real-world economics review, issue no. 74
subscribe for free

The natural capital metaphor and economic theory

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Introduction

The natural capital (NC) metaphor is currently being introduced to provide a framework for the economic measurement of environmental degradation. Advocates of the NC metaphor argue that because the depletion of "natural stocks" is not adequately measured, economic activity ignores the costs of environmental destruction. Measuring in economic terms the stocks of "natural capital" and of their "ecosystem services" is the central objective of the natural capital metaphor.

The metaphor makes a clear reference to neoclassical marginal theory that considers capital as a "factor of production", on the same footing as labour, and involves a conception of capital as a stock that produces an annual flow of final goods. The literature on natural capital typically implies there is a smooth passage from the domain of metaphor to the realm of rigorous economic analysis.

The purpose of this paper is to examine the roots, scope and limitations of the "natural capital" (NC) metaphor from the standpoint of economic theory. We identify several deep problems affecting the use of this metaphor and conclude that as a result this natural capital approach will not be able to deliver on its promises to measure natural capital stocks or the stream of natural capital services. It is likewise unable to assess the economic costs of environmental degradation or what it means to maintain natural capital intact.

The structure of this paper is as follows. The *first section* focuses on the nature and structure of this metaphor and on the attempts to provide a definition of natural capital. The *second section* examines the relation between the NC metaphor and the concept of capital in marginal economic theory and in the context of aggregate production functions. The backdrop here is provided by the Sraffa-based critique to marginal capital theory. In the *third section* we shift to general equilibrium theory, where there is no need for an aggregate production function and no uniform rate of profit. Stability analysis in general equilibrium systems, as well as the negative implications of the Sonnenschein-Mantel-Debreu theorem provide the setting for this part of the analysis. The *fourth section* concentrates on a different set of problems encountered by proponents of the NC metaphor and examines the difficulties in assigning prices to "nature's stocks" and their "environmental services", especially when reverse capital deepening becomes an empirical possibility and reswitching emerges in the use of discount rates. We include here a reference to uncertainty and to financial capital. Our concluding remarks summarize the main findings and offer some alternative approaches.

SECTION I Natural capital: metaphors and definitions

Metaphors, similes and analogies have played a role in science and in explaining abstract concepts to non-specialists. They can indeed be useful to convey an image, but what may be gained in communication may be lost in precision. There is a significant risk of making good metaphors that can lead to flawed reasoning. This is an important point because metaphors often acquire a life of their own and they can end up, as Vickers (1984) points out, owning the people that created them.

The origin, structure and scope of metaphors need to be well understood, not only to take advantage of their potential, but also to understand their limits. Failure to grasp the boundaries of a metaphor may lead to abuse in its application. In particular, when a concept is transposed metaphorically from one discipline to another, its theoretical status needs to be well understood. If that concept is undetermined, the validity of the metaphor needs to be questioned. The poetic value may be important, but its accuracy may be wanting or even misleading.

The notion of "natural capital" has a short history. It began to be used by authors like Schumacher (1973) and it appeared (under a slightly different terminology) in *Our Common Future* (1987), the report of the Brundtland Commission. The Millennium Ecosystem Assessment (2005) explicitly recognizes it as an "economic metaphor". Attempts to define this notion in more precise terms were first published by Pearce (1988), Costanza (1991), Costanza and Daly (1992), Daly (1994) and El Serafy (1996).[1]

In their attempt to define natural capital Costanza and Daly (1992) state that:

> "Since 'capital' is traditionally defined as produced (manufactured) means of production, the term 'natural capital' needs explanation. It is based on a more functional definition of capital as 'a stock that yields a flow of valuable goods or services into the future'. What is functionally important is the relation of a stock yielding a flow - whether the stock is manufactured or natural is in this view a distinction between kinds of capital and not a defining characteristic of capital itself."

The background here is of course the original definition of capital in Fisher's book *The Theory of Interest* (1930).[2] In fact, almost all of the references to the notion of natural capital depend heavily on the analysis of Irving Fisher on capital as a stock that is a source for a flow of income (see Daly 1994 and Lawn 2006). Adding the word 'natural' to Fisher's definitions of capital and income takes these and other authors to the notion of 'natural capital'.

Today the use of the terminology of natural capital follows this tradition (TEEB 2010, Voora and Venema 2008, WAVES 2015). International business organizations and conferences promoting the use of this approach rely on the same definition.[3] But the problem with these "definitions" is that their simplicity betrays their inaccuracy.

The natural capital approach is based on the premise that human societies have at their disposal a collection of "assets" that provide streams of services. The different collections of assets include manufactured production goods, financial assets, as well as "human" and

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[1] A good analysis and synthesis of the evolution of this metaphor is found in Akerman (2005).
[2] A modern account of Fisher's analysis is provided in Hirshleifer (1958).
[3] See for example the definitions used by the Natural Capital Coalition (https://www.naturalcapitalcoalition.org), the World Forum on Natural Capital (http://naturalcapitalforum.com) and the Natural capital Declaration (http://www.naturalcapitaldeclaration.org).

"social" capital. All of these have their own problems when it comes to their conceptualisation, but this paper focuses on the notion of "natural" capital.[4]

Although the natural capital approach is based on a metaphor, many of its advocates feel they must provide a definition. Definitions need to express the essence or genus of the object being considered, plus a differentia that separates this object from others that are also contained in the genus. The differentia typically describes the attributes or the specific qualities that distinguish an object from all other elements of the same class. But in all the "definitions" of natural capital in the literature there is nothing of this to be found: there is no genus and there is no differentia.

