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A Theoretical Essay on Sustainability and Environmentally Balanced Output Growth: Natural Capital, Constrained Depletion of Resources and Pollution Generation

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ABSTRACT

The fact that today's activities are imposing a heavy burden on the earth's capacity has led to an increasing interest in environmental issues. It is emphasized that rapid production growth has exhausted natural resources and polluted the environment. The objective of this essay is to offer a clear definition of natural capital, connect it to a qualitative concept of sustainability and, supported by two analytical models and a set of studies on related environmental literature, to show that sustainability can be attained via imposition of controls over production processes that use depletable natural resources and generate pollution. The methodology used contemplates an integrative approach combining a qualitative (seeking definitions)-analytical (appraising models) apparatus to reach a new conceptual perspective to conceive sustainability. As the main essay's contribution, it is showed that sustainability can be reached if compensation is allowed for, i.e., stocks of renewable being augmented as production depletes the stocks of nonrenewable natural resources. Moreover, that result is possible even considering nondecreasing output production, an important finding to contrast with the current environmentally based output growth literature, which asserts that slowing down output production is the only way to obtain sustainability.

Key words: sustainability; natural capital; depletion of natural resources; environmentally balanced output growth.

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INTRODUCTION

As suggested by Boulding (1993), the well-known fact that today's production activities are imposing a heavy burden on the earth's capacity has led to an increasing interest in environmental issues. It has been emphasized that rapid production growth depletes the current stock of natural resources and damages the environment, and there are clearly limits to this process. Daly (2008) affirms that "The limits to growth, in today's usage, refer to the limits of the ecosystem to absorb wastes and replenish raw material in order to sustain the economy" (p. 9). Despite the classical 'pro-technology' optimistic arguments, which assert, according to Barro (1997), that technical progress is what is needed to eliminate all constraints on production growth, the approaching exhaustion of earth's carrying capacity is an unquestionable reality. Goodland's (1992) assertions pointing out that current high levels of degradation of the earth's biomass and biodiversity and substantial increases in earth's average temperature are a cruel reality, are clear evidence of it. Furthermore, as Panayotou (1993) affirms, the amount of damage production activities have imposed on the environment (e.g. pollution) in the course of rapid growth is unquestionable. As suggested by Daly (2002), immediate actions are being called for and policy proposals have been formulated to deal with these issues, both in the political and academic arenas.

In spite of this evidence, the issues related to natural resource uses and pollution generation and their connections with sustainability have not yet been technically mastered to base decisions on this matter in practice. Therefore, this essay purposes to offer a clear definition of natural capital, relate it to a qualitative concept of sustainability, and present two pioneering analytical models of environmentally balanced output growth, explicitly considering, on the one hand, constrained exhaustion of a nonrenewable natural resource and, on the other, pollution control over an output production process. It will be seen that slowing down the pace of output production growth is a feasible way to be in 'fine-tune' with sustainability, for one manner to achieve this is via imposition of controls over the use of nonrenewable resources and emissions of pollution.

Thus, the main contribution of the essay is to present a new conceptual perspective, based on the qualitative-analytical apparatus used, in order to show that even allowing for the depletion of nonrenewable natural resources, it is possible to manage their uses in a way that compensation, such as augmenting the stocks of renewable natural resourses, can be conceived and total natural capital remain unchanged or even increased. An important result of this is that sustainability could be attained with no need for reducing production.

The next section presents the methodological procedures to be used, starting with a qualitative approach to the environmental literature, seeking to find a workable definition of natural capital, in order for sustainability to be appraised. An analytical apparatus used to approach two pioneering models of environmentally based output growth follows.

In Section 'Natural Capital and Sustainability: a Qualitative Conceptual Approach' we define natural capital and establish the link between it and sustainability. Section 'Environmentally Based Output Growth Models: an Analytical Apparatus' presents two pioneering models of output growth considering depletion of a nonrenewable natural resource and pollution control. Section 'Integrating the Qualitative-Analytical Approaches towards a New Conceptual Perspective on Sustainability' goes on to argue, according to the essay's main contribution, that it is possible to attain sustainability even allowing for environmental bounded damage. Section 'The New Conceptual Perspective on Sustainability: Implications to Environmental Management' focuses on implications of the analysis for environmental management and the final section gives conclusive remarks shedding light on directions for future work.

Methodological Procedure: from a Qualitative-Analytical Apparatus to a New Conceptual Perspective on Sustainability

As far as the essay's main goal is concerned, the methodological procedure used integrates two different apparatuses. First, a qualitative approach was undertaken in order to obtain, in the environmental literature, a suitable definition of natural capital. The objective is to clearly define natural capital and connect it to sustainability. This latter concept follows the premises of the Brundtland Commission (1987). A set of important contributions was selected to that end, such as, Lima (1999); Daly (2002, 2004, 2005, 2008); Lawn (2006); Turner, Brouwer, Georgiou and Bateman (2000); Sahu and Choudhury (2005); England (2006); Costantini and Monni (2008); and Irwin and Ranganathan (2007).

