A THEORETICAL FRAMEWORK ON SUSTAINABILITY BASED ON THE MAINTENANCE OF NATURAL CAPITAL STOCKS

AUGUSTO MARCOS CARVALHO DE SENA;

UNIVERSIDADE DE FORTALEZA

FORTALEZA - CE - BRASIL

amsena@unifor.br

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AGRICULTURA, MEIO AMBIENTE E DESENVOLVIMENTO SUSTENTÁVEL

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Grupo de Pesquisa: AGRICULTURA, MEIO AMBIENTE E DESENVOLVIMENTO SUSTENTÁVEL

1. INTRODUCTION

As suggested by Boulding (1993), the well-known fact that today's economy 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 production growth depletes the current stock of natural resources and damages the environment and that there are clearly limits to rapid growth. Despite the classical pro-technology optimistic arguments, which poses, according to Barro (1997), that technical progress is what is needed to eliminate all constraints on economic growth, the approaching exhaustion of earth's carrying capacity is an unquestionable reality[1]. According to Panayotou (1993), it is unquestionable the damage economic activities have imposed on the environment (e.g. pollution) in the course of rapid growth. Immediate actions are been called for and policy proposals have been formulated to deal with those issues, both at the political and academic arenas.

In spite of this, the issues related to renewable and nonrenewable natural resources uses have not yet being mastered to base decisions on this matter in practice. Owing to this, this essay purposes to offer a clear definition of natural capital and relate it to the concept of sustainability, and present a sustainable criterion that explicitly consider both depletion of nonrenewable natural resources and regeneration of a renewable natural resource (air) via controls of pollution generation. It will be seen that balancing the consumption's pace of nonrenewable natural resources with higher investments to increase the stocks of renewable natural resources is compatible with seeking sustainability, for the reason to get it is via maintenance, at least, of the entire stock of natural capital.

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. Also, it will be emphasized that the maintenance of the total stock of natural capital is key in order to obtain sustainability. Section 3 presents two models that separately considers depletion of nonrenewable natural resources and regeneration of a renewable resource, via pollution controls. Section 4 presents a criterion for sustainability based on the maintenance of natural capital stock. Last section gives some conclusive remarks and sheds light on directions for future related works.

2. NATURAL CAPITAL AND ITS RELATED CONCEPT OF SUSTAINABILITY

To start with, one 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, 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 controlling pollution generation, 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, 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.

The concept of sustainability relates to the maintenance of the constancy of the stock of total natural capital. 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. Since the stock of non-renewable 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 point is very important, since sustainability implicitly incorporate the notion of intergenerational equity. According to the Brundtland Commission[2], 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 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.

It is clear and desirable that item iii) is the most relevant one to consider in the context of sustainability. Human-made capital, renewable and nonrenewable natural capital, diverse ecosystem services, all interacts with human capital and economic process of demand-supply to determine the production level of market goods and services of an economy. 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 attain the minimum necessary condition for sustainability the maintenance of the stock of total natural capital is a requirement.

Another relevant issue relates to the standard way to conceive and measure economic growth. It is well known that the traditional 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 (ISEW – Index of Sustainable Economic Welfare[3]) has been used to allow for those corrections related to depletion of nonrenewable resources and long-run environment damages. After taking into account the corrections, while GNP increased over the 1950 to 1986 interval in the USA, the ISEW index remained relatively unchanged since about 1970. When depletion of natural capital, pollution costs, and income distribution effects are accounted for, the US economy is seen to be not improving 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.

Having given the relevant definitions of natural capital and sustainability, section 3 presents two models considering finite and depletable nonrenewable natural resources and environment regeneration via controlling of pollution generation. The first comes from Anderson (1972) who examined the consequences of imposing constraints on the uses of nonrenewable natural resources, and the second is the optimal growth-environmental model with pollution controls of Forster (1973). Both models make use of a mathematical method called *optimal control* to address the issues on environmental-based growth. The main goal of both authors is to show how production growth has to be slowed down when constraints on nonrenewable natural resources uses and pollution generation are, separately, imposed. Furthermore, such result is key to the analysis of sustainability conceived here.

Another important point is that the theory on sustainability developed in section 4 conceives the maintenance of total stock of natural capital as key to seek sustainability. This is done via joint consideration of the uses given to nonrenewable natural resources and the way environment, as a renewable natural resource, is treated, i.e., by considering regeneration of the air as an augmentation of the stock of renewable natural capital.

To meet the sustainability criterion, at the same time that we know that rapid growth lead to depletion of the stocks of natural resources and pollutes the environment, the capitalist's production process (accumulation of physical capital) has to face restrictions. 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 bad by-products of rapid growth that need to be tackled.

3. GROWTH-ENVIRONMENTAL MODELS OF NATURAL RESOURCES USES AND POLLUTION CONTROL

Two classes of models will be analyzed separately as the base to set up in section 4 a sustainable criterion towards sustainability: i) optimal growth with finite and depletable resources and ii) optimal growth with pollution as waste generation. The first model explores the implications of accounting explicitly for the depletion of nonreproducible resources, such as mineral deposits and fossil fuel reserves. The analysis is conducted by following the standard procedure of making use of a one-sector economy. The main objective is to find an optimal path of capital accumulation that maximizes the present value of per capita consumption over a finite-planning horizon, subject to some specific terminal conditions on the stocks of capital and natural resources.

3.1. AN ENVIRONMENT-ECONOMIC GROWTH MODEL WITH DEPLETABLE RESOURCES

It is important to note that when a depletable resource is considered the infinitely time-period horizon used in optimal growth models is no longer applicable. Formally, the problem of the first model is formulated by assuming a Leontief production function:

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

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[4]. From equation (1), if $F(.) < z_t.e^{\alpha t}$, we will have:

$$(2) \qquad Y_t = F(.) \quad \text{and}$$

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

Equation (2) tells us that the rate of output Y_t is a function of 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 resources to be used more efficiently.

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

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

where $0 < s_t < 1$ is the savings ratio and δ is the rate of 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]:

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

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

T

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

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 conditions[5],

where $r = \mu + \pi - n$ is the new discount rate, $\eta = \delta + n$ and $\gamma = \alpha - n$, and all 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 capital accumulation in its intensive form and (ii) is the new version of (2') above. 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 the two state variables, k_t e z_t. These two costates are the shadow price of capital stock and depletable resource, respectively. The current Hamiltonian is:

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

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:

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

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

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

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

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

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

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 $\lambda_t = 0$ and $\kappa_t = 0$:

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

(10)

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

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. 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 resources is considered, the result shows a tendency to postpone capital accumulation and spend time on growth paths where capital is used less intensively than in models of unconstrained resources uses[6]. Therefore, the basic result coming from this growth model accounting for depletable resources uses, points out to a general slowdown trend of the economy's growth pace. This is so because the constraint poses a limiting restriction on the use of the considered resources, which leads to a reduced rate of capital accumulation and increased rate of savings, which, 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 slowdown the economy's capital accumulation when depletable resources are considered.

Linking the concept of sustainability derived in section 2 with the result of this environmental-economic growth model, slowing down the pace of growth is feasible and desirable, for the stock of nonrenewable natural resources cannot be totally depleted and economic activity is in its course, despite at a slower pace. It is also possible to rule, as suggested by Sena (1997), the rate of depletion of the nonrenewable resource in such a way that the prospects of that exploitation have to be applied to the augmentation of renewable natural resources. This arrangement would preserve the constancy of the total stock of natural capital, a pre-requisite to sustainability as shown in section 2.

3.2. ENVIRONMENTAL-GROWTH MODEL WITH POLLUTION CONTROLS

The second model deals with an important feature not considered in standard growth models. Following Forster (1973), we present an optimal capital accumulation model taking into account the possibility of waste generation (pollution). According to Forster (1973, p. 544), "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."

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

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

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 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 capital accumulation is thus stated, and δ is the rate of capital depreciation as before:

(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 capital also produces pollution in addition to physical output. It is also worthy noting that by devoting output to pollution control, the community can lower the amount of pollution generated. Therefore, we can formulate an equation for pollution determination[7] 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 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. Formally, the problem is to find an optimal path for the relevant variables in order to:

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

subject to:

(a) $\dot{K}_t = I_t - \delta K_t$, K_o 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:

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

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 depletable resources. 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, given the infinite-horizon feature of this problem. The derivation of the optimal conditions leads to the following equations of motion for consumption and capital accumulation:

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

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

Using these equations we can investigate the behavior of the capital stock in the (K_t, C_t)-space in a somehow mirrored manner we mentioned earlier[8].

The relevant result coming from this optimal environmental-economic growth model points out that when pollution is accounted for and controlled, the economy tends to a lower capital stock accumulation than when pollution is not considered, the same qualitative result attained in our earlier analysis of the depletable resource model.

Having presented the two classes of optimal growth models separately accounting for environmental issues, in one hand, considering depletable resources, and in the other, pollution as waste generation, we should say that these refinements are important improvements in terms of given solid frame to advise economic-environmental policy. 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 policy on this matter.

Also, it should be emphasized 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.

Despite the importance of the two models analyzed, an important element to consider is that the bounded depletion of nonrenewable resources, as shown by the first model, can be balanced by prospects to increase stocks of renewable natural resources. Therefore, improving air conditions via reduced pollution as compensation, can be a feasible way to maintain the entire stocks of natural capital, and therefore, attaining sustainability[9].

It was seen in section 2 that to attain sustainability a pre-requisite is to preserve the total stock of natural capital. In section 3 the analysis of the two formal optimal environmental-economic growth models showed that to control the depletion of nonrenewable resources or the generation of pollution the rate of production growth has to be reduced. In section 4 we offer a sustainable criterion considering simultaneously bounded depletion of nonrenewable natural resources and controlled augmentation of renewable natural resources, the latter being possible due to devoting efforts to improve air conditions (less pollution), as the second formal model showed. It is thus an effort to conciliate the two separated analyses of the two theoretical models considered in just one.

4. A CRITERION ON SUSTAINABILITY BASED ON THE MAINTENANCE OF NATURAL CAPITAL STOCK

Jointly considering the two theoretical models analyzed above, we can conceive a situation pointing to the possibility that as long as depletion of nonrenewable natural resources is in course, augmentation of renewable natural resources is also occurring, due to some sustainable established criterion.

As section 2 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 today at least at the same level as it was in a previous period of time. So, it is possible to setup a way to obtain sustainability even if we allow for depletion of nonrenewable natural resources.

Based on the two formal models analyzed in section 3, we can list two ways to build up a sustainable criterion to deal with depletion and accumulation of nonrenewable and renewable natural resources, respectively:

- Use part of the prospects earned in economic activities that deplete nonrenewable natural resources to increase investments or improve conditions related to the augmentation of stocks of renewable natural capital;

- Follow the criterion above and, at the same time, impose a constraint so that the rate of extraction of the nonrenewable resource is always equal or lesser than the rate of regeneration of the renewable natural resource.

Two examples, based on real life events, can be offered in order to illustrate eventual situations where sustainability is at odds and where the sustainable criterion offered here can be used to in accordance.

Suppose that a functioning mineral deposit plant in a small town depletes its coal at a given bounded rate of extraction. No matter if this activity, beyond depleting the stock of a nonrenewable natural resource at a given rate, pollutes or not the environment, the local community can form a coalition to ask authorities to make mine owners invest part of the prospects earned in that activity to improve fresh air quality in the locality. If there is a way, e.g., contingent valuation approach, to quantify the depletion of the nonrenewable mineral 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 is maintained and sustainability attained.

Another situation can be illustrated as a residential constructor plans to build up a condominium in a front beach spot, bordered by lakes and trees. The local community knows that the construction will affect 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 sustainable criterion offered above, the solution would be authorities setup a way to obligate the housing builder to invest the corresponding monetary amount (equal to the value of the two vanishing paradisiacal dunes) in augmenting the populations of trees and lake fish variety. If this is feasible, sustainability can be attained via compensation, a way to maintain the entire stock of natural capital unchanged.

5. FINAL REMARKS

Fortunately, as suggested by Daly (1987), environmentalists and economists are now conscious that there is a bridge connecting economic and environmental issues. The negative by-products of rapid growth can be controlled and reduced if attention is paid to actions, hopefully supported by the sustainable criterion presented in section 4.

Summing up the main arguments, based on the theoretical models analyzed in section 3, and the sustainable criterion presented in section 4, we could setup three simple operational principles in order to seek sustainability. 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 presented a clear way for appraising sustainability and pointed to a criterion to implement it via use of an unambiguous definition of natural capital.

Given these refinements, the following principles could be persuaded if sustainability is to be attained:

i) Conceive output growth within sustainable patterns, i.e., as efficient-increasing rather than throughput-increasing, e.g., pollution generation.

ii) Impose constraints on the uses of nonrenewable natural resources, as advised by the theoretical environmental-economic growth models investigated, exploiting them at a rate equal or lesser than that of the creation of renewable natural capital. As the sustainable criterion offered here advises, by doing so, total stock of natural capital will not be depleted.

iii) 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 toward the operationalization 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 desirable and sustainable objective. 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, must find mechanisms in order to undertake needed changes towards sustainable development. Moreover, to reach such a goal, policy decisions should be supported by precise definitions of natural capital and sustainability such as the ones given in this article. Thus, close attention must be given to private business activities related to natural resources use. These activities must be closely directed towards maintaining or increasing the current level of total natural capital, a primary condition to sustainability attainment.

Regarding future works, the theoretical framework presented here can be used as an important support to empirical studies related to the uses of nonrenewable and renewable natural resources. Some problems might come from the difficult to quantify stocks of these resources, but the contingent valuation approach is an available way to face this problem.

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ENDNOTES

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[1] Goodland (1992) shows the current high level of degradation of the earth's biomass and biodiversity, as well as the substantial increase in the earth's average temperature.

[2] Holmberg and Samdbrook (1992) emphasize that the Brundland Commission (World Commission on Environment and Development) gave geopolitical significance to the use of the sustainable development concept.

[3] Daly and Coob Jr (1989) present the index and according to Harris (1995) such measure has not yet been used in developing countries.

[4] It is important to note that α imposes bounded depletion of nonrenewable natural resources, in the sense that they cannot be totally exhausted by use. A sustainable criterion, to be developed in section 3, is to balance uses of renewable natural resources in a way that rate of extraction at time t is lesser of equal to rate of regeneration at time t-1.

[5] The set of transversality conditions involves a complex mathematical procedure that it is not feasible to treat here. For a detailed analysis on optimal control problems with several constraints and end-point transversality conditions, see Chiang (1992), chapter 10.

[6] For the complete analysis of the phase-diagramatical representation, see Anderson (1972), 261-262.

[7] Note that there is no stock accumulation of pollutant in this model, a recognizable shortcoming. But, it can be easily introduced without substantial changes. See Foster (1993) for this extension.

[8] The detailed phase-diagramatical and mathematical analyses are presented in Forster (1973, pp. 546-547).