Take into account the following example. The World Forum on Natural Capital (held in Edinburgh in November 2015) considered that "Natural Capital can be defined as the world's stocks of natural assets which include geology, soil, air, water and all living things". According to this text nature's components are a stock of capital, an asset. In this text, as in many others that make the same mistake, there is no explanation of the essence of the genus: there is no explanation of the essence of 'natural capital' and no account of the qualities of the differentia.

In addition, texts discussing natural capital typically involve circularity: natural capital, we are told, is the name given to a stock of capital assets that we find in nature. This adds nothing to our knowledge and fails the test of any definition. This type of "reasoning" is deeply flawed: in logic one cannot use the term being defined as a part of the definition.

The lack of a serious definition is accompanied by a shift from metaphorical analogy to identity as the notion that "Nature Is Capital" is repeated without respite. As Vickers (1984) points out this is similar to the procedure followed by Paracelsus and other alchemists who supported their "assertions with a style of argument that moved directly from analogy to identify, literalizing metaphors to elide distinctions and fuse disparate realms". In this process the limits of analogies become lost in translation and metaphors are transformed into identities.

Proponents of the NC metaphor say that the objective is to be able to measure natural capital in economic terms. Their procedure consists of two steps. First, the natural capital metaphor is used to establish an identity: "Nature's assets are Capital". In the second step the actual measurement of these 'assets' is attempted. Since these 'natural assets' are not man-made and many do not have prices attached to them, pricing the different components of "natural capital" and its flow of services requires different valuation techniques. But there is a question that should be examined first: is it possible to measure "capital" in economic terms?

Section II. Natural capital and the aggregate production function

How much natural capital is there available? This is a question that adherents to the NC approach would like to answer. They also seem to think that in economic theory the same question about man-made capital has been answered satisfactorily. Indeed, this is not the

[4] The notion of capital is therefore extended to almost everything that exists in our universe when this list of "assets" is considered. Proponents of this approach should be aware of the fact that when one word serves to designate everything (as in "Everything is Capital") it can become meaningless.

case. In this section we will see why the question 'What is the quantity of capital?' does not receive an unambiguous answer in economic theory.

The concept of capital has always been at the centre of theoretical discussions in economics. The most important theoretical debate in the second half of the twentieth century, known as the Cambridge controversy centred precisely on the concept of capital. The use of the natural capital (NC) metaphor cannot ignore the essence and implications of this debate.[5] The classic and comprehensive account of this debate is Harcourt (1972), while a more recent description is Cohen and Harcourt (2003).

The centre of this debate is simple. The word 'capital' has two different meanings in economic theory: it denotes a sum of money and it also serves to designate a set of machines, tools and other heterogeneous production instruments. Of course, it can be assumed (not without problems) that labour can be measured in man-hours with the help of some kind of index number solution, but capital poses a unique problem. Machine tools, blast furnaces, trucks and shuttle-less looms are heterogeneous objects that cannot be added in any simple manner. In other terms, there is no physically homogeneous and malleable substance called 'Capital' that can be applied to the production of all kinds of goods. However, neoclassical economists assume that the two notions can be used interchangeably: the money value of machine tools and buildings is assumed to be a good proxy for the physical quantities of these production goods. This is something analogue to the "solution" of the proponents of the natural capital approach: we only need to put a price on the different components of Nature (the stock) and on the stream of ecosystem services (the flow) in order to have a measure of Natural Capital.

Providing a theoretical foundation for this view of capital as a factor of production was a key component of marginalist theory (Wicksteed 1894, Clark 1899). The main objective of this variant of Neoclassical theory was to prove that the laws of distribution of income in a capitalist society were linked to the contribution to output made by each component of society (for a modern exposition see Ferguson 1969). In its simplest form, the neoclassical theory of marginal productivity formulation used an aggregate production function:

(1) $$Q = f(K, L)$$

In this expression Q is total output and K and L denote the "factors of production", capital and labour respectively. The marginal product of the factor capital is defined as the change in output Q that results from employing an additional unit of the factor K. A similar procedure defines the marginal product of the factor labour. The marginal product of each one of these two factors is given by the following expressions:

(1a) $$MP_K = \frac{\Delta Q}{\Delta K}, \quad MP_L = \frac{\Delta Q}{\Delta L}$$

From equations (1a) it is clear that Neoclassical economic theory required a measure of capital that was independent of prices and distribution for a fundamental reason. However, the result of the Cambridge controversy on capital theory showed that this is the case. The

[5] Winnett (2005) is one of the few analyses where the Cambridge controversies are mentioned as an important issue in the context of debates on natural capital, but technical details are not examined.

starting point of the critique of the aggregate production function takes into account the crucial fact that these capital or productive goods are themselves commodities that have been produced. Once we take this into consideration it is possible to observe that the money value of machinery cannot be used as a proxy for the amount of machinery used in production.

The problem arises because machines and tools are themselves produced commodities and their prices depend on the rate of profit. Or, in other terms, the distribution of income affects prices. This is the crucial element in the debate on capital theory and the demonstration of this was first presented in Sraffa (1960). In his model prices are determined by conditions of production (i.e., technology) and by the distribution of income. So in order to determine prices it is first necessary to know what the distribution of income looks like.

This has devastating consequences: the entire neoclassical edifice is affected by circularity and this has fatal implications for the neoclassical concept of capital. The rate of profit is the output divided by the value (price) of the capital good used in production: Rate of profit = Output/Price of Capital. But if the price of capital is affected by distribution this involves circularity: the rate of profit depends on the price of capital, but the price of capital depends on the rate of profit. This means that the rate of profit cannot be determined endogenously in these models.