Second, an analytical approach was used in order to conceive two different models regarding optimal output production growth – one considering output production constrained by the use of a nonrenewable natural resource input, and the other contemplating pollution control over a production process that damages air quality (pollution) as output paces its path. To that end, two pioneering models of optimal output growth were intentionally selected due to their innovative approach on optimal environmentally based production growth away back in the seventies. To provide updated support for the two pioneering models used, a set of important recent contributions was used, including Geldrop and Withagen (2000); Palmada (2003); Islan (2005); Charles (2005); Comolli (2006); Auty (2007); Bretschger and Smulders (2006); and Voinov and Farley (2007); all using analytical frames jointly treating output production and environmental variables under a single approach – optimal environmentally based output growth.

The main objective of applying this methodology was to setup a way leading to a new conceptual qualitative perspective allowing for sustainability being appraised even with constrained environmental damage, e. g., via renewing renewable natural resources, as a compensating device counterbalancing the depletion of nonrenewable natural resources. Thus, the analysis to be undertaken in what follows has to be understood, under the methodological procedure here delineated, in the context of a qualitative frame (even using two analytical theoretical models) in order to reach a new conceptual construct to better understand and analyze sustainability.

Natural Capital and Sustainability: a Qualitative Conceptual Approach

A general definition of capital is very important to clearly understand natural capital. Capital here is to be considered as a stock that yields a flow of valuable goods and services into the future, as suggested by England (2006), no matter whether the stock is manufactured or natural. If it is natural, e.g., a population of trees or fish, the sustainable flow or annual yield of new trees or fish is called sustainable income, and the stock that yields it is defined as natural capital. Natural capital may also provide services such as recycling waste materials or pollution (or even erosion) control, which are also considered as sustainable income. From this definition we can see that the structure and diversity of the system is an important component of natural capital, according to Daly (2008), since the flow of services from ecosystems requires that they function as whole systems. Irwin and Ranganathan (2007) propose an interesting action agenda showing ways to sustain ecosystem services. Another qualification has to do with the distinctive character of natural capital, income and natural resources. All three concepts are distinct, in the sense that natural capital and natural income are just the stock and flow components of natural resources.

According to Daly (2005) and Lima (1999), there are two broad types of natural capital, renewable (RNC) or active and nonrenewable (NRNC) or inactive. Examples of RNC are ecosystems and of NRNC, fossil fuel and mineral deposits. There is an interesting analogy between RNC/NRNC and

machines/inventories. Renewable natural capital is analogous to machines and is subject to depreciation; nonrenewable natural capital is analogous to inventories and is subject to liquidation.

Having defined natural capital, a definition of sustainability is needed in order to establish a logical connection between them. First of all, it is important to note that, as affirmed by Daly (2004), the stock of total natural capital equals renewable natural capital plus nonrenewable natural capital.

The concept of sustainability is related to the maintenance of the constancy of the stock of total natural capital. According to Lawn (2006) and Costantini and Monni (2008), a minimum necessary condition for sustainability is the maintenance of the total natural capital stock at or above the current level. Hence, the constancy of the stock of total natural capital is the key idea behind the sustainability concept. Since the stock of nonrenewable natural capital can be depleted with use, a logical way to maintain constant total natural capital is to reinvest part of the prospects coming from the use of nonrenewable natural capital into renewable natural capital.

It is important for operational purposes to define sustainability in terms of constant or nondeclining stock of total natural capital. This is a very significant point, since sustainability implicitly incorporates the notion of intergenerational equity. According to the Brundtland Commission (1987), the primary implication of sustainability is that future generations should inherit an undiminished stock of 'quality of life' assets. According to England (2006), this broad stock of assets can be measured or interpreted in the following three ways: i) as comprising human-made and environmental assets; ii) as comprising only environmental assets; or iii) as comprising human-made, environmental, and human capital assets. The notion of intergenerational equity, thus, lies at the core of the definition of sustainability. Najam, Papa and Taiyab (2006) and Najam, Runnalls and Halle (2007) developed important contributions related to sustainability definitions and their relations to governance and globalization.

Holmberg and Samdbrook (1992) emphasize that the Brundtland Commission (1987), - The World Commission on Environment and Development -, was the first entity to give geopolitical significance to the use of the sustainable development concept, and thus is an important benchmark on environmental issues.

It is clear and desirable that item iii) above is the most relevant one to consider under the given definition of sustainability. According to Daly (2002), human-made capital, renewable and nonrenewable natural capital and diverse ecosystem services all interact with human capital and productive processes to determine the production level of market goods and services of a country. The specific form of this interaction is very important to sustainability. As suggested by Sahu and Choudhury (2005), linking those more general arguments with the definition of total natural capital given above and owing to the intergenerational issue, the frame developed up to this point is crucial for an appropriate definition of sustainability.

We see the interconnections between natural capital and sustainability. It is necessary to have the definition of the former in order to achieve the latter, and to reach the minimum necessary condition for sustainability the maintenance of the stocks of total natural capital is a requirement.

A tangent issue is related to the traditional way to conceive and measure standard production growth. It is well known that the measure of welfare via gross national product [GNP] misconceives the relevance of natural capital, despite its significance in terms of the production of real goods and services in the ecological-economic system. To deal with this shortcoming, there has been recent interest in improving national income and welfare measures to account for natural capital depletion and other corrections of mismeasured variables of economic welfare. As a consequence, a new index (Index of Sustainable Economic Welfare [ISEW]) has been used to allow for those corrections related to the depletion of nonrenewable resources and long-run environmental damage.

According to Daly and Coob (1994), after taking into account the corrections, while GNP increased over the 1950 to 1986 interval in the USA, the ISEW index remained relatively unchanged from around 1970 onwards. When depletion of natural capital, pollution costs, and income distribution

effects are accounted for, the USA is seen as making no improvements at all. Therefore, it is possible that if we continue to ignore natural capital, we may well push welfare down while we think we are building it up. England (2006) shows the importance of the ISEW-index to recent research on environmental economics. The ISEW-index is presented in Daly and Coob (1994) and, according to Harris (1995), such a measure has not yet been used in developing countries. Boyd (2006) also shows what is needed to take into account when green gross domestic product (GGDP) is under focus.

Another relevant issue concerns the constraints posed by measurement problems on quantifying environmental assets. As posted by Turner *et al.* (2000), ecosystems are characterized by extreme complexity and to handle computations under different management structures is always a formidable challenge. Issues regarding environmental measurability will be discussed under the emergence of the so-called contingent valuation approach in 'Section Integrating the Qualitative-Analytical Approaches towards a New Conceptual Perspective on Sustainability'.

Having given the relevant definitions of natural capital and sustainability, Section 'Environmentally Based Output Growth Models: an Analytical Apparatus' presents two environmentally balanced output growth models considering, in one perspective, a finite and depletable natural resource, and in another, pollution control as a way of augmenting the stock of a renewable natural resource (fresh air). The choice of both models was intentional, due to their pioneering contribution applying optimal constrained output growth to environmental issues and also the fact that they fit perfectly to the essay's main contribution of jointly considering separate theoretical pieces and contemplating an integrative perspective.

The first model of production growth by Anderson (1972) will be examined, and in the second model, output growth with pollution controls by Forster (1973) will be analyzed. Both models make use of a mathematical method called optimal control theory to address issues on environmental-production growth. The main goal is to show how standard production growth has to be slowed down when constraints on natural resource uses and pollution generation are imposed. Furthermore, this result is a key factor for the analysis of sustainability conceived here.

To meet the sustainability criterion, at the same time that we know that rapid production growth leads to depletion of the stocks of natural resources and pollutes the environment, production processes (accumulation of physical capital) have to face constraints. The possibility of using productive factors (e.g. natural resources) in an unsustainable manner and the eventuality of damaging the environment (e.g. pollution) are two negative by-products of rapid production growth that need to be tackled.

ENVIRONMENTALLY BASED OUTPUT GROWTH MODELS: AN ANALYTICAL APPARATUS

Two classes of environmentally based output growth models will be analyzed in this section: i) production growth using finite and depletable natural resources and ii) output growth with pollution as waste generation. The first pioneering model comes from Anderson (1972), who explores the implications for production growth of accounting explicitly for the depletion of a nonreproducible natural resource, such as a fossil fuel reserve. Stiglitz (1974) uses a similar construction to model production growth in the presence of exhaustible natural resources. More recently, Palmada (2003) makes extensive use of the quantitative tools used in optimal growth models and applies them to formalize optimal allocations of different natural resources, such as air, water and forests during production growth phases.

The analysis to be conducted below follows the standard procedure of considering a one-sector economy, such as in the Bretschger and Smulders (2006) analysis of optimal uses of nonrenewable resources, as well as in Farzin and Akao (2006) and Voinov and Farley (2007), both treating explicitly environmentally based output production models using optimal control in a one-sector economy. The

main objective of these models is to find an optimal capital accumulation trajectory that maximizes the present value of per capita consumption over a finite-planning horizon, subject to some specific terminal conditions on the stocks of traditional capital and natural resources.

An Environmentally Based Output Growth Model with a Depletable Resource

It is worth noting that when a depletable natural resource is considered, the infinitely time-period horizon used in optimal growth models, as suggested in Chiang (1992), is no longer applicable. For an accurate analysis of the mathematical modeling of growth and sustainability, Islan (2005) is an important reference. Other models of optimal output production growth with finite and depletable natural resources are due to Le Van, Schubert and Nguyen (2007), whose focus relies on developing countries and poverty, and Auty (2007), who analyzes the inverse relation between low income countries and natural resource wealth. The problem of the optimal model by Anderson (1972) is formulated by assuming a Leontief production function:

$$Y_t = \text{Min}\,[F(K_t, L_t), \dot{z}_t e^{\alpha t}], \tag{1}$$

where F(.) is the production function, Y_t, the rate of output, K_t, the stock of capital, L_t, input labor, z_t is the stock of depletable resources and α is the relative rate of technological progress in resource requirements. Sa, Reis and Palma (2004) show how technology could optimally control for exhaustion of a nonrenewable natural resource in a competitive sector, in the same way technological progress enters in Anderson's model here analyzed. From equation (1), if $F(.) < \dot{z}_t e^{\alpha t}$, we will have:

$$Y_t = F(K_t, L_t) \quad \text{and} \tag{2}$$

$$\dot{z}_t = -e^{-\alpha t} F(.). \tag{2'}$$

Equation (2) tells us that the rate of output Y_t is a function of physical capital and labor over time and equation (2') states that the rate of resource depletion is proportional to the rate of output production. The depletion proportion diminishes as time passes due to exogenous technological advances (increasing α) that permit depletable natural resources to be used more efficiently. Bretschger and Smulders (2006) show an interesting relationship between the shadow-price of an exhaustible resource and investment spends on R&D in the sector using the natural resource intensively.

The saving-investment identity, i.e., the equation of physical capital accumulation, is:

$$\dot{K}_t = s_t F(.) - \delta K_t, \tag{3}$$

where $0 < s_t < 1$ is the savings ratio and δ is the rate of physical capital depreciation. Now, the optimal growth problem is to find the optimal path for s_t (the control variable) that maximizes the following present value of consumption over the planning horizon [0, T]:

$$\int_0^T [1 - s_t][F(.)/P_t]e^{-\mu t}dt, \tag{4}$$

where P_t is the rate of population and μ is the discount rate. We can rewrite (4) in its intensive form. To do so, all that is required is to assume that population and input labor grow according to $P_t = P_0 e^{\pi t}$ and $L_t = L_0 e^{nt}$, respectively. Thus, the optimal growth problem is:

$$\text{Max} \int_0^T [(1 - s_t)f(\kappa_t)]e^{-rt}dt, \tag{5}$$

subject to:

(i) $\dot{K}_t = s_t f(\kappa_t) - \eta\kappa_t$.

(ii) $\dot{z}_t = -f(\kappa_t)e^{-\gamma t}$.

(iii) $0 \leq s_t \leq 1$, $\kappa_t \geq 0$, $z_t \geq 0$.

(iv) Relevant transversality conditions,

where $r = [\mu + \pi - n]$ is the new discount rate, $\eta = [\delta + n]$ and $\gamma = [\alpha - n]$ are strictly positive. It is also clear that $(1 - s_t)$ is per capita consumption and $f(\kappa_t)$ is the intensive form of the production function. Thus, (i) is the equation of physical capital accumulation in its intensive form and (ii) is the new version of (2'). The set of transversality conditions involves a complex mathematical procedure that it is not feasible to deal with here. Its detailed analysis, which involves an optimal control problem with several constraints and end-point transversality conditions, is presented in Chiang (1992).

The next step is to setup the current Hamiltonian. In optimal dynamic output growth models, the practice of using Hamiltonians is analogous to the use of Lagrangians in static optimization setups. Applications of the optimal dynamic versions in the context of environmental economics are done by Geldrop and Withagen (2000) and Islan (2005) in analyzing mathematical models of natural capital and sustainability using Hamiltonians with renewable and nonrenewable natural resources constraints. The two relevant constraints are (i) and (ii), which lead to a problem with two costate variables, λ_t and m_t and two state variables, k_t e z_t. The two costates are the shadow-price of physical capital stock and depletable natural resource, respectively. The current Hamiltonian is:

$$H^c = (1 - s_t)f(\kappa) + \lambda_t[s_t f(\kappa_t) - \eta\kappa_\tau] + m_t[- f(\kappa_t)e^{-\gamma t}]. \quad (6)$$

Clearly, this current Hamiltonian brings the depletable resource constraint in the very last part of the equation and the new end-point restrictions. Because of the necessity of considering the transversality conditions, to maximize H^c at each point in time with respect to s_t, we need the following decision rules:

If $\lambda_t > 1$, set $s_t = 1$. (7)

If $\lambda_t = 1$, set $s_t \varepsilon [0, 1]$.

If $\lambda_t < 1$, set $s_t = 0$.

We need the maximum principle conditions and the motion equations for λ_t and m_t:

$$\dot{\lambda}_t = \lambda_t r - \partial H^c / \partial \kappa_t. \quad (8)$$

$$\dot{m}_t = m_t r - \partial H^c / \partial z_t.$$

Taking partial derivatives of H^c with respect to the two state variables and using (8):

$$\dot{\lambda}_t = [(r + \eta) - s_t.f'(\kappa_t)]\lambda_t - [(1 - s_t)f'(\kappa_t) - m_t f'(\kappa_t)e^{-\gamma t}]. \quad (9)$$

$$\dot{m}_t = m_t r.$$

Using the decision rules stated in equation (7), and taking into account the conditions in equation (9) [s_t can be eliminated from the first equation in (9) and (i) in equation (5)], we derive the two relevant loci of motion:

$$\dot{\lambda}_t = \begin{cases} [r + \eta - f'(\kappa_t)]\lambda_t, \text{ for } \lambda_t > 1 \text{ and } s_t = 1. \\ m_0 f'(\kappa_t) e^{(r-\gamma)t} + \{ [(r + \eta) - f'(\kappa_t)], \text{ for } \lambda_t = 1 \text{ and } s_t \varepsilon [0, 1]. \\ [(r + \eta)\lambda_t - f'(\kappa_t), \text{ for } \lambda_t < 1 \text{ and } s_t = 0. \end{cases} \quad (10)$$

$$\dot{\kappa}_t = \begin{cases} f(\kappa_t) - \eta\kappa_t, \text{ for } \lambda_t > 1 \text{ and } s_t = 1. \\ s_t f(\kappa_t) - \eta\kappa_t, \text{ for } \lambda_t = 1 \text{ and } s_t \varepsilon [0, 1]. \\ -\eta\kappa_t, \text{ for } \lambda_t < 1 \text{ and } s_t = 0. \end{cases}$$

In spite of the apparent complexity, those conditions are quite easy to understand in terms of drawing a phase-diagram in the (λ_t, κ_t)-space. In the complete analysis of the phase-diagrammatical representation, Anderson (1972) shows that using the end-point transversality conditions, it is possible to visualize the optimal behavior for capital κ_t and its shadow-price λ_t. When the nonreproducible stock of natural resources is considered, the result shows a tendency to postpone capital accumulation and spend time on production growth paths where capital is used less intensively than in models of unconstrained natural resource uses.

Therefore, the basic result, coming from this production growth model accounting for depletable natural resource uses, points to a general slowdown trend of the production growth pace. This is so because the constraint poses a limiting restriction on the use of the considered depletable resources, which leads to a reduced rate of physical capital accumulation and increased rate of savings (less consumption), while acting as the control variable, drives per capita consumption downwards. It should be emphasized that this behavior is the optimal one, in terms of maximizing the present value of the consumption stream over time and at the same time satisfying the relevant constraints. It is optimal to slow down the country's capital accumulation (decreasing production) when depletable natural resources are considered. More recent contributions have shown this same result in different contexts, such as Comolli (2006) in investigating the relations between natural and physical capital during specific economic growth phases, and also Farzin and Akao (2006) as far as optimal exhaustion of a nonrenewable is concerned within a finite time horizon plan.

Linking the concept of sustainability derived in Section ‘Natural Capital and Sustainability: a Qualitative Conceptual Approach’ with the result of this environmentally sounded growth model by Anderson (1972), slowing down the pace of output growth is feasible and desirable, for the stock of nonrenewable natural resources cannot be totally depleted and production activity is in its course, albeit at a slower pace. It is also possible to rule the rate of depletion of the nonrenewable natural resource in such a way that the rate of regeneration of renewable natural capital is always higher, and thus augmentation of total natural capital is obtained. This arrangement would at least preserve the constancy of the total stock of natural capital, a pre-requisite to sustainability as shown in Section ‘Natural Capital and Sustainability: a Qualitative Conceptual Approach’.

An Environmentally Based Output Growth Model with Pollution Generation

The second model deals with an important feature not considered in standard production growth models. Following Forster (1973), we present an optimal physical capital accumulation model taking into account the possibility of waste generation (pollution). As Forster (1973) states, “It is naive to think that no wastes are produced and fairly obvious that the free disposal assumption of the neoclassical growth model is not satisfied in the real world” (p. 544). Again, the choice of this optimal output model was intentional, due to its pioneering role in optimal environmental economics. Other recent models of pollution generation under optimal environmentally based output growth can be cited, such as Lyon and Lee (2003); and Chakravorty, Moreaux and Tidball (2006). Making use of the usual procedure, we begin, following Foster (1973), assuming a standard production function:

$$Y_t = F(K_t). \quad (11)$$

Once again, it is assumed that this production function is well behaved, in the sense that all standard characteristics apply. It is also assumed that the labor force is a constant proportion of a constant population. The produced output can be either consumed (C_t), invested in physical capital stock (I_t) or in pollution control (E_t). Therefore, an additional restriction must be imposed in the following way:

$$Y_t = F(K_t) \geq C_t + I_t + E_t. \quad (12)$$

The usual equation for physical capital accumulation is thus stated, and δ is the rate of capital depreciation:

$$\dot{K}_t = I_t - \delta K_t \quad (13)$$

At this stage we have the equations to setup the optimal control problem, but it is reasonable to suppose that physical capital also produces pollution in addition to output. It is also worth noting that by devoting output to pollution control, the community can lower the amount of pollution generated, refreshing air quality. Note that there is no stock accumulation of pollutant in this model, which is a recognizable shortcoming. But, as in Forster (1980), it can be easily introduced without substantial changes.

Therefore, following Foster (1973), we can formulate an equation for pollution determination as:

$$P_t = P(K_t , E_t), \quad (14)$$

where $\partial P/\partial K_t > 0$, $\partial^2 P/\partial K_t^2 > 0$, $\partial P/\partial E_t < 0$ and $\partial^2 P/\partial E_t^2 > 0$. Finally, the last equation to consider in order to setup the optimal control problem is the linearly separable utility function, assumed to be a function of consumption C_t and pollution P_t,:

$$U(C_t , P_t) = U_1(C_t) + U_2(P_t), \quad (15)$$

where the marginal utility of consumption is positive but diminishing as usual, and the marginal utility of pollution is negative and decreasing. Now we are ready to state the optimal control problem. The objective is to maximize the discounted flow of utility over an infinite time horizon. The problem is to find an optimal path for the variables in order to:

$$\text{Max} \int_0^{\infty} U(Ct, Pt)e^{-rt}dt, \quad (16)$$

subject to:

a) $\dot{K}_t = I_t - \delta K_t$, K_0 given.

b) $P_t = P(K_t , E_t)$, $P_t \geq 0$.

c) $F(K_t) \geq C_t + I_t + E_t$, $E_t \geq 0$.

To analyze the solution for this problem, we need to formulate the current Hamiltonian, which in this case is as follows:

$$H^c = U(C_t , P_t) + \lambda_t[I_t - \delta K_t] + m_t[F(K_t) - C_t - I_t - E_t] + \varphi_t E_t + \theta_t P_t. \quad (17)$$

Again, λ_t is the shadow-price of capital. We have a similar problem as the one we derived in the last model of optimal capital accumulation in the presence of a depletable resource. The only difference is that the very last two terms in (17) and the fact that transversality conditions do not have a role to play, as stated in Chiang (1992), given the infinite-horizon feature of this problem. The derivation of the

optimal conditions leads to the following equations of motion for the two loci in consumption and capital accumulation:

$$\dot{C}_t = U_1'/U_1'' [r + \delta - \partial P/\partial K_t / \partial P_t/\partial E_t - F'(K_t)], \quad (18)$$

$$\dot{K}_t = I_t - \delta K_t.$$

Using these two equations we can investigate the behavior of the capital stock in the (K_t, C_t)-space in a somewhat mirrored manner we mentioned earlier. The detailed phase-diagrammatical and mathematical analysis for the solution of this problem is presented in Forster (1973). The relevant result coming from this optimal environmentally sounded growth model points out that when pollution is accounted for, the production process tends to a lower physical capital stock accumulation than when pollution control is not considered, the same qualitative result attained in our earlier analysis of the depletable natural resource model.

Having presented the two pioneering optimal output growth models accounting for environmental issues, on the one hand, considering exhaustible natural resources, and on the other, pollution as waste generation, we should say that these refinements are important improvements in terms of offering a solid theoretical frame to advise environmental policy in practice. Surely, at least in terms of considering the introduction of environmental issues, the models discussed above seem to have their relevance for the design and implementation of policy on this matter. As posed by Auty (2007), introduction of environmental variables into output growth models has helped by "reinforcing the rationale for the sound management of natural resources and also … providing an index of policy sustainability" (p. 627).

It is true that depletable resources, pollution generation, output production and consumption are all interrelated issues, and thus, to be fully complete such models would have to consider all at the same time. Another set of criticisms refers to the formal and mechanistic manner upon which optimal control models are based. To deal with environmental issues in a pertinent way, political and institutional frameworks must play a very important role, a feature that the formal analysis of optimal control theory is far from acquiring. A recent contribution considering an institutional framework under an optimal dynamic setup applied to output production is Costantini and Monni (2008).

Rethinking the main point, it was seen in Section 'Natural Capital and Sustainability: a Qualitative Conceptual Approach' that in order to attain sustainability a pre-requisite is to preserve the total stock of natural capital. In Section 'Environmentally Based Output Growth Models: an Analytical Apparatus', the analysis of the two pioneering and environmentally-sounded output growth models showed that to control the exhaustion of nonrenewable natural resources or the generation of pollution the rate of production growth has to be reduced. Moreover, it was suggested that it is possible to set up a way allowing for depletion of nonrenewable resources and, at the same time, compensating such environmental damages with improvements upon the available stocks of renewable natural capital, and thus sustainability could be obtained even with no need for reducing an economy's output production.

INTEGRATING THE QUALITATIVE-ANALYTICAL APPROACHES TOWARDS A NEW CONCEPTUAL PERSPECTIVE ON SUSTAINABILITY

Many authors have considered alternative ways to exploit natural resources under sustainable rules, as production growth paces its trajectory. Amigues, Favard, Gaudet and Moreaux (1998) show that by using the general equilibrium approach, the order of extracting a depletable natural resource is to start with the most expensive one, when renewable substitutes are available. Holland (2003), in a partial equilibrium analysis, presents an interesting criterion to optimally use natural exhaustible resources taking into account different orders of extraction, not necessarily starting with the most expensive one. Chakravorty, Moreaux *et al.* (2006) affirm that if exhaustible natural resources are differentiated by

cost, than the cheapest one must be exploited first. Also, Chakravorty, Magné and Moreaux (2006), referring to the Kyoto Protocol, suggest that the joint use of nonrenewable (coal) and renewable natural resources (solar energy) must be imposed even if the renewable solar energy is relatively more costly than coal.

Lafforgue, Magné and Moreaux (2007) present an interesting optimal control application on a depletable and polluting natural resource (fossil fuel), considering, at the same time, a clean renewable resource (air). They conclude that pollution can be generated, but a ceiling has to be imposed, meaning that the dirty absorption by the clean renewable resource can only start when the ceiling is bidding. Moreover, Lafforgue *et al*. (2007) show that "if the renewable natural resource is abundant, optimal sequestration only has to be implemented once the ceiling is reached" (p. 1).

Considering these relevant contributions, the two pioneering output production models analyzed in Section 'Environmentally Based Output Growth Models: an Analytical Apparatus', and the definition of natural capital and its related qualitative concept of sustainability developed in Section 'Natural Capital and Sustainability: a Qualitative Conceptual Approach', we can imagine a scenario where, as long as depletion of nonrenewable natural resources is in course, the augmentation of renewable natural resources can feasibly occur, and thus a new perspective on appraising sustainability can be offered, without implying diminishing produced output.

As showed in Section 'Natural Capital and Sustainability: a Qualitative Conceptual Approach', the total stock of natural capital is the simple sum of the stocks of nonrenewable and renewable natural resources. Sustainability is attained as long as the entire stock of natural capital remains into future at least at the same level as it is today. Thus, it is possible to setup a way, based on the theoretical support used, to obtain sustainability, even if we allow for bounded depletion of nonrenewable natural resources.

Therefore, we can list two ways to reach sustainability in the presence of nonrenewable natural resource depletion, but, at the same time, allowing for the accumulation of renewable natural capital: i) use part of the prospects earned in production activities that deplete nonrenewable natural resources to increase investments towards (or to improve conditions related to) the augmentation of the stocks of renewable natural capital; ii) follow the criterion above and, at the same time, impose a constraint ruling the rate of extraction of the nonrenewable resource to be always less or at least equal to the rate of regeneration of the renewable natural resource.

In the first model of environmentally sounded growth by Anderson (1972), and also in the updated set of contributions referred in subsection 'An Environmentally Based Output Growth Model with a Depletable Resource', it was seen that imposing restrictions on nonrenewable natural resource uses will unambiguously decrease the pace of production growth and thus the environment with its natural resources could be better protected. This was not enough to achieve sustainability, even though it is an important way to preserve natural capital stocks. Regarding the second production model by Forster (1973), and the other recent contributions referred to in subsection 'An Environmentally Based Output Growth Model with Pollution Generation', allowing for pollution controls, the same results are obtained: production growth is slowed down as controls are imposed on pollution generation. This is also not sufficient to attain sustainability, but it is a relevant step towards the main goal of preserving the stocks of natural resources.

The most important result coming from the joint consideration of these two different pieces of environmentally-sound growth models is to see how they can offer an important clue, both at the theoretical and practical point of view, that sheds light on sustainability attainment. In the sustainable development literature it is far more difficult to find approaches that bring together depletion and augmentation of natural resources in a consistent frame such as the one presented here, offering a new conceptual perspective and showing ways to unambiguously attain sustainability.

Two illustrations can be given in order to highlight real world situations where sustainability could be under focus and the new sustainable conceptual perspective used. Suppose that an operating

industrial plant in a small town depletes its nonrenewable coal input at a given bounded rate of extraction. It does not matter whether this production activity, other than depleting the stock of a nonrenewable natural resource at the given rate, pollutes the environment or not, the local community can form a coalition to ask authorities to make the industry owners invest part of the prospects earned to improve fresh air (as a renewable natural resource) quality in their town. If there is a way to take into account the depletion of the nonrenewable mineral stock and the improvements in air quality due to more financial resources being applied to control pollution, the total natural capital stock of the small town could be at least maintained and sustainability attained.

Another situation can be conjectured as a local housing company plans to build up a condominium at a beach front location, bordered by lakes and trees. The local community knows that the construction will damage the natural view of the place, since two paradisiacal dunes will disappear, although the lakes and trees will not be affected. Again, based on the new sustainable conceptual perspective developed above, the solution remains with the authorities to set up a way to obligate the housing company to invest a corresponding monetary amount (equal to the contingent value of the two paradisiacal dunes) to augment the population of wild trees and/or increase birds and fish varieties. If these arrangements are feasible, sustainability can be attained via compensation, a way to maintain the entire stock of natural capital at least unchanged.

As far as the measurement of environmental variables is concerned, the new rich and growing approach of contingent valuation can be cited as a relevant theoretical development to deal with skeptical concerns, for instance, measuring paradisiacal views, and accounting for the valuations of tree populations and the beauty of species varieties. Owing to these developments, a variety of these types of environmental variables can easily be taken in formal quantitative analysis, as done by Bateman and Turner (1992), who developed a comprehensive study on evaluating environmental resources using the contingent valuation method, specifying methods and techniques designed to price environmental goods and services provided by ecosystems. Also, Turner *et al.* (2002) critically review the literature on environmental valuation and conclude that net natural capital services value unambiguously diminishes as biodiversity and ecosystem depletion occur. Alternatively, Bateman, Georgiou and Lake (2005) develop an approach to value aggregate natural resources via estimating a spatially sensitive value function that predicts a declining value for a natural resource as households' distance from it increases. Azqueta and Sotelsek (2007) argue that economic valuations of environmental assets are currently well established.

THE NEW CONCEPTUAL PERSPECTIVE ON SUSTAINABILITY: IMPLICATIONS TO ENVIRONMENTAL MANAGEMENT

It should be said that the essay's main contribution is not to implement an empirical application of any analytical model of optimal environmentally based output growth, but to use the theoretical support referred to conceive an alternative qualitative perspective towards appraising sustainability.

The signaling contribution of this essay, i.e., pointing to the possibility of taking into account environmental assets on production processes, preserving the total sum of these assets (sustainability) and at the same time not slowing down the pace of output production, is an important conjecture to bring 'fine-tuning' both at the environmental and business-profit levels. Regarding the latter, environmental management issues are important to bring into analysis.

At the industry-firm level, many contributions by different authors relate to this essay's main tenets. Labuschagne, Brent and Erck (2005) propose a new framework to assess business sustainability via introducing economic efficiency and environmental performance into a manufacturing sector's operational activities in South Africa, which included an operational criterion for sustainable uses of natural resources. Also, Labuschagne and Brent (2008) use a technological life cycle management framework to allow for industrial sustainability under natural resource uses, also in South Africa's

manufacturing sector. Giljum, Behrens, Hinterberger, Lutz and Meyer (2008) model sustainable scenarios contemplating the "evaluation of the three scenarios with regard to the extraction of natural resources on the European and global level, concluding that suitable environmental management by Europe's industries might lead to unsustainable patterns in natural resources intensive developing countries" (p. 204).

In short, although the main tenets of this essay are not directly connected to the environmental management vein, close implications can be given on this matter. Thus, it is possible even to improve upon the two ways, given in Section 'Integrating the Qualitative-Analytical Approaches towards a New Conceptual Perspective on Sustainability', regarding the attainment of sustainability under the new conceptual qualitative perspective offered and closely related to environmental management works: i) use part of the prospects earned in industrial production processes that depletes nonrenewable natural resources (negative impact on the rate of industry production + positive environmental impact) to increase investments towards the augmentation of the stocks of renewable natural capital (positive environmental impact + positive impact on the rate of industry production, under certain circumstances); ii) Follow the above criterion and, at the same time, impose a constraint ruling the rate of an industry extraction of the nonrenewable natural resource to be always less or at least equal to the rate of regeneration of that industry correlated renewable natural resource. As far as the 'under certain circumstances' prevails, counteracting the first negative impact due to imposing restrictions on nonrenewable natural resource uses by industry production processes, environmental gains can be obtained with no need for industry production decreases.

Final Considerations

In conclusion of the main arguments, we could set up four simple operational principles in order to seek sustainability. It should be said that there have been a number of criticisms of the sustainability literature due to its vagueness in defining key concepts precisely. This essay offers a clear way for appraising sustainability and pointing to a criterion, based on the theoretical support, to implement it via the use of an unambiguous definition of natural capital.

Given these refinements, the following operational principles could be pursued if sustainability is to be attained: i) limit industry production scale to a level that is at least within the carrying capacity of the remaining stocks of natural capital; ii) conceive industrial production growth within sustainable patterns, i.e., as efficient-increasing rather than throughput-increasing, e.g., pollution as waste generation; iii) impose constraints on the uses of nonrenewable natural resources, as advised by the environmentally balanced output growth models presented; iv) exploit renewable natural capital on a sustainable basis, meaning that extraction rates should not exceed regeneration rates, and waste emissions (pollution) should not exceed the renewable assimilative capacity of the environment.

These principles can be conceived towards the functioning of the basic notion that we should satisfy the needs of the present without sacrificing the ability of future populations to meet their needs, a feasible and desirable objective. The challenge is posed and the consequences of not taking into account these issues seriously can be disastrous in the near future. A conscious society, including its institutions, must find mechanisms in order to undertake efforts to make the changes required for sustainable development. Moreover, to achieve this goal, policy decisions should be supported by precise definitions of both natural capital and sustainability such as those provided in this essay. Despite the importance of general policy (macro level) such as population control and income distribution, close attention must be paid to private production activities (micro level) concerning natural resource uses. These activities must be ruled towards maintaining or increasing the current level of total natural capital, a primary condition for the attainment of sustainability.

Fortunately, as suggested by Daly (1987), environmentalists and economists are now conscious that there is a bridge connecting production growth and environmental issues. The negative by-products of rapid output growth can be controlled and reduced if attention is paid to actions, hopefully supported

by theory, that impose constraints on output production, and thereby reduce both pollution generation and depletion of nonrenewable natural resources.

Regarding the essay's main contribution, it should be said that both optimally managing exhaustion of a depletable natural resource and controlling pollution generation over productive processes are not enough to attain sustainability, but, as shown, are important steps towards it. The existing literature already well establishes this result and links it to output production slowdown, as the analytical models have shown us. By integrating the analytical results of the two pioneering models of environmentally based output growth, the innovative conceptual qualitative perspective offered in this essay goes beyond showing that there is a possibility open to attain sustainability throughout bounded depletion of a nonrenewable resource, if compensation were reasonable to occur via augmentation of the stocks of renewable natural resources. Moreover, this can be attainable even with no need for depleting physical output production.

An important issue, not broached in this essay but deserving a mention, is environmental ethics. It is known that nature and its natural flows and stocks cannot be treated as standard market goods and services, and therefore different types of valuations have to be considered. The analysis undertaken in this essay does not consider such ethical issues, and thus can be considered as part of an economical anthropocentric perspective. Many Brazilian authors, such as Lima (2004), who criticize conventional economical-development models in the name of a more social-based management of the environment; and Batata and Siqueira (2006), as using social-constructivist management to apprise public policy on environmental issues, have developed important critical contributions focusing on the inconsistency of biased economical approaches to the environment, and this could be an interesting direction for future work on this theme.

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