Sustainability under Balanced Natural Capital Uses at the Industry Level: A Theoretical Approach

Autoria: Augusto Marcos Carvalho de Sena

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 industrial production growth has exhausted natural resources and polluted the environment. Also, people in society seem not to base their 'pro-green' hysteria in accordance to pragmatic standards, condemning activities that reduce environment quality and disregarding any attempt to eventually consider application of some compensation criterion. The objective of this article is twofold: offer a definition of natural capital and connect it with the concept of sustainability; and present two models of environmentally sounded industrial production growth, where formal analysis shows that imposing controls over the uses of depletable resources and generation of pollution led to an unambiguously slowdown in industrial production. The main contribution relates to mixing the two models in one to reach a feasible outcome that is both in 'fine-tune' with sustainability and industry production growth. We conclude that it is possible, both in theory and practice, to manage depletion of nonrenewable natural resources in such a way that total stock of natural capital can even increase, e.g., via renovating renewable natural resources as a compensation device.

Introduction

As suggested by Boulding (1993), the well-known fact that today's industrial production activities are imposing a heavy burden on earth's capacity has led to an increasing interest in environmental issues. It has been emphasized that rapid production growth at the industry level depletes the current stock of natural resources and damages the environment and that there are clearly limits to this process. Despite the classical 'pro-technology' optimistic arguments, following Barro (1997), that technical progress is what is needed to eliminate all constraints on industry production growth, the approaching exhaustion of earth's carrying capacity is a reality.

Goodland's (1992) argument pointing that current high levels of degradation of the earth's biomass and biodiversity and substantial increases on earth's average temperature are a cruel reality, is a clear evidence of it. Also, as Panayotou (1993) affirms, it is already known the damage industrial production activities have imposed on the environment (e.g. pollution) in the course of rapid growth. Immediate actions are been called for and corrective proposals have been formulated to deal with those issues, both at the academic and managerial arenas.

Also, the traditional way to conceive and measure standard aggregated production in a country, 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-industrial system.

To deal with this shortcoming, there has been recent interest in improving aggregate production and welfare measures to account for natural capital depletion and other corrections of mismeasured economic variables. As a consequence, a new index (ISEW – Index of Sustainable Economic Welfare) has been used to allow for those corrections related to depletion of nonrenewable resources and long-run environment damages. According to Daly and Coob Jr (1994), after taking into account the corrections, while aggregate production increased over the 1950 to 1986 interval in the USA, the ISEW index remained relatively unchanged since about 1970. When depletion of natural capital and pollution costs are accounted for, the USA is seen to be not improving at all. Therefore, it is possible that if we continue to ignore natural capital, we may well push ‘life quality’ down while we think we are building it up. The ISEW-index is presented in Daly and Coob Jr (1994) and, according to Harris (1995), such measure has not yet been used in developing countries.

In spite of this evidence, the issues related to natural resources’ uses have not yet been technically mastered by managers, at the industry level, to base decisions on this matter in practice. Owing to this, this article purposes to offer a definition of natural capital, relate it to the concept of sustainability, and present its main contribution, i.e., showing that specific industrial production processes, as natural resources raw-material consuming, can be managed in a way that sustainability is guaranteed, with no need to slowdown the pace of industrial production growth. The argument is that it is fair industry production to continue consuming nonrenewable natural resources, but that has to be compatible with managing them in a way that compensation, such as augmentation of the stocks of renewable natural resources, can be undertaken and total stocks of natural capital remain unchanged or even increased into the future, without any reduction in the industrial production of goods. This is an important new perspective, since optimal environmentally balanced industry production growth models predict low levels of production as restrictions on natural resources uses and on pollution generation are imposed.

Two of such models of environmentally balanced industry production, explicitly considering exhaustion of nonrenewable and renovation of renewable natural resources, will be summarized. It will be seen that slowing down the pace of industry production is a ‘for sure’ result of both models. Of course, they both present feasible ways to be in ‘fine-tune’ with sustainability, but if and only if low levels of industry production is obtained, a somehow not in ‘fine-tune’ with business and profits. The new theoretical perspective proposed in this article points to merging these two models in one in such a way that sustainabilty could be reached with no need to reduce industrial production.