Following Sraffa and using a formulation in Pasinetti (1977) for an economy producing n commodities (and where the means of production are themselves produced commodities) the price system can be written as follows:

(2) $$pA(1+\pi)+l_n w = p$$

In this expression **A** is the matrix of technical (interindustry) coefficients, **p** is the price vector, π is the rate of profit, l_n is the n-dimensional vector of direct labour coefficients (for the n industries) and w is the wage rate. The methods of production are such that each industry produces a single commodity by using certain physical quantity of direct labour (represented by the corresponding component of vector l_n) and certain physical quantities of other commodities (represented by the corresponding technical coefficients of matrix **A**).

The solution of this system is given by:

(3) $$p = l_n\left[I-(1+\pi)A\right]^{-1} w$$

In equation (2) we can observe that each price is thus determined by the conditions of production, but also by the state of distribution (given by the levels of w and r). In other terms, the structure of the price system depends in general on the technical coefficients of production (labour given by l_n and inputs given by matrix **A**), as well as on the particular level of the profit rate.[6]

[6] Under certain conditions on matrix **A** the price vector **p** is strictly positive. The first is that matrix **A** must be non-negative. The second is that the maximum eigenvalue (λ_m) of matrix **A** must respect the condition $\lambda_m \leq 1$. If this condition is not satisfied we would be dealing with a system so backward that it would not be able to generate a profit even with a zero wage rate (Pasinetti 1977).

Prices of capital goods (such as machines) thus depend on their production conditions, but also on the state of the distribution variables (wages and profits). This brings about serious problems for the measurement of capital. To give an idea of how prices change when distribution is modified consider the price of capital good j expressed in terms of commodity 1 (and setting $w = 1$) as given by the following expression (Pasinetti 1977:82):

(4) $$\frac{p_j}{p_1} = \frac{l_{nj} + (1+\pi)\sum_{j=1}^{n-1} a_{ij} p_i}{l_{n1} + (1+\pi)\sum_{i=1}^{n-1} a_{i1} p_i}$$

The derivative of this expression with respect to the rate of profit, π, is:

(5) $$\frac{d}{d\pi}\left(\frac{p_j}{p_1}\right) = \left[p_1 \sum_{i=1}^{n-1} a_{ij} p_i - p_j \sum_{i=1}^{n-1} a_{i1} p_i\right] + (1+\pi)\left[p_1 \sum_{i=1}^{n-1} a_{ij} \frac{dp_i}{d\pi} - p_j \sum_{i=1}^{n-1} a_{i1} \frac{dp_i}{d\pi}\right]$$

It will be positive or negative

$$\frac{d}{d\pi}\left(\frac{p_j}{p_1}\right) > 0 \quad \text{or} \quad \frac{d}{d\pi}\left(\frac{p_j}{p_1}\right) < 0$$

depending on two different factors. First, the sign depends on the capital intensity effect given by the comparison of the costs of production of commodity j (the capital good) and commodity 1. This comparison is contained in the first bracket of equation (5). For commodities that have a greater (lower) capital intensity than commodity 1, this effect will always be positive (negative).

The second factor can be called the price effect: it is related to the movement of all prices in the economy. This is captured in the second bracket of equation (5). The main difference with the capital intensity effect is that the price effect cannot be determined unambiguously at the level of the commodity being considered (capital good j). Now changes in the price of any commodity (including capital goods) depend on how all the prices change in the whole system. The price effect is not predictable at the level of any given industry. Thus the sign of this derivative depends on the price system of the entire economy.

There are several implications from this. The first is that it is not possible to think of a sum of money (the aggregated prices of machines) as a good representation or proxy of the collection of heterogeneous machines and tools that economists would like to consider "capital". It is now impossible to talk about the "quantity of capital" as an autonomous concept: if the price of machines and equipment depends on the distribution of income, then the *quantity of capital* depends on the distribution of income. In other terms, for every state of the distribution variables there corresponds a new set of prices and, thus, a new "quantity of capital". The reference used by advocates of the natural capital metaphor cannot provide a good foundation for the objective of measuring "nature's assets".

The second implication is that the neoclassical relation between the quantity of capital and the rate of profit is destroyed. Neoclassical theory wanted to show that marginal productivity would fall as the quantity of capital increased. In fact, the problem we are examining here reveals that not only is there no uniform relationship between the rate of profit and the amount of capital, but also the direction of causation works in the opposite direction too. The amount of capital depends on the rate of profit and not the other way around.

Finally, the third implication is that because the quantity of capital depends on its price it is not possible to rank the techniques of production in terms of their "intensity of capital": the order or ranking of these techniques of production is modified each time distribution changes. Choice of techniques becomes a problem and this affects the assumption that firms are rational agents that select the more efficient combination of 'factors of production'.

This opens the door for the phenomenon of "reswitching" (Sraffa 1960, Pasinetti 1966): if at the rate of profit π_1 method M1 is the most profitable method of production, and if at profit rate π_2 ($\pi_2 > \pi_1$) technical method of production M2 (for producing the same commodity) becomes the most profitable one, then reswitching occurs when technique M1 becomes once again the most profitable one at an even higher rate of profit π_3 ($\pi_3 > \pi_2 > \pi_1$). The possibility of reswitching contradicts the neoclassical postulate that techniques with lower intensities of capital become eligible at higher rates of profit.

What are the implications of reswitching for the notion of natural capital? One of the most important implications concerns the issue of substitutability between man-made capital and natural capital. Using an aggregate production function where natural capital is introduced as a factor of production carries the assumption of factor substitution. In the case of man-made capital and labour, substitution takes place in accordance with movements in the relative prices of these two "production factors". What happens when natural capital is added as a third "factor of production"?

