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ANALYSIS

Constraints on dematerialisation and allocation of natural capital along a sustainable growth path

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Abstract

To study societal and biophysical constraints on sustainability, we present an extension of the neoclassical growth model with two new concepts: allocation of natural capital and dematerialisation. We consider that anthropogenic environmental impact is correlated with the material throughput of the economy (materialisation) and that, due to composition change and innovation, this throughput can be reduced—the process of dematerialisation. We also consider that the allocation of natural capital to production negatively affects the endogenous dynamics of ecosystems, reducing the total amount of environmental services ecosystems provide. According to our model, it is possible to achieve unbounded economic growth by keeping the natural system in steady state. Balanced growth, however, is only possible for special parameter values.

Keywords: Economic growth; Sustainability constraints; Materialisation; Allocation of natural capital

1. Introduction

Sustainable development is a topic of concern among economists and natural scientists, as well as among development agencies and the general public, even though the concept carries different meanings for these different actors (Hart, 2002).

Neoclassical growth theory has tried to address this problem (Solow, 1974; Aghion and Howitt, 1998) but it has been greeted with some skepticism due to its tenuous biophysical rigour.[1]

The aim of this paper is to contribute to a more satisfactory depiction of economic–environmental interactions within the framework of neoclassical

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[1] For critiques of neoclassical economics, see Blaug (1991) on methodological aspects, Nelson (1997) on policy implications, Hall (2000) on biophysical basis, and Cabeza Gutés (1996) on the assumptions of growth theory.

growth theory. We do so by exploring the possibility of sustainable growth when natural capital plays the double role of a fund and of a provider and absorber of flows (Kraev, 2002).

To do so, we base ourselves on the growth model of Belbute (1999), where built and natural capitals are used as production factors, with natural capital subject to logistic regeneration. In the present paper, a model of natural capital dynamics is presented where, besides dynamic environmental impact (that reduces available natural capital), society causes a structural interference on the natural system that diminishes the carrying capacity of natural capital. In the present paper, dynamic and structural human–nature interactions are endogenised by the introduction of two new concepts: dematerialisation and allocation of natural capital.

According to some authors, the problems of resource exhaustion and pollution (inputs and outputs of the production process) can both be assigned to the material throughput of the economy (Hinterberger et al., 1997), which we define as its degree of materialisation. If the material throughput per unit of income decreases fast enough (the process of dematerialisation), then it is possible to reconcile the ecological economic requirement for a non-increasing material economy (Costanza et al., 1997a) and the conventional political goal of unbounded economic growth. We explain this process of dematerialisation through innovation (new technologies may be resource-saving) and composition change (less materialised sectors of society may grow faster than average).

Human society depends on a variety of ecosystem services, most of which are invisible and unrewarded (Daily, 1997). The extent of human dominion of the biosphere, for productive purposes, is threatening ecosystem functioning (Vitousek et al., 1997). The competition between ecosystem services and human dominion is addressed in the model through the concept of allocation of natural capital: natural capital is either free or enslaved to production (England, 1998, 2000). Free natural capital provides direct environmental services to society (Belbute, 1999) and contributes to ecological functioning, while enslaved natural capital fuels the productive process but is unable to perform any of those two functions.

The structure of the paper is as follows. In Sections 2–4), a general growth model is presented (Section 2 focuses on the biophysical aspect, Section 3 on technology, and Section 4 on consumer behaviour). In Section 5, an analysis of the model is presented, focusing on the constraints that arise along a sustainable growth path. Section 6 closes the paper with conclusions.

2. Role and dynamics of natural capital

2.1. Role of natural capital

Natural capital is the aggregation of all environmental assets, and is used by society for three broadly defined purposes: (1) environmental services, (2) resource uptake, and (3) waste disposal (Dunlap, 1993; England, 1998).

Regarding environmental services, Georgescu-Roegen (1971) called nature "the silent companion of man" to draw attention to the fact that nature works as a fund (i.e., it produces a service and is not consumed), performing a diversity of functions such as the maintenance of soil fertility, climate control, or natural beauty.[2] The spatial and temporal scales of ecosystem functioning vary greatly, and there is presently great uncertainty regarding the true extent of societal dependence on natural ecosystems (Daily, 1997; Levin, 1999).

The economic process needs not only environmental services but also material and energy flows of low entropy. These flows can be classified as renewable and non-renewable resources (e.g., timber and minerals). Because most resources used by humans are, to a great extent, a result of ecosystem processes (notice that oil is a fossil fuel), we will assume that aggregate natural resources will behave as renewable resources.

At the other end of the economic process, the disposal of high entropy residuals is unavoidable, both in the production process and during consump-

[2] Kaufmann (1995) considers only climate control as the fund action of natural systems, while van den Bergh and Hofkes (1997) do not consider the fund function of natural capital, in the framework of a neoclassical growth model. Belbute (1998a) considers that environmental services affect utility but not the productive process.

tion. Nature receives what society no longer wants, and its assimilation capacity is subject to critical loads and bounded degradation rates. Aghion and Howitt (1998) consider that the rate at which the environment assimilates pollution increases as the pollution load increases, ending abruptly as a critical load is reached. This is highly unrealistic, and a sort of logistic behaviour is instead to be expected (Belbute, 1998b).

Pollution (outflow of the production process) and natural resources (inflow to production) are, from an ecological point of view, disturbances that can be grouped into natural capital depletion. Natural capital is the provider and absorber of flows, not the flows themselves. Environmental amenities are used without being consumed, but human action does interfere with ecosystems' ability to deliver them (Kraev, 2002).

2.2. Dynamics of the natural system

Natural capital, N, obeys the balance equation:

$$\frac{dN}{dt} = R(N) - P(Y), \tag{1}$$

where $R(N)$ is natural regeneration, which depends on the stock of natural capital, and $P(Y)$ is a throughput disturbance, which includes the negative effects of both resource depletion and pollution and depends on the level of economic activity or aggregate output, Y. We will discuss $P(Y)$ further ahead in Section 3.3, and now we will focus on the endogenous dynamics of natural capital. In Box 1, several equations that compose the model are summarised.

Box 1
Summary of the model, with main equations, variables, and constants

Objective functional (Eq. (9)):

$$U = \ln C + \phi \ln((1-u)N)$$

Built capital accumulation (Eq. (5)):

$$\frac{dK}{dt} = Y - C - \delta K$$

Production function (Eq. (7)):

$$Y = AK^{\alpha}(uN)^{1-\alpha}$$

Environmental impact (Eq. (8)):

$$P = m_0 A^{\alpha} Y^{-n}$$

Natural system (Eqs. (1)–(4)):

$$\frac{dN}{dt} = rN(CC - N) - P$$

$$\frac{1}{l}\frac{dCC}{dt} = \frac{1}{N}\frac{dN}{dt} - \frac{1}{1-u}\frac{du}{dt}$$

Productivity growth (Eq. (6)):

$$\frac{1}{A}\frac{dA}{dt} = g\left(\frac{1}{K}\frac{dK}{dt}\right)$$

Variables
U = Utility
C = Consumption
N = Natural capital
CC = Carrying capacity of natural capital
Y = Economic output
K = Built capital
A = Total productivity
P = Environmental impact
u = Fraction of enslaved natural capital

Constants
ϕ = Environmental concerns
α = Share of capital
δ = Depreciation rate
r = Growth parameter of N
l = Growth parameter of CC
m_0 = Materialisation parameter
a = Innovation parameter
n = Composition change parameter

In some models (Aghion and Howitt, 1998 for pollution; Kolstad and Toman, 2001 for climate change), regeneration is considered to be linear. Following Belbute (1998a), we consider that regeneration, $R(N)$, should be of logistic form, decreasing both as the system increases to its carrying capacity, CC, and decreases to zero. An explicit functional form is:[3]

$$R(N) = rN(CC - N). \tag{2}$$

A constant carrying capacity implies that all environmental impacts are reversible because, once the disturbance has ceased (if $P(Y)$ becomes zero), no matter how harsh the disturbance has been, the system will always return to the original steady state (the carrying capacity). A way to overcome this problem is to consider a changing carrying capacity. Following an analogy from population dynamics, an equation for CC, originally presented by Cohen (1995), is adapted to the context of natural capital as follows:

$$\frac{dCC}{dt} = \frac{l}{N}\frac{dN}{dt} - dist. \tag{3}$$

In this equation, the term $(l/N)(dN/dt)$ accounts for the endogenous dynamics of natural capital and the term dist accounts for human-induced structural interference.

Eq. (3) describes a positive effect on the increase of carrying capacity originated by an increase in the stock of natural capital (i.e., dCC/dt increases with dN/dt). Yet, the benefit on ecosystem functioning due to natural capital increase is decreasing; hence the term l/N. As N rises, an extra increase of N will be reflected in a smaller increase of CC.[4] The dynamics of the undisturbed natural system (given by Eq. (3) when dist is 0 and by Eq. (1) when P is 0 and R is given by Eq. (2)) follows a sort of generalized logistic path, with a stable finite equilibrium at $N = CC$ when time goes to infinity.

The mechanistic basis for Eq. (3) is as follows. Consider natural capital to be the sum of all biological populations in the ecosystem and that every population serves some ecological function, offering services to other species. The instantaneous carrying capacity is the total population supported, given the present services supported. However, as a population grows, the services it provides to other populations increase and hence the carrying capacity of the total system expands at the same rate as population growth itself (i.e., dCC/dt increases with dN/dt). However, populations are not only supported by services provided by other species but also by abiotic factors. Some abiotic factors are complementary to ecological services (e.g., the primary energy source). As population grows, limitation by abiotic factors becomes more important and population growth yields, decreasing benefits for the increase of carrying capacity, so dCC/dt decreases with N.

The term dist > 0 reflects a structural interference caused by human action that disturbs the natural system not because of the consumption or the release of flows (that effect is captured in $P(Y)$) but because of human disturbance on ecosystem structure and functioning. For example, in the timber exploitation of a forested area, there is a negative dynamic impact (associated with flows, and occurring only during the exploitation time) due to timber extraction, erosion while the soil is uncovered, soil compaction, noise, and other forms of pollution. There is also an impact associated with human action that does not cease immediately when human action ceases, and must therefore be reflected as a decrease in carrying capacity. This structural interference may be habitat fragmentation due to road construction, the removal of native species or the introduction of exotic species, waterline diversion, and interference with the hydrological regime. Notice that, in our model, following human disturbance, the natural system may return, in the long run, to the original, to a larger or to a smaller steady state of natural capital. All depends on the duration and relative intensity of $P(Y)$ and dist.

2.3. Allocation of natural capital

England (2000) advanced the stimulating insight that ecological services are only provided by the

[3] Our definition of specific growth rate, r, is slightly different from usual. The mathematical properties of the logistic are given in Belbute (1998b) and applied in a bioeconomic context in Clark (1976). For a critique of the ubiquity and applicability of the logistic equation, see Peters (1991).

[4] Conversely, the marginal effect on CC of an increase in N will rise to infinity as N approaches zero. This is unrealistic but it should not distress us because we will make our analysis along a sustainable growth path, imposing that N is away from zero.

fraction of land not occupied by mankind. As Odum (1969) shows, modern agriculture and modern land occupation are, in general, highly disruptive of ecosystem function. Even though purely geographical space does not correspond to ecological space, we can conceptualise that natural capital is in fact composed of a fraction used for productive processes ("the biological slaves of mankind") and a fraction of "free" natural capital. If we think of an intensity of use of land rather than an absolute dichotomy between allocated forms of natural capital, we can consider that from the total stock of natural capital, N, society may choose to use for productive purposes a certain fraction, uN. The remaining part, $(1-u)N$, is what we call free natural capital, which provides direct environmental services that directly affect human well being[5] and is the only contributor to the increase in carrying capacity. Hence, we can model structural interference as:

$$\frac{dCC}{dt} = \frac{l}{(1-u)N}\frac{d(1-u)N}{dt} = \frac{l}{N}\frac{dN}{dt} - \frac{l}{1-u}\frac{du}{dt}. \tag{4}$$

Comparing with Eq. (3), it is immediately clear that the structural interference term, dist, is related to the allocation of natural capital to production.

2.4. The problem of aggregation and validation

We are assuming substitutability among the different functions of natural capital. This is at least debatable, as is the aggregation of any kind of capital itself, with the particular handicap of the extremely diverse dynamics of ecosystems for the aggregation of natural capital. We aggregate all functions of natural capital so competition among functions is only addressed if we add the competing functions—the burden is passed on to the empirical aggregation work. Unfortunately, this problem seems to be pervasive: a forest is a stock of timber as much as a life support for biodiversity. Comprehensive listing of all the functions of natural capital for human use is necessary.[6]

In fact, the valuation and aggregation of capital are even today rather controversial (van den Bergh and Verbruggen, 1999). Harte (1995) claims that ecosystems are dynamic entities and therefore it is meaningless to talk about a "stock" of natural capital. According to Kaufmann (1995), natural capital should be valued by the goods and services it provides to humans, measured in terms of their opportunity costs, therefore depending on human tastes and technological abilities. Hinterberger et al. (1997) point out that a rise in the prices of natural assets may increase the value of natural capital even in the case of severe depletion. Ecosystem and biophysical cycles behave independently of human choices.

So we face a conceptual dilemma, regarding the valuation of natural capital: economic when it is used for human purposes, biophysical for matters of endogenous dynamics. Still, an important result of the valuation of ecosystem services (Costanza et al., 1997b) was the finding of a strong correlation between value and primary productivity for most ecosystems (Costanza et al., 1998). This result is important because it suggests that biophysical and economic valuation may, in many aspects, coincide.

Regarding empirical assessment, the several parameters alluded to so far may be estimated even without a precise quantification of natural capital, making use of existing results from the ecological literature. Wackernagel and Rees (1997) refer to the ecological footprint as the "appropriated carrying capacity," or the ecological space required for the economy or population. Vitousek et al. (1997) estimated that man appropriates about 40% of terrestrial net primary production. Hall (2000), among others, estimated total primary solar energy embodied in units of economic wealth. Ulanowicz (1986) proposed ascendancy as a measure of the degree of organisation of ecosystems. According to Schneider and Kay (1994), the maturity of ecosystems can be measured as their ability to dissipate solar radiation. These several measures and

[5] Endres and Radke (1999) present a growth model to study the effect of the allocation of land use between agriculture and forest, where only the latter enters a logistic regeneration function for natural capital. Even though the modelling options are different, we are modelling the same phenomenon.

[6] Dunlap (1993) proposes that competition among the three functions should be considered, as well as a carrying capacity for them as a whole—nature's ability to tolerate man's demands.

measurement methods may, in principle, be used to estimate the parameters and variables of our biophysical model (r, l, N, and CC).

3. Technology

3.1. Built capital and knowledge

According to Georgescu-Roegen (1971) and England (1998), fund agents act on the process, not being consumed (although they can be damaged) and thus keeping their identity. Conventional production factors are funds. Flows are usually not considered in aggregate models (they are referred to as intermediate goods). In our model, we will use K (built capital) and A (knowledge or total productivity) as human production factors (Rebelo, 1991). We consider that A encompasses intellectual capital (Aghion and Howitt, 1998), human capital (Lucas, 1988), and institutions (North, 1990).

Built capital includes several types of tools and equipment of the private sector and society's infrastructures. As usual, we assume that this stock depreciates at a constant rate, $\delta > 0$, but it may be increased by gross investment (the fraction of production, Y, that is not consumed, C) so that the net increase in the stock of physical capital at any point in time can given by:

$$\frac{\mathrm{d}K}{\mathrm{d}t} = Y - C - \delta K. \tag{5}$$

An extensive literature on the dynamics of A exists (endogenous growth theory) and attempts to introduce the environment into this theory date from the past decade (Aghion and Howitt, 1998). Recently, more attention has been devoted to the link between technological change and environment (see Löschel, 2002; Hart, 2002, or the special issue of *Resource and Energy Economics*, 2003). Since this topic has already been explored elsewhere and, in the present work, we focus our attention on human–nature interactions, we consider that:

$$\frac{\dot{A}}{A} = g\left(\frac{\dot{K}}{K}\right), \tag{6}$$

such that $g(\cdot)=0$ when the argument is smaller than zero, g is concave and continuous when the argument is greater than 0, and when $\dot{K}/K \rightarrow \infty$, $g \rightarrow g^*$.

Eq. (6) is uncommon but is a natural extension of traditional (exogenous) growth theory, where g is assumed constant. Assuming constant g, in our model, would bias the results in two ways. It would lead to unbounded growth in output, even without increasing input factors. It would also lead, par force, to absolute dematerialisation (discussed further ahead). Assuming Eq. (6), an increase in productivity is only possible if there is accumulation of one production factor (built capital); if that accumulation rate is constant, the rate of growth of A is also constant, which is the case assumed in traditional growth theory. According to our model, if capital accumulation is non-existing, there occurs no increase in productivity. If there is capital accumulation, productivity rises, but the increase in productivity resulting from increasing capital accumulation yields diminishing returns, tending to an asymptote at g^*.

In short, we assume that knowledge does not depreciate, that it exhibits increasing returns to scale, and that its growth requires capital accumulation. The motivation for the properties of g comes from the idea of learning-by-doing. New knowledge is created by performing novel tasks, resulting from the need to adapt to new equipment, and so on. Without the employment of new machinery, according to our model, no increase in productivity occurs, as only routine operations are performed. This is a crude simplification, but it is sufficient for our purposes.

3.2. Substitutability between man-made and natural capital

The degree of substitutability between natural and built capital is important because it affects the choice of the specific form for the production function. Following the idea that they are substitutes, Cobb–Douglas (Solow, 1974), AK (Belbute, 1999), or Schumpeterian (Aghion and Howitt, 1998) production functions have been used. In contrast, England (2000) presents a growth model with natural and built capital as perfect complements.

We will discuss how our model addresses three of the criticisms posed by ecological economists against a high degree of substitutability: the existence of viability thresholds, embodiment concerns, and indirect resource use.[7]

If there is a critical value of natural capital below which human economy cannot survive, then the substitutability between man-made and natural capital can only be marginal. In Daly's (1997) example, we can survive a given decrease in the thickness of the ozone layer by buying more sunglasses, but if the ozone layer were to disappear completely, it would not be feasible to supply all living beings with sunglasses. In our model, these criticality effects are captured in the dynamics of the carrying capacity. We consider that structural interference (with the specific functional form of natural capital allocation) causes a loss of natural capital's carrying capacity. If this interference is strong enough, the natural system may collapse, entailing the collapse of the economic subsystem.

Embodiment concerns arise because built capital is, from a physical point of view, transformed natural capital. Because of the inevitability of thermodynamic inefficiency, even if some degree of substitutability exists, it must be bounded (Kaufmann, 1995). In our model, the problem of embodiment is captured by the joint dynamics of built capital accumulation and environmental impact. For capital to be accumulated, it must first be produced, and production, by requiring allocated natural capital, reduces available natural capital for further production.

The problem of indirect resource use, referred by Stern (1997) in page 201 and Fig. 2, implies that the isoquants in a macroeconomic production function should be backward-bending. The explanation is that at the macrolevel, production factors are never primary inputs, but instead, the use of a given input requires the use of all other inputs. Thus, built capital requires material and energy inputs for its maintenance. In fact, this indirect resource use is just the depreciation of neoclassical economics or the "wear and tear" of funds in Georgescu-Roegen's terminology. Notice that if built capital is subject to depreciation and the production function is concave, backward-bending isoquants for net output (gross output minus depreciation) are obtained.[8] So, the problem of indirect resource use is already taken into account.

Because we can address these criticisms outside the production function, we can consider built and natural capital as imperfect substitutes. Let the production function be continuous, concave, class C^2, positive, and unbounded, and let both inputs, allocated natural capital, uN, and built capital, K, be essential inputs (Belbute, 1998b; Solow, 1974). Knowledge, A, is a scale factor whose dynamics is given by Eq. (6). We will use the Cobb–Douglas functional form:

$$Y = AK^{\alpha}(uN)^{1-\alpha}. \tag{7}$$

Output, Y, is first-degree homogeneous in K and uN and possesses elasticity α in respect to built capital and elasticity $1-\alpha$ in respect to natural capital allocated to production.

3.3. Dematerialisation

According to the Environmental Kuznets Hypothesis (EKH), environmental problems and income should have an inverse-U relation, and so, from a certain point in time onward, environmental impact should decrease as the economy grows (Grossman and Krueger, 1995). The factors that might explain the EKH in a simple economy are scale, composition, and technological change (Torras and Boyce, 1998).[9] As the economy grows, pollution and the demand for resources also grow (the scale effect), but if economic sectors with lower-than-average environmental impact grow above average (composition effect) and new cleaner technologies are invented (technological change; i.e., innovation), overall environmental impact may decrease.

To simplify, we assume that environmental impact, P, is proportional to total material throughput. Thus, environmental impact is the product of the market activity of the whole society and a coefficient that expresses the material throughput per unit of econom-

[7] Keil (1998) presents a different but convincing criticism of similar questions based on Georgescu-Roegen's production theoretical approach.

[8] If net output is $Y'=Y-\delta K$ and gross output is obtained with a Cobb–Douglas production function (Eq. (7)), $uN(K)$ for constant Y' is given by $uN = (Y'A^{-1}K^{-\alpha} + \delta K^{1-\alpha})^{\frac{1}{1-\alpha}}$, which yields a backward bending curve, qualitatively similar to the one displayed by Stern (1997).

[9] Many other factors have been considered, such as pollution export or inequality (Rothman, 1998). To study such effects would require modelling a socially structured open economy.

ic activity, $P=mY$. Let us call materialisation or material intensity to $m=m(A,Y)$. As innovation takes place and society learns to use resources better, we expect m to decrease, thus $\partial m/\partial A<0$. If the composition effect is taking place, then economic growth will also lead to a decrease in m, and $\partial m/\partial Y<0$. The decrease in total material throughput (dematerialisation) must comprehend these two dimensions of innovation and composition change.

A way to capture both effects is to use the functional form:

$$P = m_0 A^{-a} Y^n, \tag{8}$$

with positive n, a, and m_0. The term m_0 is a scale factor, which ensures that P has dimensions of natural capital flow. The term a is the elasticity of total material throughput with respect to knowledge (capturing the environmental benefit of technological change), and n is the elasticity of total material throughput with respect to production (capturing the environmental impact of the composition effect). We will consider as a first approach that a and n are constant and exogenous. We suspect that composition change is demand-controlled, with an environmentally friendly society favouring the success of environmentally benign economic activities. We also suspect that scientific research in an environmentally friendly society will have increased environmental spillovers, yielding a higher a.

Let relative dematerialisation mean a decrease in the material intensity of the economy, $\mathrm{d}m/\mathrm{d}t<0$, and let absolute dematerialisation mean a decrease in total material throughput, $\mathrm{d}P/\mathrm{d}t<0$. Using the definition of materialisation and Eq. (8), we obtain $m=m_0A^{-a}Y^{n-1}$. Thus, if $n<1$, there is a positive composition effect on dematerialisation (decreasing returns of economic output to environmental impact). And if innovation takes place (increase of A), since a is assumed to be positive, there is a positive effect of technological change on dematerialisation. In both situations, relative dematerialisation takes place. For absolute dematerialisation to take place, we must have:

$$\frac{a}{n} > \frac{\dot{A}/A}{\dot{Y}/Y}.$$

Some authors (Cogoy, 2002; Luzzati, 2002) argue that dematerialisation possibilities are bounded by thermodynamic limits and thus materialisation can never decrease to zero. That is, materialisation should be of the form $m=m_L+\sigma(A,Y)$, with m_L constant and σ as a general function of knowledge and output. However, we believe that our functional form, which possesses no fixed lower threshold m_L, not only lends itself to greater mathematical tractability but actually describes more accurately the productive process. The argument in favour of a lower materialisation threshold comes from the inevitability of thermodynamic inefficiency in irreversible processes. However, the economic system is not a single process but a network of different processes that can be operated with different technologies. All processes, whatever the technology used, must have a lower materialisation bound, but the magnitude of this bound decreases with the technology used. The thermodynamic efficiency of using animal power is less than their energy conversion efficiency, around 6% (Krebs, 1994). The conversion efficiency of an internal combustion engine working at ambient temperature (such as that of a modern tractor) is bounded at around 40%. Hence, even though each technology has a lower materialisation bound, new technologies can have increasingly lower bounds.

As new production sectors appear, they may be less affected by physical constraints. Baumgärtner (2003) argues that to produce 1 kg of iron nails, one needs at least 1 kg of iron. The problem is that no one is interested in buying 1 kg of *iron* nails, but rather 1 kg of nails in order to (say) hang paintings on walls. Thus, another material besides iron might be used. Or people might use other devices to hang paintings that do not involve nails. Or people might simply not want paintings anymore.

Notice that unbounded relative dematerialisation need not lead to unbounded absolute dematerialisation. According to our formulation, the production of a finite amount of economic goods requires a finite material throughput. In the limit case of an infinite amount of economic goods, total material throughput is an indeterminacy, solved by the relative weight of a, n, and the rates of knowledge and output growth. Notice also that infinite time or economic output is an abstraction; we believe that the time horizon of growth theory should be taken as the long run (Stiglitz, 1997 speaks of a period of 50 years).

The concept of materialisation is not common in growth theory but deserves greater attention. For example, Hinterberger et al. (1997) argue that natural capital stock maintenance concerns should be dropped in favour of material flow accounting, for purposes of sustainability assessment; here in fact we are integrating the two perspectives in a single framework.

3.4. Environmental expenditure

It is common in models that deal with environmental issues to consider a trade-off between pollution abatement and consumption. In the present paper, we do not consider pollution abatement explicitly on two grounds. One reason is analytical simplicity, as one trade-off (and hence a control variable) is already taken into account (allocation of natural capital allocated to production or generation of environmental services); to account for pollution abatement would require another control variable. The other reason is that environmental expenditure, or at least pollution abatement, does not change significantly over time (Brock and Taylor, 2003 in their Fig. 2), and, as such, it can be considered a part of the endogenous dynamics of the economy.

We consider that environmental expenditure consists of three parcels with different properties: pollution abatement, restoration effort, and environmentally biased innovation. Pollution abatement, the expenditure usually considered in this context (Belbute, 1999; Aghion and Howitt, 1998; Andreoni and Levinson, 2001; Lieb, 2001), manifests itself in a reduction of the flow of pollution released to the natural environment. Therefore, the flow of pollution being abated cannot exceed the flow of pollution being generated. Restoration effort (such as reforestation) accelerates natural regeneration and is therefore limited by environmental quality (the ratio between natural capital and its carrying capacity). Environmentally biased innovation is the investment in purposefully natural capital-saving technology.

Environmental expenditure in these several forms is the true control variable of the society. We believe that through allocation of resources to environmental protection, society is able to change the technical exogenous parameters a, n, and α. We suspect that the optimal amount of environmental investment is a function of ϕ because environmental concerns work as the price of natural capital, which is essentially a public good. Thus, high environmental concerns promote natural capital-saving innovation and policies. On the other hand, the optimal allocation of environmental investment (in pollution control, restoration, or innovation policy) will depend on the biophysical state and the technological level of the society. That is, for a very materialised society, it may be optimal to invest in abatement, while if environmental quality is very poor, restoration may be the best option. The formalisation of these ideas in a full endogenous model is beyond the scope of the present work.

4. Consumer behaviour and sustainability

4.1. Utility function and environmental concerns

We consider in our model that a continuously overlapping succession of individuals will behave so as to maximise their utility function throughout their lives. Therefore, utility, $U(t)$, should be such that the integral of present-value utility between initial and infinite time, $\int_0^\infty e^{-\rho t} U(t) dt$, is a maximum, where ρ is the pure rate of time preference.[10]

We consider that utility is a function of consumption, $C(t)$, and of direct environmental services provided by free natural capital, $(1-u(t))N(t)$. Following Belbute (1999), we consider that utility has constant and unitary intertemporal elasticity of substitution for both C and $(1-u)N$ (Eq. (9)):

$$U(C,(1-u)N) = \ln C + \phi \ln((1-u)N), \tag{9}$$

where the constant parameter ϕ expresses society's environmental concerns. With this formulation, there is diminishing but ever positive marginal utility and the usual properties of the utility function are observed (Belbute, 1998b). There are two important assumptions in the functional form of Eq. (9).

The first important assumption is that consumption is independent of the environmental context in which it takes place (i.e., the crossderivative $\partial^2 U / \partial C \partial((1-u)N)$ is zero).

[10] We will consider a constant rate of time preference (see Azar and Holmberg, 1995; Rabl, 1996; Hall, 2000 for a discussion on intergenerational discounting; and Bruce, 1994 on the biological basis of discounting).

The second important assumption is that there is a constant elasticity of substitution between consumption and free natural capital in providing utility. In fact, the parameter ϕ is the elasticity of substitution between consumption and direct environmental services for constant utility, since we can obtain from Eq. (9) that (Eq. (10)):

$$\phi = -\frac{\mathrm{d}C}{C}\frac{(1-u)N}{\mathrm{d}((1-u)N)}\bigg|_{U=\text{constant}} \tag{10}$$

This is supported by Aghion and Howitt (1998), who point out that in the last centuries, humankind has successfully substituted many environmental services by economic ones, therefore replacing N by C in the utility function. However, this assumption may not be applicable in the case of extreme depletion of natural capital, which is the same as talking about basic needs, which involve limits to substitutability (Stern, 1997). It is reasonable to assume that as $(1-u)N$ (or C) tends to zero, marginal utility on that argument becomes infinitely large, $\lim_{c\to 0}\frac{\partial U}{\partial C}=\infty$; $\lim_{(1-u)N\to 0}\frac{\partial U}{\partial((1-u)N)}=\infty$; hence no finite amount of the other good can substitute for the loss of welfare of becoming deprived of the good being considered.

The solution to this problem depends on whether we interpret the role of direct environmental services as hedonistic or materialistic (i.e., whether they are immaterial "wants" or physiological "needs"). On the one hand, it has been suggested that environmental concerns rise with income (Martínez-Alier, 1995). On the other hand, the physiological needs of humans vary with the environment (mostly with latitude; Parker, 2000), supporting the view of a materialistic role.

We believe that for low levels of both N and C, we are talking about "needs," but in an affluent society or environment, the individual will satisfy his "wants." In this case, ϕ may be not only dependent on the environment but also be able to change according to societal preferences. Still, for simplicity, in our model, we consider constant ϕ.

4.2. Sustainability constraints

According to the Brundtland Report, sustainable development "meets the needs of the present generation without compromising the ability of future generations to meet their own needs." In this statement, we find the concepts of intergenerational equity, intragenerational equity, and efficiency. The traditional concepts of weak (Cabeza Gutés, 1996), strong (Costanza et al., 1998), and sensible sustainability (Serageldin and Steer, 1994) are based on considerations about technology (the degree of complementarity between built and natural capital) and ecosystem functioning (whether there are or not lower thresholds of ecological viability).

We will not make use of these traditional concepts as operational tools because they take empirical facts as theoretical assumptions and because they do not accommodate the specificities of our model (dynamics for CC, dematerialisation, and direct environmental services). We will consider an operational definition of sustainability based on two constraints: intergenerational equity and biophysical sustainability.

Intergenerational equity, an implicit assumption of traditional sustainability concepts (Arrow et al., 2002), demands:

$$\mathrm{d}U/\mathrm{d}t \geq 0, \tag{11}$$

or non-diminishing social welfare (here interpreted as utility). Because we consider $U=U(C,N)$ and $Y=Y(N,K)$, environmental degradation is reflected twofold upon U: through diminishment of direct services, provision, and depletion of resources for production.

Biophysical sustainability imposes as a general constraint that the ecological system does not collapse. We will consider that natural capital, N, and its carrying capacity, CC, must both remain non-negative:

$$N>0 \text{ and } CC>0. \tag{12}$$

Regarding what a sustainable scenario may be, Daly (1977) proposed that an optimal size for the human economy exists and that a "steady-state" economy should be reached. Endogenous growth theory allows growth to continue indefinitely if environmental concerns and innovation are taken into the picture, so that the "material" side of the economy ceases to grow while its intellectual side keeps on growing (Aghion and Howitt, 1998). For the moment, depletion of natural capital is still increasing (Vitousek et al., 1997), raising the suspicion that our current growth path is not verifying biophysical sustainability. Moreover, even the condition of non-decreasing utility (intergenerational equity) is currently not verified for a number of poor countries (in Africa and in the Indian sub-continent) (Arrow et al., 2002).

5. Sustainable growth

5.1. Biophysical steady state

In this section, we show that, under some conditions, it is possible to achieve the biophysical steady state and at the same time verify intergenerational solidarity.

The dynamics of the natural system is given by Eqs. (13) and (14):

$$\dot{N} = rN(CC - N) - P, \tag{13}$$

$$\dot{CC} = l\left(\frac{\dot{N}}{N} - \frac{\dot{u}}{1-u}\right), \tag{14}$$

where P is given by Eq. (8). The steady state condition, $dN/dt = dCC/dt = 0$, implies that $N = N^*$, $CC = CC^*$, and, through Eqs. (13) and (14), $u = u^*$ and $P = P^*$ are all constants, where the superscript * denotes the equilibrium value.

Since P is constant, by differentiating Eq. (8) and setting equal to zero, one sees that, under technological change with learning-by-doing (Eq. (6)), the growth rate of output is given by:

$$\frac{\dot{Y}}{Y} = \frac{a}{n} g\left(\frac{\dot{K}}{K}\right). \tag{15}$$

By derivating the production function (Eq. (7)), replacing the growth rates of A and Y, and noting that u and N are constant, one finds that the accumulation of built capital also occurs at constant rate, given by the solution of:

$$\frac{\dot{K}}{K} = \frac{1}{\alpha}\left(\frac{a}{n} - 1\right) g\left(\frac{\dot{K}}{K}\right). \tag{16}$$

The derivative of g is maximal for $\dot{K}/K = 0$ and decreasing for positive $\dot{K}/K$. Let g'_0 denote the derivative of g when $\dot{K}/K = 0$. Eq. (16) only has real positive solutions if $g'_0(a/n - 1)/\alpha \geq 1$. If the equality holds, the only solution is $g_K = 0$. If the inequality holds, besides the zero root, there is a non-trivial solution, $\dot{K}/K \equiv g_K > 0$. The condition can be restated as $a/n \geq 1 + \alpha/g'_0$, where the dematerialisation parameters a and n are constrained by technological parameters.

Assume that the parameters are such that there is a non-trivial solution, g_K. Let g_A and g_Y denote the rate of knowledge accumulation and the rate of output growth in the biophysical steady state. Using Eqs., (6), (15), and (16), we obtain

$$g_A = \alpha \frac{1}{a/n - 1} g_K \text{ and } g_Y = \alpha \frac{a/n}{a/n - 1} g_K.$$

Both output and capital stock grow at a constant rate, but these rates are not necessarily the same. Inserting $\dot{K}/K = g_K$ *in (Eq. (5))* and solving for $C(t)$, we obtain:

$$C(t) = Y(t) - (g_K + \delta)K(t).$$

Alternatively, it is possible to write consumption as an explicit function of time:

$$C(t) = Y_0 e^{\alpha \frac{a/n}{a/n-1} g_K t} - (g_K + \delta) K_0 e^{g_K t}, \tag{17}$$

where Y_0 and K_0 are initial output and initial stock of capital. The initial conditions of the state variables, A_0, K_0, N^*, and CC^* fully specify Y_0, u^*, and initial consumption C_0. However, we must check if $0 \leq u^* < 1$, where the strict inequality when all natural capitals are allocated to production ($u = 1$) arises because of the role of natural capital as a provider of direct environmental services in utility (Eq. (9)). We must also check if $C(0) = C_0 \geq 0$, where the biophysical steady state is implemented at time 0.

An explicit expression for u^* is obtained by replacing $Y_0 = A_0 K_0^\alpha (u^* N^*)^{1-\alpha}$ (Eq. (7)) in $P_0 = m_0 A_0^{-a} Y_0^n$ (Eq. (8)) and in $P_0 = rN^*(CC - N^*)$ (Eq. (13)) and solving for u^*. One obtains:

$$u^{*1-\alpha} = A_0^{a/n-1} K_0^{-\alpha} N^{*-(1-\alpha)} \left(\frac{r}{m_0} N^*(CC^* - N^*)\right)^{1/n}. \tag{18}$$

For u^* to remain inside the controllability domain, $u^* \geq 0$ implies that $CC^* \geq N^*$, which is in general verified; it means that the productivity of natural capital is positive. On the other hand, $u^* < 1$ implies, through algebraic manipulation and solving for K_0:

$$K_0 > A_0^{(a/n-1)/\alpha} N^{*-(1-\alpha)/\alpha} \left(\frac{r}{m_0} N^*(CC^* - N^*)\right)^{1/\alpha n}. \tag{19}$$

The constraint on consumption implies that (from Eq. (17) and setting time to 0):

$$C_0 = Y_0 - (g_K + \delta)K_0.$$

Substituting as above and imposing $C_0 \geq 0$, one obtains:

$$K_0 \leq \frac{A_0^{a/n}}{(g_K + \delta)} \left(\frac{r}{m_0} N^*(CC^* - N^*) \right)^{1/n}. \tag{20}$$

Initial built capital is constrained by an upper and a lower bound, as a function of the other state variables. Since the stock of built capital must be positive, Eqs. (19) and (20) must be verified simultaneously, yielding a condition in A_0 (Eq. (21)):

$$A_0^{1-(1-\alpha)a/n} > \frac{N^{*1-\alpha}}{(g_K + \delta)^{\alpha}} \left(\frac{r}{m_0} N^*(CC^* - N^*) \right)^{-(1-\alpha)/n}. \tag{21}$$

Eq. (21) implies that A_0 is constrained by a lower bound. An increase in N^* or an increase in the productivity of natural capital (N^* approaching CC^*) implies an increase in threshold of knowledge required to achieve sustainability.

In a biophysical steady state, the constraint of intergenerational solidarity is observed if consumption is non-decreasing, $\mathrm{d}C/\mathrm{d}t \geq 0$. If initial consumption is positive, to obey this condition, the rate of output growth must exceed the rate of capital accumulation, at every instance (Eq. (17)). Hence, the ratio of dematerialisation parameters a and n is constrained by $a/n \leq 1/(1-\alpha)$. Combining with the parameter constraint arising from Eq. (16):

$$1 + \frac{\alpha}{g_0'} \leq \frac{a}{n} \leq 1 + \frac{\alpha}{1-\alpha}. \tag{22}$$

These are constraints on dematerialisation, implying that in the effect of innovation on dematerialisation, as compared to composition change, the ratio a/n is bounded from below and from above, implying in turn the technological constraint that $g_0' \geq 1 - \alpha$. That is, the effect of capital accumulation on innovation must be higher than the production share of natural capital. Returning to Eq. (21), it is now possible to see that the higher the a/n, the higher the minimum necessary stock of capital for sustainability, becoming infinite as a/n approaches its upper bound.

The constraints on initial conditions are that the productivity of natural capital should be positive, that the stock of knowledge should be larger than a lower threshold (Eq. (21)), and that the initial stock of built capital should be bounded from above and from below (Eqs. (19) and (20)). The constraints on parameters are Eq. (22) and $g_0' \geq 1 - \alpha$. If these conditions on the parameters and initial conditions hold, it is possible to maintain increasing consumption while maintaining the biophysical system in steady state.

6. Discussion

In Section 5, we showed the existence of a sustainable growth path verifying simultaneously a biophysical steady state and non-decreasing welfare arising from non-decreasing consumption. However, we should emphasise that other solutions besides the steady state may be consistent with biophysical sustainability, such as attaining constant C and N only for infinite time, or limit cycles. We should also make the remark that, for ecological systems, more important than the existence of an equilibrium is the stability and permanence of the system (Hofbauer and Sigmund, 1998). We defer the analysis of these topics to later work.

The sustainable growth path studied can be reached if two sets of constraints are verified: constraints on the parameters, more precisely on the relative weight of composition change and innovation on dematerialisation; and constraints on the initial stocks of built and intellectual capital, as a function of the biophysical initial conditions. Interestingly, the constraints on built capital and the dematerialisation parameters exhibit lower and upper boundaries. This means that overcapitalisation can endanger sustainability, implying that it might be necessary not to use all productive capital, and that the effects of innovation and composition change must be balanced; if society only dematerialises through one of these mechanisms, the biophysical steady state becomes incompatible with economic growth. The constraint on the initial stock of intellectual capital is different because it imposes only a lower threshold. From the point of view of sustainability, all knowledge is good.

The fraction of enslaved natural capital along the sustainable growth path is inversely correlated to the initial stock of built capital (Eq. (18)). Since this initial capital stock is bounded from below and from above, this implies that the fraction of enslaved natural capital is always an inner solution. That is, the enslavement of all or of almost all natural capital is incompatible with the biophysical steady state. Along the sustainable growth path, environmental pressure remains constant, which implies that relative but not absolute dematerialisation is taking place.

Environmental concerns and the discount rate affect the choice of the control variables and the welfare along the growth path, if an optimisation were to be performed. However, they do no affect the solution we have obtained here, since it was obtained without an optimisation. This solution corresponds to a non-decreasing growth rate of consumption. However, the growth rate of consumption is only constant if the dematerialisation parameters verify the special constraint $a/n = 1/(1-\alpha)$. In the opposite bound, if $a/n = 1 + \alpha/g'_0$, there is no growth at all (it is both a biophysical and an economic steady-state). In between these bounds, the consumption pattern can be increasing and is consistent with the biophysical steady state, but it does not verify the conventional balanced growth solution of neoclassical economics.

A important question that remains open is the transition to sustainability. A biophysical steady state, even though it corresponds only to a very particular solution consistent with sustainability, is easy to enforce and is thus good policy option (if it ever becomes a socially accepted goal). Thus, given the stringent initial conditions of the steady-state solution, one might ask what would be the optimal strategy to achieve this goal: To move slowly and allow for natural capital depletion while built and intellectual stocks are accumulated, or to move fast, enforcing sustainability before the natural system degrades even more? This is a key issue, which we defer to later work.

7. Conclusions

We presented an extension of the neoclassical growth model with natural capital and exogenous technological change with two main novelties: allocation of natural capital and dematerialisation. The first idea acknowledges that natural capital used for productive processes does not provide the same positive externalities as free natural capital. Therefore, there is a trade-off between the extension of human domination of the biosphere, increasing production, and the maintenance of ecosystem services, necessary both for ecological integrity and provision of direct welfare to humans. The second idea draws on the assumption that the environmental impact of the economic process depends on the material throughput of the economy and that throughput per unit of production may decrease over time. Therefore, long-run sustainability is achievable if dematerialisation, which is caused by the change of the composition of the production sector and by innovation, outweighs the environmental impact of economic growth.

We found that, for some set of technological parameters and initial conditions, it is possible to experience unbounded economic growth and to keep the natural system in steady state. The constraints on the parameters state that the relative effects of innovation and composition change in dematerialisation must be balanced, subject to technological constraints. The constraints on the initial conditions state that the initial stock of intellectual capital must exceed a certain lower threshold (which is a function of the biophysical system) and that the initial stock of built capital is bounded from above and from below (where these bounds are a function of the other stocks).

Along the sustainable growth path studied, the fraction of enslaved natural capital is kept constant and, for any admissible set of initial conditions, is always an inner solution, which implies that it is not sustainable to enslave a too small or a too large share of natural capital. Along the sustainable growth path, relative dematerialisation (decrease of environmental intensity with time) is taking place but absolute dematerialisation (decrease of total environmental pressure with time) is not, since total environmental pressure is held constant. We also found that the discount rate and environmental concerns do not affect qualitatively the solution.

Thus, we found that it is possible to reconcile Herman Daly's ideas of a steady-state economy with the quest for economic growth, if the physical dimension of the economy (its environmental impact and the enslaved fraction of natural capital) is kept constant, while the economy grows at the pace allowed by knowledge formation and dematerialisation. That is, sustainability requires the replacement of quantitative growth (increase in throughput and increasing allocation of natural capital) by qualitative development (dematerialisation and biophysical steady state).

In the model, a number of simplifying assumptions are made, of which the most important are that natural capital can be aggregated; that there is a clear-cut separation between natural capital allocated to production or to generate environmental services; that the dynamics of natural capital follows particular dynamics; and that dematerialisation elasticities are constant. The model, and hence its underlying assumption, may be subject to empirical testing given appropriate data. In fact, the empirical work currently done in ecosystem service accounting and material flow analysis may in time provide such data, validating or not the assumptions made here.

With this work, we hope to have contributed to a more realistic depiction of the interactions between ecosystems and human societies, within economic theory.

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References

Aghion, P., Howitt, P., 1998. Endogenous Growth Theory. MIT Press, Cambridge.

Andreoni, J., Levinson, A., 2001. The simple analytics of the environmental Kuznets curve. Journal of Public Economics 80, 269–286.

Arrow, K., Daily, G., Dasgupta, P., Ehrlich, P., Goulder, L., Heal, G., Levin, S., Mäler, L.-G., Schneider, S., Starret, D., Walker, B., 2002. Are we consuming too much? Discussion Paper, vol. 151. Beijer Institute.

Azar, C., Holmberg, J., 1995. Defining the generational environmental debt. Ecological Economics 14, 7–19.

Baumgärtner, S., 2003. The Inada conditions for material resources reconsidered. Discussion Paper, vol. 396. University of Heidelberg, Department of Economics.

Belbute, J., 1998a. Algumas reflexões sobre as interacções entre a economia e o ambiente. Economia e Sociologia 67, 31–56.

Belbute, J., 1998b. Acumulação de capital num contexto de interacções entre economia e ambiente. Estudos de Economia XVIII (4), 443–461.

Belbute, J., 1999. Preferências, crescimento endógeno e sustentabilidade. Estudos de Economia XIX (3), 295–317.

Blaug, M., 1991. Methodology in Economics, 4th ed. Cambridge University Press, Cambridge.

Brock, W., Taylor, M.S., 2003. Economic growth and the environment: matching the stylised facts. University of Wisconsin Working Paper.

Bruce, H., 1994. Sense of place: geographic discounting by people, animals and plants. Ecological Economics 10, 157–174.

Cabeza Gutés, M., 1996. The concept of weak sustainability. Ecological Economics 17, 147–156.

Clark, C.W., 1976. Mathematical Bioeconomics. John Wiley & Sons, New York.

Cogoy, M., 2002. Industrial ecology and economic dynamics. 3rd International Conference of the International Society for Ecological Economics, Sousse.

Cohen, J.E., 1995. Population growth and earth's human carrying capacity. Science 269, 341–348.

Costanza, R., Cumberland, J., Daly, H., Goodland, R., Norgaard, R., 1997a. An Introduction to Ecological Economics. St. Lucie Press, Boca Raton.

Costanza, R., d' Arge, R., de Groot, R., Farber, S., Grasso, M., Hannon, B., Naeem, S., Limburg, K., Paruelo, J., O'Neill, R.V., Raskin, R., Sutton, P., van den Belt, M., 1997b. The value of the world's ecosystem services and natural capital. Nature 387, 253–260.

Costanza, R., d' Arge, R., de Groot, R., Farber, S., Grasso, M., Hannon, B., Naeem, S., Limburg, K., Paruelo, J., O'Neill, R.V., Raskin, R., Sutton, P., van den Belt, M., 1998. The value of ecosystem services: putting the issues in perspective. Ecological Economics 25, 67–72.

Daily, G.C. (Ed.), 1997. Nature's Services: Societal Dependence on Natural Ecosystems. Island Press, Washington, DC.

Daly, H.E., 1977. Steady State Economics: The Political Economy of Biophysical Equilibrium and Moral Growth. W.H. Freeman & Co., San Francisco.

Daly, H.E., 1997. Georgescu-Roegen versus Solow–Stiglitz. Ecological Economics 22, 261–266.

Dunlap, R.E., 1993. From environmental to ecological problems. In: Calhoun, C., et al., (Eds.), Social Problems. McGraw-Hill, New York.

Endres, A., Radke, V., 1999. Land use, biodiversity, and sustainability. Journal of Economics-Zeitschrift für Nationalökonomie 70 (1), 1–16.

England, R.W., 1998. Should we pursue measurement of the natural capital stock? Ecological Economics 27, 257–266.

England, R.W., 2000. Natural capital and the theory of economic growth. Ecological Economics 34 (3), 425–431.
Georgescu-Roegen, N., 1971. The Entropy Law and the Economic Process. Harvard University Press, Cambridge.
Grossman, G., Krueger, A., 1995. Economic growth and the environment. Quarterly Journal of Economics 110, 353–377.
Hall, C.A.S., 2000. Quantifying Sustainable Development. Academic Press, New York.
Hart, R., 2002. Growth, environment, and culture—encompassing competing ideologies in one "new growth" model. Ecological Economics 40, 253–267.
Harte, M.J., 1995. Ecology, sustainability, and environment as capital. