function on its share of land is given by the first term on the right hand side of the equation below,

$$ES = g(1 - f(T)) + K(f(T)),\ g' < 0,\ g'' > 0,\ K'(s) > 0,\ K''(S) < 0. \tag{A.3}$$

The second term on the right hand side is the positive technical externality that benefits the producer of environmental services arising from tree production. The technology specializing in producing ES is characterized by diminishing returns as is the character of the environmental services arising from the land specializing in tree production.

Then from (A.3),

$$\frac{dES}{dT} = g' f' + K' f'. \tag{A.4}$$

Since $g'f' < 0$ and $K'f' > 0$, the PPF has an ambiguous sign;
$dES/dT > 0$ when

$$K' > -g'. \tag{A.5}$$

Qualitatively, the condition specified in (A.5) is unaffected by making the more general assumption that the production of timber is subject to diminishing returns.

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