Natural capital and weak sustainability

The idea that natural capital is a factor of production leads directly to the question of substitutability between factors. To their credit, many authors who advocate the use of the natural capital metaphor disapprove the idea of replacing natural capital by manufactured capital (Costanza and Daly 1992). However, the use of aggregate production functions implies factor substitution and this possibility lies at the heart of the notion of weak sustainability.

According to Pezzey (1992) the most commonly used definition of sustainable development (that welfare of future generations should not be less than the welfare of the current generation) can be interpreted in terms of non-declining utility and maintaining stable total capital stocks at a macroeconomic scale. This allows for the problem of weak sustainability to be examined at an aggregate level in order to determine the conditions under which these outcomes can be attained.

A strong connection can then be established with well-known problems in neoclassical growth theory when exhaustible resources are explicitly taken into account in the context of an aggregate production function. For example, Stiglitz (1974) uses a model with an aggregate production function to characterize steady state paths in economies with exhaustible natural resources and examine the conditions under which a sustainable level of per capita consumption is feasible. Solow (1974) looks at the conditions under which a non-declining positive level of output or consumption can be sustained indefinitely when production depends on the non-renewable natural capital. Substitution between all factors of production, including man-made capital and natural capital is a central assumption to prove the validity of this condition (Hamilton 1995).

The phenomenon of reswitching has deep negative implications for neoclassical models when only two factors of production are considered. These problems do not go away when a third factor called “natural capital” is introduced. Consider for example the model in Facheux, Muir and O’Connor (1996): it is an overlapping generations model with a production function using manufactured capital, labour and natural capital. The model uses a standard Cobb-Douglas function

$$Q = f(M, L, R, t) = M^{\alpha 1} L^{\alpha 2} R^{\alpha 3} e^{\lambda t}$$

where Q is output, M is manufactured capital, L is labour, R is natural capital (used in production) and λ is the rate of (time invariant) technical progress. The parameters $\alpha 1$, $\alpha 2$ and $\alpha 3$ designate the respective output elasticity of the three inputs, manufactured capital, human capital and natural capital. As in any Cobb-Douglas function the elasticity of substitution between the three forms of “capital” is equal to unity (that is, $\alpha 1 + \alpha 2 + \alpha 3 = 1$). And as in standard definitions of weak sustainability manufactured capital and natural capital can be perfect substitutes and the type of welfare they generate is essentially undistinguishable (Ekins et al 2003).

But how exactly should agents in the model decide to replace one form of capital for another? Can they select more or less “natural-capital intensive” technologies? The aggregate models that incorporate natural capital do not specify microeconomic (behavioural) rules for the substitution between man-made capital, labour and natural capital. Clearly substitution cannot be assumed to take place in accordance with the rules set forth in neoclassical capital theory because, among other things, we would re-encounter the problem of reswitching. Modellers working with natural capital have not explicitly discussed this problem. Thus, the models assume substitutability but do not specify just how agents should go about in the process of substituting natural capital for the other two forms of capital.

It can be stated that behavioural rules for capital substitution are not specified in the models because like their relatives in neoclassical growth theory, their objective is to derive macroeconomic conditions for certain types of growth paths. For example, the Hartwick-Solow condition states that investing (natural capital) resource rents in producing man-made capital is a sufficient condition for weak sustainability. In other words, the problem at hand is to define macroeconomic conditions that are required to maintain natural capital stock intact or how consumption (and utility) can be sustained indefinitely.[7] Unfortunately, the building blocks of these models are flawed because there is no unambiguous measure of man-made capital. The foundations that a policy-relevant model should possess are lacking.

Aggregate models using the notion of natural capital to examine conditions of weak sustainability cannot serve the purpose for which they were created. Those conditions cannot

[7] This explains why Cabeza Gutés (1996) concludes that the notion of weak sustainability “can be presented as a direct application of the savings-investment rule from growth theory with exhaustible resources”.

be related to decentralized market economies and the problems associated with the measurement of man-made capital do not allow us to rely on those models for policy making. For example, through the assumption of perfect substitutability of factors of production, the metaphor of natural capital is directly related to the notion of biodiversity offsetting. There are many definitions of biodiversity offsetting, but they all involve different mechanisms that allow for full compensation for negative impacts on biodiversity through other investment projects. It is a notion closely related to the goal of "no net loss" when it comes to negative impacts on biodiversity. There are many problems associated to this idea but our analysis uncovers a new difficulty: reswitching means that using a monetary measure for the components of man-made and "natural capital" can lead to erroneous choices and mistakes in the attempt to achieve offsetting and "neutral impact" schemes.[8] The entire discussion on natural capital in the context of so-called weak sustainability becomes meaningless.

This is not the only problem. Most of these models use the notion of a "representative agent". For example, Pezzey (2001) uses a representative agent model with an aggregate production function to examine weak sustainability conditions and the role of policy instruments. He recognizes that the model's simplifying assumptions limit the policy relevance of its results and states that the representative agent framework obscures the interaction of separate generations. On the other hand, Faucheux et al (1996:529) affirm that we can think of these models as "expressions of social choices".

But the problem with the "representative agent" is not that it obscures relations between generations. And this notion cannot be used to model expressions of social choices. The difficulty is that the aggregation process needed to arrive at this fiction does not conserve the properties of individual rationality that are ascribed to the representative agent. This is a fiction that has been logically discredited by the simple fact that the weak axiom of revealed preferences does not hold for market excess demand functions. In addition, the Sonnenschein-Mantel-Debreu theorem has revealed that aggregation of preferences in the context of general intertemporal systems only conserves continuity, Walras' law and homogeneity of degree zero of the excess demand functions. These properties are not enough to provide a suitable structure to the market excess demand function. Models relying on the fiction of a representative agent are misleading in macroeconomics and are deceptive in environmental policy making.

The critique raised by academics in Cambridge University gave a devastating blow to the school of neoclassical economics that relies on an aggregate production function. In a well-known article Samuelson (1966) conceded defeat and accepted the arguments of the critics to the neoclassical school stating that "If all of this causes headaches for those nostalgic for the old time parables of neoclassical writing, we must remind ourselves that scholars are not born to live an easy existence".[9] Advocates of the natural capital metaphor need to stop living in a world of parables and metaphors and should derive the logical consequences of the critique to the marginalist version of neoclassical economic theory.

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[8] One important question relates to the negative incentives that this creates for the reduction of negative environmental impacts when an investor can simply "compensate" or "offset" it. The problem of reswitching exacerbates this problem.

[9] One key result of the Cambridge controversies is that the use of time-preference, "patience" and "time" did not allow for escape the criticism addressed by the Sraffian model (the same applies to the approach *à la* Böhm-Bawerk on the "average period of production" to characterize methods of production). In none of these cases is there a concept of capital that is independent of the rate of profit.

SECTION III. General equilibrium theory: disequilibrium and scarcity

The critique outlined in the previous section is addressed to neoclassical capital theory based on long-term stationary equilibrium using an aggregate production function and assuming the existence of a uniform rate of profit throughout the economy. But what happens if we move into the realm of general inter-temporal equilibrium models where the frame of reference is the short term and there is no uniform rate of profit? This is a relevant question since work on natural resource management has already begun using applied general equilibrium systems (Jorgenson and Wilcoxen 1990, Persson and Munasinghe 1995, Conrad 1999).[10]

In general equilibrium theory there is no aggregate measure of capital and every capital good has its own rate of return. The different versions of the Arrow-Debreu model accommodate a large number of producers and each one may use any of a number of capital goods (and intermediate inputs) as it maximizes its profit function on its production possibility set. Each capital good has its own price and ecause each different capital good has its own rate of return, there is no reference to a thing called "capital" or to a uniform rate of profit. According to Hahn (1975, 1982) general equilibrium theory is unaffected by the Sraffa-based critique that led the attack on marginalist theories.[11] That is a debatable assessment: both Garegnani (2011) and Schefold (2005) have shown that the Sraffa-based critique is also relevant for inter-temporal general equilibrium models. Schefold in particular has proven that reswitching has negative implications for the stability of equilibrium. This makes the Arrow-Debreu model of little use when seeking for good theoretical foundations for the natural capital approach.

There are other serious problems affecting general equilibrium models that are of great relevance to the natural capital metaphor, especially from the vantage point of the valuation of the stock of natural capital and the flow of ecosystem services. Perhaps the most important problem is that Arrow-Debreu general equilibrium models have not been able to yield good results when it comes to stability theory (i.e., the formation of equilibrium prices). This has deep implications for the objective of putting a monetary value on natures "assets".

In the late fifties Arrow and Hurwicz (1958) and Arrow, Block and Hurwicz (1959) were able to prove stability theorems in a general equilibrium framework, but only after extreme conditions were assumed: gross substitutability and the weak axiom of revealed preferences at the market level.[12] The first involves rather strange economies that are difficult to imagine, while the second involves a contradiction because the weak axiom of revealed preferences is not valid at the market level. Scarf (1960) showed through a counter-example that conjecturing about the generality of stability in GE models was unjustified. Stability has remained an intractable problem for general equilibrium theory. Efforts to build better tâtonnement and non-tâtonnement models (where trading takes place at disequilibrium prices) in a general

[10] For a detailed critique of computable general equilibrium models, see Taylor and Arnim (2006), Ackerman and Gallagher (2004) and Stanford (2003).

[11] Garegnani (1976) attributes this feature to a change in the notion of equilibrium and the abandonment of the long-term perspective where all individual profit rates converge to a uniform rate. These changes are due to "weaknesses in the dominant theory of distribution and, in particular, of the conception of capital it relies on. The attempt to overcome the deficiencies of the received notion of capital (...) provides the main explanation of the move towards short-period equilibria and their sequence in time."

[12] It is important to note that both *tâtonnement* and *non-tâtonnement* models require the presence of a auctioneer, an agent that announces prices, calculates market excess demands and adjusts prices (according to the law of supply and demand) in a centralized manner. This of course belies a good representation of a decentralized market economy.

equilibrium context failed to provide a satisfactory answer to the question of equilibrium price formation.

This is highly relevant for any discussion about market-based policy instruments. In neoclassical economics only in equilibrium are prices a signal of scarcity and only in that case can it be said that there is an efficient allocation. In disequilibrium there are positive excess demands and therefore prices do not reflect in any sense scarcity. This has deep implications for the valuation techniques of “natural capital”, a point to which we return below.

In 1974 a new and even more serious problem surfaced affecting every aspect of general equilibrium theory, including the disaggregated measure of all capital goods. The Sonnenschein-Mantel-Debreu theorem of 1974 (Sonnenschein 1973, Debreu 1974, Mantel 1974) showed that for a continuous function that is homogeneous of degree zero and that respects Walras’ law, there is an economy with at least as many agents as goods such that for prices bounded away from zero the function is the aggregate demand function of the economy. This means that the assumptions that specify well-behaved demand functions at the microeconomic level do not carry over to the aggregate level. In other terms, the market demand curve does not necessarily have a downward slope. This poses a serious problem: stability results (attaining an equilibrium price vector) will not be able to be attained unless *ad hoc* restrictions are imposed on the excess demand functions.