Next section defines natural capital and connects it to sustainability. It will be seen that without a clear definition of natural capital the task of seeking sustainability will be hard to address. Section 2 presents two models of industry production that explicitly consider depletion of a nonrenewable natural resource (such as coal) and augmentation of a renewable one (fresh air), as long as industrial pollution is controlled. Section 3 goes on to argue that it is possible to obtain sustainability even allowing for “bounded” environmental damage, if compensation is feasible. Last section gives some conclusive remarks on inerent difficulties involved and sheds light on directions for future related work.

1. Natural capital and its related concept of sustainability

To start with, one general definition of capital is important to clearly understand natural capital. Capital is to be considered as a stock that yields a flow of valuable goods and services into the future, no matter if the stock is manufactured or natural. If it is natural, e.g., a population of trees or fishes, the sustainable flow or annual yield of new trees or fishes is called sustainable income, and the stock that yields it is defined as natural capital. Natural capital may also provides services such as recycling waste materials or erosion and pollution 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, since the flow of services from ecosystems requires that they function as whole systems. Another qualification refers to the distinctive character of natural capital, natural 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.

There are two broad types of natural capital, renewable (RNC) or active and nonrenewable (NRNC) or inactive. Examples of the first type are ecosystems and of the second, 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 the stock of total natural capital (TNC) equals renewable natural capital (RNC) plus nonrenewable natural capital (NRNC), i.e., TNC = RNC + NRNC. Also, total natural capital should be interpreted as a dynamic and not as a static concept, since intergenerational concerns will be present.

Thus, the concept of sustainability relates to the maintenance of the constancy of the stock of total natural capital into the future. 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 industrial production activities that use nonrenewable resources in activities related to renewing renewable natural capital stocks.

It is important for operational purposes to define sustainability in terms of constant or non-declining stock of total natural capital. This point is very important, since sustainability implicitly incorporate the notion of intergenerational equity. According to the Brundtland Commission, the primary implication of sustainability is that future generations should inherit an undiminished stock of ‘quality of life’ assets. This broad stock of assets can be measured or interpreted in three ways: i) as comprising only human-made 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.

Holmberg and Samdbrook (1992) emphasize that the Brundtland Commission (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 desirable that item iii) above is the most relevant one to consider under the given definition of sustainability. Human-made capital, renewable and nonrenewable natural capital, diverse ecosystem services, all interacts with human capital and productive processes to determine the production level of market goods and services in a country. The specific form of this interaction is very important to sustainability. Linking those more general arguments with the definition of TNC given above and owing to the intergenerational issue, the frame developed up to this point is crucial to an appropriate definition of sustainability.

We see the interconnections between natural capital and sustainability. It is needed the definition of the first to attain the second, and to reach the minimum necessary condition for sustainability the maintenance of the stocks of total natural capital is a requirement.

A side relevant issue relates to the constraints posed by quantifying environmental assets. As posted by Turner, Brouwer, Georgiou and Bateman (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 3.

Having given the relevant definitions of natural capital and sustainability, section 2 presents two environmentally balanced industry production growth models considering, in one perspective, the use of a finite and depletable natural resource, and in other, pollution elimination as a way to augment the stock of a renewable natural resource. In the first, the industry production model of Anderson (1972) will be examined and in the second, the production model with pollution controls of Forster (1973) will be summarized. Both models make use of a mathematical method called optimal control theory to address issues on environmental-production growth and were intentionally selected due to their pioneer status on this subject. The main goal is to show how industry production growth has to be slowed down when constraints on nonrenewable natural resources' uses and pollution generation are imposed on industrial production processes.

To meet the sustainability criterion, at the same time that we know that rapid industry production growth leads to depletion of the stocks of natural resources and pollutes the environment, production processes have to face constraints.

The possibility of using productive factors (e.g. natural resources) in an unsustainable manner and eventuality of damaging the environment (e.g. pollution) are two bad by-products of rapid industrial production growth that need to be tackled. These two models deal with this matter, but both predict decreasing levels of industry production as natural resources and pollution controls are imposed.

The theoretical approach here proposed tries, as paper's main contribution, to conceive sustainability without the need for reducing industrial production, as prospects earned in projects demanding high uses of nonrenewable natural resources are applied to renew renewable natural resources.

2. Environmentally based industrial production growth models, natural resources uses and pollution generation and control

Two classes of optimal environmentally based industry production growth models will be analyzed in this section: i) production process using a finite and depletable natural resource and ii) output production with controlling pollution as waste generation. The first model comes from Anderson (1972), who explores the implications to industrial output growth of accounting explicitly for the depletion of a non-reproducible resource, such as a raw mineral (e.g., coal). Stiglitz (1974) also uses a similar construction to model industrial production growth in the presence of exhaustible natural resources. More recently, Palmada (2003) makes extensive use of the quantitative tools used in optimal industrial production growth models and apply them to formalize optimal allocations of different natural resources, such as air, water and forest, during specific production phases. The choice to use the old model by Anderson (1972) relies on its pioneering status as the first applying optimal control theory to a production process using an exhaustible natural resource.

The analysis to be undertaken below follows the standard procedure of considering a one-sector economy. The main objective is to find an optimal capital accumulation (stream of optimal production) trajectory that maximizes the present value of per capita consumption of the industry products over a finite-planning horizon, subject to some specific terminal conditions on the stocks of traditional physical capital and nonrenewable natural resource. Note that the specific time-horizon, over which the objective functional has to be maximized under optimization, is compatible with the sustainable intergenerational feature.

2.1. An optimal environmentally balanced industrial production growth model with a depletable natural resource

It is worth noting that when a depletable natural resource is considered the infinitely time-period horizon used in optimal production growth models, as suggested in Chiang

(1992), is no longer applicable. Formally, the problem of the model by Anderson (1972) is set up by assuming a Leontief production function:

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

where F(.) is a standard production function, Y_t the rate of industry output, K_t, the stock of physical capital applied to the industry, L_t, input labor used by it, z_t is the stock of a depletable natural resource (e.g., coal) and α is the relative rate of technological progress in the depletable natural resource requirements. From equation (1), if $F(.) < \dot{z}_t e^{\alpha t}$, we will have:

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

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

Equation (2) tells us that the rate of industry's output Y_t is a function of physical capital and labor over time and equation (2') states that the rate of coal depletion is proportional to the rate of industry's output production. The coal depletion proportion diminishes as time passes due to exogenous technological advances (increasing α) that permit the depletable natural resource to be 'bounded' used more efficiently. That means that there is no chance for the complete exhaustion of coal occurs at the terminal-T condition. Moreover, technological advances will postpone complete exhaustion as T-terminal point approaches.

The equation of physical capital accumulation in industry output production is:

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

where $0 < s_t < 1$ is the industry investments ratio and δ is the rate of physical capital depreciation for the industry. The optimal industry production 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]:

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

where P_t is the rate of population and μ is the discount rate used to calculate the present value. We can rewrite (4) in its intensive form. To do so, it is needed just 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 industry production growth problem is the following:

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

subject to:

(i) $\dot{\kappa}_t = s_t f(\kappa_t) - \eta\kappa_t.$
(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 T-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') above. The set of transversality T-conditions involves a complex mathematical procedure that it is not feasible to treat 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. 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 (coal), respectively. The current Hamiltonian is:

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

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 T-conditions, to maximize H^c at each point in time with respect to s_t (the industry investments rate), we need the following decision rules:

$$\begin{array}{l} \text{If } \lambda_t > 1, \text{ set } s_t = 1. \\ \text{If } \lambda_t = 1, \text{ set } s_t \varepsilon [0, 1]. \\ \text{If } \lambda_t < 1, \text{ set } s_t = 0. \end{array} \tag{7}$$

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

$$\begin{array}{l} \dot{\lambda}_t = \lambda_t r - \partial H^c/\partial \kappa_t. \\ \dot{m}_t = m_t r - \partial H^c/\partial z_t. \end{array} \tag{8}$$

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

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

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:

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

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 non-reproducible stock of the natural resource is considered, the result shows a tendency to postpone capital accumulation (production) and spend time on industrial output growth paths where physical capital is used less intensively than in models of unconstrained natural resources uses.