The SMD theorem applies even under extreme conditions. Mantel (1976) was able to demonstrate that even with homothetic preferences the conclusion of the SMD theorem is verified. And Kirman and Koch (1986) showed that even if we assume that collinear endowments (fixed income distribution) the theorem still holds. Price formation processes become anarchic and will not necessarily lead to equilibrium (efficient) allocations. The traditional interpretations of a price formation mechanism simply fall apart under the impact of the SMD theorem. This explains why Mas-Collel, Whinston and Green (1995) aptly describe this theorem as the “Anything Goes Theorem”.

How does this affect the natural capital approach? First, the SMD theorem shows that the market excess demand curve has no structure and therefore implies that the law of supply and demand does not apply to the market demand curve. This means that, for example, the demand curve for natural capital that Pascual and Muradian (2010) borrow from Farley (2008) does not have the negative slope indicated in their diagram. That curve may show segments with a positive slope and this throws any conceivable economic adjustment process in disarray. For example, it is conceivable that as the price of natural capital increases its demand could also rise.

Second, if stability is not an intrinsic property of equilibrium then we need to focus on disequilibrium prices. But the nature of these prices is very different from equilibrium prices: in disequilibrium agents are aware of arbitraging opportunities and adapt their plans to take advantage of them. Disequilibrium prices may convey the weight of market power and strategic behaviour of different agents, but these prices are not signals of scarcity or of market efficiency. In other terms, disequilibrium prices do not denote in any meaningful way what is the real scarcity of natural capital. These prices are not a good reference for environmental policy. As Rizvi (2006) has pointed out, “observations on market prices alone do not restrict in any meaningful way the sort of economy that could have generated them”.

SECTION IV The fallacy of measurement

There is another angle to the problems associated with the NC metaphor: how exactly are the values of natural capital measured and in what units of account? The valuation techniques used in the context of the natural capital approach have serious limitations that have been identified by many ecologists (Chee 2004 and references therein). Here we highlight the inconsistencies and shortcomings of these valuation techniques from the standpoint of economic theory.

TEEB (2010a) contains a description of methods commonly used to determine the value of natural capital and of the flows of ecosystem services. It also classifies valuation techniques into three categories: direct market valuation, revealed preferences and stated preferences approaches. The first group includes market and cost-based approaches, as well as the production function approach.[13] The second involves a travel cost method and a hedonic pricing scheme to estimate (monetary) values for NC and ecosystem services. The third category comprises techniques that simulate markets and demand for ecosystem services.

The valuation techniques used in the context of the natural capital approach yield monetary values or prices. But, once again, these are not equilibrium prices: they are affected by distortions, rigidities and imperfections existing in the real economy. Because they are disequilibrium prices, it is not possible to assume that they embody accurate information about scarcity or efficiency. The data they generate may lead to gross misallocation of resources and cannot provide reliable guidance for environment policy-making.

Several valuation techniques involve aggregating individual preferences and estimating demand functions. But aggregation of individual preferences is not a valid procedure: a well-known fact is that the weak axiom of revealed preferences (due to Samuelson 1938) is not valid at the market level. This result was strengthened by the Sonnenschein-Mantel-Debreu theorem we examined before. Strong restrictions are needed to justify the hypothesis that a market demand function has the characteristics of a consumer demand function (Shafer and Sonnenschein 1982). Using valuation techniques that ignore this result will inevitably yield useless or misleading information on the value of "natural capital".

One final consideration is that all of the valuation techniques used in the NC approach rely on a partial equilibrium frame of reference and thus ignore the interdependencies that make price formation so complex and unpredictable. Relying on partial equilibrium to measure "natural capital" leads to invalid results because it rules out income effects, as well as repercussions of disequilibria across markets. In this context, policy-makers will receive misleading information concerning the value and the demand curve for "natural capital". In the rest of this section we examine three more specific problems associated with the valuation techniques used by advocates of the NC metaphor.

[13] The many authors that are involved in TEEB-related exercises seem to ignore that the controversy over capital theory is not a simple theoretical discussion that has relevant empirical implications for a discussion on valuation of "natural capital". For example, in a study of thirty-two input-output matrices from an OECD database Han and Schefold (2005) found evidence of reswitching or reverse capital deepening. Estimating production functions for natural capital and its components is a misleading enterprise.

Reswitching and discount rates

Because the notion of natural capital involves a stream of ecosystem services across time, discount rates are used in calculations involving net present value. Whether one should use discount rates at all in choosing between alternatives in environmental policies is an open and delicate question involving crucial ethical issues (Ackerman and Heinzerling 2004). In addition, the choice of the relevant discount rate is a well-known: selecting a low versus a high discount rate has been discussed in many contexts, from climate change to life insurance.

Furthermore, there is a difficulty that has been neglected in most of the literature and that is highly relevant in the context of our previous analysis on capital theory. Baumol (1997) presents a model to assess a project entailing both economic benefits and environmental costs. Determining the net present value of the investment project and its costs involves "a standard reswitching phenomenon and may, perhaps, represent one of the more persuasive illustrations of the significance of reswitching in practice" (Id.:49)

Baumol's model can be applied *ceteris paribus* to a vast array of cases. It was originally developed by comparing the net costs and benefits of a project in the context of a stream of services. The model involves multiple solutions for a project's internal rate of return. The crucial equations show that at very low interest rates (high discount factors) and at very high interest rates (low discount factors) the project must be rejected. The reason for this is that at very high interest rates only the immediate cost and amenity loss will matter and the project will not be justified. On the other hand, when the interest rate is very low the discount factor approximates unity and "the loss of amenity value for the indefinite future becomes overwhelming" so that the project also fails the cost-benefit test and must be rejected.

Thus, only for intermediate values of the interest rate is the project acceptable. We have here a case of reswitching where multiple solutions exist for the project's rate of return. The project is to be rejected at low interest rates, approved at intermediate interest rates and, then once again, rejected at higher interest rates. And if we relax the assumption that the value of the stream of net benefits and net losses does not change (for example if there is a growing population that demands more of the amenity value), the reswitching phenomenon can become even stronger. According to Baumol (1997: 55)

> "The fruitful debate on reswitching offered substantial illumination to capital theory, its original domain. (We) show that analytic tools that played an important role in the reswitching discussion also shed light on other economic issues. (...) This is so because of the reswitching phenomenon, the possibility that both a low and a high discount rate can yield the same present-value figure for a given project."

The consequences of reswitching are as serious for cost benefit analysis as they are for capital theory. It is not possible to have a monotonic ordering of projects as a function of discount rates. This is due to the possibility, for example, that a project that was approved at a given discount factor D_1 but was discarded at a higher discount factor D_2 ($D_2 > D_1$) may return to be approved at a new discount factor D_3 that is even higher ($D_3 > D_2 > D_1$). Discount rates are not an infallible technical tool for the valuation of 'natural capital' and its stream of ecosystem services.

The question of reswitching should not be underestimated. It arises in the context of environmental policy choice and thus is a real possibility in the context of valuation of 'natural capital'. Viscusi and Zeckhauser (1976) discuss the possibility of reswitching while applying a Markovian model to three cases where policy choices need to be made. The first case involves uncertainty as a significant ingredient, while the second deals with situations where there is the possibility of irreversibility. Because of reswitching these authors recognize that "in deterministic policy contexts there may be no unambiguous way to ascertain whether one policy is more future-minded than another" (Ibid: 98):

> "Policy A may be preferred to policy B when payoff streams are discounted at rate r_1, and B preferred to A when r_2 is used. Yet policy A would once more be preferred at rate r_3, where $r_3 > r_2 > r_1$. Situations in which there is a second reversal in project preference will be referred to as instances of 'reswitching'. For such situations, it is not possible to state which of two projects is favoured as the discount rate is lowered and the future is in effect given greater weight."

The problem of reswitching will haunt anyone who believes there is a possibility for putting a monetary value on the components of so-called "natural capital".

Uncertainty

Uncertainty, we are told, must be taken in a sense radically distinct from the familiar notion of risk (Knight 1964: 19). According to Knight's classic formulation risk is a quantity susceptible of measurement, while uncertainty is essentially unmeasurable. Risk involves knowing the probability distribution of events but in many cases we are unable to calculate probability distributions (in fact, we may even be unable to describe them adequately).

The valuation of so-called natural capital is affected by both risk and uncertainty. In the first case, it is possible to calculate probabilities of potential outcomes. And this information may be thought of relevance in various valuation techniques. However, in the case of uncertainty the impact on valuation is devastating. Although some authors working on valuation techniques do recognize the difference between risk and true uncertainty, the use of these techniques ignores the radical difference between them. Some authors are quite candid about the choice they must make in order to put a "total economic value" on the components of "natural capital". Pascual and Muradian (2010) acknowledge the essential difference but conclude that they will use the term uncertainty "to refer to the one commonly used in economic valuation of the environment, i.e., the conflated risk and uncertainty notion". Of course, while blending these notions makes some problems more tractable, this does not mean that the analysis gains in rigour.

An ideal and well-behaved universe where probability distributions are known may go well with the valuation techniques for 'natural capital'. But it is very different from the real world where uncertainty commands a dominant position. In the real world the dynamic processes that help form new states are led by self-reinforcing or cumulative dynamics, lock-in situations, non-linear developments, irreversibility, recursive loops and complex interdependencies. Radical uncertainty makes contingent valuations of NC worthless.

Estimating risk requires a sample of the universe that is being analysed. We may be able to calculate probabilities for events in horse racing, but we do not have anything comparable for estimating the net present value of a stream of "ecosystem services" that goes into the distant future. It makes sense to recall what Keynes (1937:213-4) had to say about this essential difference between events where probability calculus can be applied and those that belong to the realm of uncertainty.[14]

Valuation in financial markets

Adherents to the NC approach have repeatedly made references to the similarities between "natural capital" and "financial capital". Thus natural capital is the stock that provides interest for human welfare. In the terms of the Natural Capital declaration (http://www.naturalcapitaldeclaration.org) "neither of these services, nor the stock of natural capital that provides them, are adequately valued in terms comparable to manufactured and financial capital."

But pricing financial assets is not an easy operation, as traders and regulators of financial markets well know. This is evident in the case of derivatives such as futures, options, interest rate swaps, forward currency contracts and credit default swaps. The bigger the gap between a financial asset such as any of these derivatives and its underlying asset, the riskier adequate pricing becomes. Also, where the opacity of financial assets and/or the complexity of financial innovations increase, the more difficult the task of "price-discovery" becomes in a financial market. It is therefore inaccurate and misleading to affirm that we can go ahead in valuing natural capital in a similar way to financial assets.

Financial markets and institutions have expanded significantly since the early 1970s. Deregulation has accompanied this process and global markets have become increasingly integrated. In addition, financial innovations have augmented the scale of complexity and opacity in many types of transactions. Two good examples of this are securitization and the generalization of over-the-counter transactions with derivatives. Securitization was considered an efficient method to hedge risk as assets were repackaged and sold in the international financial market. In fact, risk diversification does not eliminate risk and OTC transactions increased opacity. In the end, the market freeze that struck financial markets in the midst of the crisis was due to uncertainty about fair asset prices (Easley and O'Hara 2010). Unless one is a firm believer in Fama (1970) and the "efficient market hypothesis" (i.e., that market prices always fully reflect available information) it is clear that financial markets do not offer a good reference for something like valuation of "natural capital" for environmental policy.

In fact, this is the reason why financial markets are marked by greater instability. The global financial crisis that erupted in 2007 is a reminder that the hypothesis of efficiency, rationality and self-regulating markets is inadequate, especially when applied to financial markets. There are multiple signs of this in the banking and financial sectors.[15] Financial instability is at the heart of modern and well-developed financial markets. The methodologies that led to placing

[14] As Brady (2012) has shown Keynes made several critical breakthroughs in his *Treatise on Probability* that are relevant in the discussion on valuation of "natural capital". The problems identified by Keynes involve intractable difficulties for any attempt to measure in monetary terms the components of NC and their flow of services.

[15] An interesting example for this discussion on natural capital concerns the deregulation of the commodity futures markets in the 1980s and 1990s that culminated with the Commodities Futures Modernization Act of 2000. This led to legalized speculative over the counter trading in derivatives (Stout 2011) that brought about greater instability in commodity markets.

so many bad bets on derivatives in over-the-counter transactions and that led to the 2007 crisis cannot be used to provide adequate prices on "natural capital".

Concluding remarks

Metaphors and analogies are often used to provide insights on complex phenomena. But using metaphors requires caution. What is gained in ease of communication may be lost in precision. Above all, those who rely on metaphorical thinking should be aware that similarities involved in metaphors are not indicators of identity or of causal relations. Drawing policy conclusions from metaphors can be a risky proposition if their limitations are not well understood.

The proposition that natural capital can be thought of as another form of "capital" is used as a metaphor to try to quantify the value of "natural assets" and of the flow of "ecosystem services". This metaphor is presented by its advocates as having firm bases in economics, especially in the concept of capital in marginalist neoclassical theory. We have shown that the metaphor of "Nature as Capital" does not stem from any scientific enterprise and does not respond to technical imperatives. Our analysis reveals that the metaphor does not have rigorous foundations in economic theory and that it cannot provide adequate economic measurements of what are supposed to be "nature's assets". This may explain why supporters of the NC metaphor have never engaged in a detailed discussion of the concepts and the economic theory they claim to underpin their imagery.

We can now summarize our findings as follows. First, the marginalist theory of capital cannot provide a solid foundation for the natural capital metaphor. Because prices are affected by distribution, rather than the rate of profit depending on the amount of capital, it is the measured quantity of capital that depends on the rate of profit. Therefore, aggregate measures of man-made capital are not as unambiguous as advocates of the 'natural capital' metaphor would like to think.

Second, factor substitution is an essential feature of marginalist theory of capital. It is also a key element of models trying to introduce "natural capital" as a third factor of production. This is especially important in models used to analyse conditions for weak sustainability. However, the possibility of reswitching cancels out any possibility of defining behavioural rules for substitution between man-made and "natural" capital. Reswitching also has negative implications for the definition of the macroeconomic conditions that are required to put an economy on a (weak) sustainability path.

Third, general equilibrium models are equally ill suited to provide a foundation for the natural capital metaphor. Poor results in stability theory have been compounded by the negative implications of the Sonnenschein-Mantel-Debreu theorem. The traditional interpretations of a price formation mechanism simply fall apart under the impact of the SMD theorem. General equilibrium theory cannot provide the underpinnings for adequate valuations of "natural capital".

Fourth, macroeconomic models used to discuss natural capital and weak sustainability bring in a new defect as they rely on representative agents. The aggregative process behind these entities does not allow us to conserve the rationality the theory assumes exists at the level of individual agents and market demand curves do not necessarily have a downward slope.

Using an inconsistent theory cannot provide useful information for policy makers on environmental degradation.

Fifth, the valuation techniques used by supporters of the NC approach can only yield current or disequilibrium prices. These prices do not provide correct scarcity signals and cannot guide the allocation of resources. In addition, these valuation techniques are based on a partial equilibrium framework that assumes away all the problems of income effects and market interdependencies. They also ignore the empirical relevance of reverse capital deepening and reswitching when using discount rates. They take no notice of the difficulties in correctly pricing financial products, especially complex derivatives, and they conflate uncertainty and risk. The valuation techniques used in the NC approach do not yield accurate measurements of environmental destruction and may lead to dangerous misallocations of resources.

Proponents of this metaphor believe that the passage from metaphor to the realm of economic analysis is automatic. A short text that exemplifies all of the shortcomings of the natural capital approach is provided by Hughes (2013) who thinks that "…by valuing natural capital in a similar way to financial, manufactured, social and human capital, we can make decisions on stewardship of the natural environment based on hard-nosed economics, and not just on the vitally important moral case for saving nature for nature's sake". We have shown that the NC metaphor is not a useful instrument for environmental conservation or for sustainability and should not be used as a signpost for policy-making. The NC metaphor cannot lead to anything resembling "hard-nosed" economic analysis.

Perhaps the most serious shortcoming of the natural capital metaphor is that it is incapable of providing information on the drivers of environmental degradation. The economic forces that lead to overinvestment, waste and large-scale environmental destruction cannot be analysed through the use of this metaphor. The role of macroeconomic and sector-level policies cannot be understood through this simple-minded discourse. Factors such as the global financial crisis, inequality or the international macroeconomic imbalances that affect the world economy today will remain invisible to followers of the "natural capital" approach. Thinking that the best way to prevent damages to the environment is by "correcting" prices to avoid externalities entails an inadequate vision of theory and real world economics. Serious work on the economic drivers of environmental degradation is urgently required and cannot be based on the flawed metaphor of natural capital.

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SUGGESTED CITATION:

Alejandro Nadal, "The natural capital metaphor and economic theory", *real-world economics review*, issue no. 74, 07 April 2016, pp. 64-84, http://www.paecon.net/PAEReview/issue74/Nadal74.pdf