Therefore, the basic result coming from this industry production growth model accounting for consuming a depletable natural resource (coal), points out to a general slowdown trend of the industry production growth pace. This is so because the constraint poses a limiting restriction on the use of the considered depletable resource, which leads to a reduced rate of physical capital accumulation (less production), driving per capita consumption downwards. It should be emphasized that this behavior is the optimal one, in terms of maximizing the present value of the industry output consumption stream over time and at the same time satisfying the relevant constraints. It is optimal to slowdown the industry's capital accumulation (decreasing production) when a depletable natural resource is considered.

Linking the concept of sustainability derived in section 1 with the result of this environmentally balanced industry production growth model, slowing down the pace of industry output growth is feasible and desirable, via imposing a constraint over the use of the nonrenewable natural resource (coal).

Other than considering the predictions of the optimal industrial production growth model, an alternative possibility to rule the rate of depletion of the nonrenewable natural resource is to manage it in such a way that the rate of regeneration of any industry correlated renewable natural resource is always higher, and thus augmentation of total natural capital can be 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 1.

2.2. An optimal environmentally balanced industrial production growth model with pollution as waste generation

The second model deals with an important feature not considered in standard industry production growth models. Following Forster (1973), we present an optimal physical capital accumulation (production) model taking into account the possibility of waste generation (pollution). As Forster (1973, p.544) states, “It is naive to think that no wastes are produced and fairly obvious that the free disposal assumption of the neoclassical industrial production growth model is not satisfied in the real world”. Again, the choice of this old model relies on the fact that it was also the first using optimal control theory with an industry production process that generates both industrial output and pollution.

Making use of the usual procedure, we start with assuming a standard production function of the following form:

$$Y_t = F(K_t). \tag{11}$$

Once again, it is assumed that this industry 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 industrial 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:

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

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

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

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

Therefore, we can formulate an equation for industry pollution determination in the following manner:

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

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 (production) consumption C_t and pollution P_t,:

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

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. Regarding to this, it is straightforward to allow for the intergenerational feature related to sustainability, since here there is no time upper bound involved and T-terminal point constraints do not have a role to play. Formally, the problem is to find an optimal path for the relevant variables in order to:

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

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:

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

Again, λ_t is the shadow-price of physical capital. We have a similar problem as the one we derived in the previous model of optimal capital accumulation in the presence of a depletable natural resource (coal). The only difference is the very last two terms in (17) and the fact that transversality conditions do not have a role to play, given the infinite-horizon feature of this problem. The derivation of the optimal industry production conditions leads to the following equations of motion for the two loci in consumption and physical capital accumulation (production):

$$\dot{C}t = U_1^{'}/U_1^{''}[r + \delta - \partial P/\partial K_t \,/\, \partial P_t/\partial E_t - F'(K_t)], \tag{18}$$

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

Using these two equations we can investigate the behavior of the physical capital stock in the (K_t, C_t)-space in a somehow mirrored manner we mentioned earlier in the previous model. 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 balanced industry production growth model points out that when pollution is accounted for, the industrial production process tends to a lower physical capital stock accumulation than when pollution is not considered, the same qualitative result in our earlier analysis of the depletable natural resource model.

Having presented the two optimal industry production growth models accounting for environmental issues, on one hand, considering a exhaustible natural resource, and on the other, pollution as waste generation, we should say that these refinements are important improvements in terms of given solid theoretical frame to advise environmental proposals in practice. Surely, at least in terms of considering the introduction of environmental issues, the models discussed above seem to have their relevance for design and implementation of proposals on this matter.

But, it is true that depletable resources, pollution generation, industrial output production and consumption are all interrelated issues, and thus, to be fully complete such models would have to consider all of them at the same time. Also, a more serious problem is that optimal environmentally balanced production growth models bring about a set of weakness in their formulations. First, there is an important internal difficulty related to the use of a given discount rate, issue which authors rarely discuss. It is very hard to find an appropriate discount rate to perform the calculations involved in those optimal control problems, and thus, empirical work on this theme poses a lot of challenges and, at the same time, difficulties. 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 framework must play a very important role, a feature that the formal analysis of optimal control theory is far to acquire.

It should be emphasized, however, that those theoretical efforts must be understood with care, since we cannot say they represent unquestionable improvements. It was put that the mechanistic nature of the optimal control theory is not well suited to deal with environmental issues, the reason being that institutional and political action may be much more important to bring into the analysis. But, at least as long as we are assured to make a good use of an analytical tool like the optimal control theory, suggestive results may rise. According to Chiang (1992, p. 314):

> After so much time and effort to master the various facets of the dynamic-optimization tool (particularly, optimal control theory), we really ought not to end on a negative note. So by all means go ahead and have fun playing with Hamiltonians, transversality conditions, and phase-diagrams to your heart's content. But do please bear in mind what they can and cannot do for you.

It was seen in section 1 that to attain sustainability a pre-requisite is to preserve the total stock of natural capital. In section 2 the analysis of the formal environmentally balanced industry production growth models showed that to control the exhaustion of nonrenewable natural resources or the generation of pollution the rate of industrial production growth has to be reduced. Also, it was suggested that it is possible to set up a way allowing for depletion of nonrenewable natural resources and at the same time compensating such an environmental damage with improvements upon the available stocks of renewable types of natural capital. Therefore, would it be possible reaching a different outcome, e.g., being in fine-tune both with sustainability and industrial production growth?

3. Sustainability based on maintenance of natural capital stock with no slowdown of industry production: mixing the two models

It should be said, to begin with, that implementation of optimal models of industrial production processes is hard to handle. Among the difficulties is the complex task to quantify environmental assets. Many authors have been using methods and approaches to tackle the difficulties involved in managing and measuring natural resources under sustainable patterns as industrial production growth paces its trajectory.

Amigues, Favard, Gaudet and Moreaux (1998) shows, using a general equilibrium approach, that 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 and Tidball (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, Lafforg et al. (2007, p. 1) show that “if the renewable natural resource is abundant, optimal sequestration only has to be implemented once the ceiling is reached.”

Considering these relevant insights and the two theoretical models analyzed above, we can conceive situations allowing for the possibility that, as long as depletion of nonrenewable natural resources is in course, augmentation of renewable natural resources is also feasible, in accordance to the sustainable criterion presented in section 1.

As showed, 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. So, it is possible to setup a way, based on the theoretical environmentally balanced industrial production models analyzed, to obtain sustainability, even if we allow for ‘bounded’ depletion of nonrenewable natural resources. It is also possible to do that with no need to decrease industry output production, an important perspective in terms of being in ‘fine-tune’ with industrial businesses.

Based on the two formal models of section 2, we can list two ways to reach sustainability in the presence of nonrenewable natural resources depletion, but, at the same time, allowing for accumulation of renewable natural capital and with no need for decreasing production:

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 criterion above and, at the same time, impose a constraint ruling the rate of extraction of the nonrenewable natural resource to be always lesser or at least equal to the rate of regeneration of an 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 resources uses by industry production processes, environmental gains can be obtained with no need for industry production decreases.

In the first model of environmentally sounded production growth by Anderson (1972), it was seen that imposing restrictions on nonrenewable natural resources uses will unambiguously decrease the pace of an industry production growth and thus environment with its natural resources could be better used. This was not enough to reach sustainability, even though it is an important way to preserve natural capital stocks. Regarding the second production model by Forster (1973) allowing for pollution controls, the same results are obtained: production growth is slowed down as controls are imposed on pollution generation. This also is not sufficient to attain sustainability, but it is a relevant step towards the goal.

The important contribution of this paper, by jointly considering the two environmentally balanced industry production growth models, is to see how they can offer an important clue, both at the theoretical and practical point of view, to shed light to sustainability attainment without impinging upon industrial production. There is a gap to be filled in the sustainable development literature regarding approaches that bring together depletion and augmentation of natural resources in a consistent analytical frame as the one presented here, offering criteria and showing ways to unambiguously attain sustainability.

An illustration can be given in order to highlight real world industrial situations where sustainability could be under focus and the sustainable criterion offered here be applied. Suppose that an operating industry plant in a small town uses and depletes coal in its production process at a given bounded rate of extraction. No matter if industrial production activity, other than depleting the stock of a nonrenewable natural resource at the given rate, pollutes or not the environment, the community can form a coalition to ask local authorities to make the industry owners invest part of the prospects earned to improve fresh air quality in town. If there is a way to take into account the depletion of the nonrenewable mineral coal and the improvements in air quality due to more financial resources being applied to clean the air, and also if the better air quality positively affects, via positive externalities, coal mining workers to be more productive, the total natural capital stock of the small town could be at least maintained and sustainability attained, plus no decrease of industry's production, which could even increase to 'bounded' levels due to higher labor productivity.

As far as measurement of environmental variables is concerned, the new growing approach of contingent valuation can be cited as a relevant practical-theoretical development to deal with skeptical concerns relating to, e.g., measuring paradisiacal views or valuating population of trees and the of beauty of species varieties. Due to these developments, different types of environmental variables can easily be taken into account in formal quantitative analysis. Bateman and Turner (1992) present 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, Paavola, Cooper, Farber, Jessamy and Georgiou (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.

Therefore, the signaling contribution of this paper, i.e., pointing to the possibility of taking into account environmental assets on industry production processes, preserving these assets and at the same time not slowing down the pace of industrial output production, is an important conjecture to bring together 'fine-tunings' both regarding environmental issues and business prospects.

Final considerations

Summing up the main arguments, we could setup four simple operational principles in order to seek sustainability at a restrict industry level. It should be said that a lot of criticisms have been put on the sustainability literature, because of its vagueness in precisely defining key concepts. This article offered a clear way for appraising sustainability and pointing to a criterion to be applied at the industry level, advancing thus over the existing theoretical literature on this theme. It also gave important clues to implement sustainability via use of an unambiguous definition of natural capital.

Given these refinements, the following principles could be pursued if sustainability is to be attained at the industry level:

i) Limit industry production scale to a level that is at least within the carrying capacity of the industry correlated remaining stocks of natural capital;

ii) Conceive industry production growth within sustainable patterns, i.e., as efficient-increasing rather than throughput-increasing, e.g., controlling pollution;

iii) Impose constraints on the uses of nonrenewable natural resources by production processes, as advised in the first environmentally balanced industry production growth model analyzed in subsection 2.1;

iv) Exploit nonrenewable and renewable natural capital on a sustainable basis, meaning that extraction rates of the former should not exceed regeneration rates of the latter, and waste emissions (pollution) should not exceed the renewable assimilative capacity of the environment;

v) Allocate part of the financial prospects from the consuming nonrenewable natural resources industry production processes to augment the stocks of any industry correlated renewable natural resource.

These principles should be used, at the industry level, towards the functioning of the basic notion that we must satisfy the needs of the present without sacrificing the ability of future populations to meet their needs, a feasible and desirable objective that not only governments but also industrials, managers, etc., have to seek. The challenge is posed and the consequences of not taking into account these issues seriously can be disastrous in near future. A conscious society, including its institutions, corporations, enterprises, etc., must find mechanisms in order to undertake needed changes towards sustainable development.

Moreover, to reach such a goal at an industry level, entrepreneurial decisions should be supported by precise definitions of both natural capital and sustainability such as the ones offered in this article. Despite the importance of general government policies (macro level), close attention must be given to private industrial production activities (micro level) related to natural resources uses. These industrial activities must be ruled in a manner compatible with maintenance or augmentation of the current levels of industry related total stocks of natural capital, a primary condition to sustainability attainment.

Fortunately, as suggested by Daly (1987), environmentalists and economists are now conscious that there is a bridge connecting industrial production growth and environmental issues. The negative by-products of rapid industrial output growth can be controlled and reduced if attention is paid to actions, hopefully supported by formal theoretical contributions such as the one suggested here, that take into account sustainable uses of natural capital.

References

Amigues, J-P., Favard, P., Gaudet, G., & Moreaux, M. (1998). On the optimal order of natural resource use when the capacity of the inexhaustible substitute is limited. *Journal of Economic Theory*, 80 (1), 153-170.

Anderson, K. (1972). Optimal growth when the stock of resources is finite and depletable. *Journal of Economic Theory*, 4 (2), 256-267.

Barro, R. (1997). *Getting it right: market and choices in a free society*. Cambridge: MIT Press.

Bateman, I., Georgiou, S. & Lake, I. (2005). The aggregation of environmental benefits values: a spatially sensitive valuation function approach [Working Paper EDM Nº 05-04]. *Centre for Social and Economic Research on the Global Environment*. School of Environmental Sciences, Norwich, University of East Anglia.

Bateman, I. & Turner, R. (1992). Evaluation of the environment: the contingent valuation method [Working Paper GEC Nº 92-18]. *Centre for Social and Economic Research on the Global Environment*. School of Environmental Sciences, Norwich, University of East Anglia.

Boulding, K. (1993). The economics of the coming spaceship earth. In: H. Daly & K. Townsend (Eds.), *Valuing the earth: economics, ecology, ethics* (pp. 28-39). Cambridge: MIT Press.

Chakravorty, U., Magné, B. & Moreaux, M. (2006). A Hotelling model with a ceiling on the stock of pollution. *Journal of Economic Dynamics and Control*, 30 (12), 2875-2904.

Chakravorty, U., Moreaux, M. and Tidball, M. (2006). Ordering the extraction of polluting nonrenewable resources [Working Paper]. *Department of Economics*, Orlando, University of Central Florida.

Chiang, A. (1992). *Elements of dynamic optimization*. Cincinnati: McGraw-Hill.

Daly, H. (1987). The economic growth debate: what some economists have learned but many have not. *Journal of Environment Economics and Management*, 14 (4), 323-336.

Daly, H. & Coob Jr, J. (1994). *For the common good: redirecting the economy toward community, the environment, and a sustainable future*. (Appendix: The index of sustainable economic welfare). Boston: Bacon Press.

Forster, B. (1973). Optimal capital accumulation in a polluted environment. *Southern Economics Journal*, 39 (4), 544-547.

Forster, B. (1980). Optimal energy use in a polluted environment. *Journal of Environmental Economics and. Management*, 7 (4), 321-333.

Goodland, R. (1992). The case that the world has reached limits. In: R. Goodland, H. Daly & S. Serafy (Eds.), *Population, technology and lifestyle: the transition to sustainability* (pp. 3-22). Washington: Island Press.

Harris, J. (1995). Overview Essay. In: R. Krishnan, J. Harris & N. Goodwin (Eds.), *A survey of ecological economics* (pp. 233-239). Washington: Island Press.

Holland, S. (2003). Extraction capacity and the optimal order of extraction. *Journal of Environmental Economics and Management*, 45 (3), 569-588.

Holmberg, J. & Sandbrook, R. (1992). Sustainable development: what is to be done? In: J. Holmberg (Ed.), *Making development sustainable* (pp. 19-38). Washington: Island Press.

Lafforgue, G., Magné, B. & Moreaux, M. (2007). Energy substitutions, climate changes and carbon sinks [Working Paper]. Toulouse, University of Toulouse 1.

Palmada, A. (2003). Optimal management of natural resources: accounting for heterogeneity. Unpublished Doctoral dissertation, Universitat de Girona, Girona.

Panayotou, T. (1993). The economics of environmental degradation: problems, causes, and responses. In: A. Markandya and J. Richardson (Eds.), *Environmental economics: a reader* (pp. 316-363). New York: St. Martin’s Press.

Stiglitz, J. (1974). Growth with exhaustible natural resources: efficient and optimal growth paths. *The Review of Economic Studies*, Symposium on the Economics of Exhaustible Resources, 41, 123-137.

Turner, R., Brouwer, R., Georgiou, S. & Bateman, I. (2000). Ecosystem functions and services: an integrated framework and case study for environmental evaluation [Working Paper GEC Nº 2002-21]. *Centre for Social and Economic Research on the Global Environment*. School of Environmental Sciences, Norwich, University of East Anglia.

Turner, R., Paavola, J., Cooper, P., Farber, S., Jessamy, V. & Georgiou, S. (2002). Valuing nature: lessons learned and future research directions [Working Paper EDM Nº 02-05]. *Centre for Social and Economic Research on the Global Environment*. School of Environmental Sciences, Norwich, University of East Anglia.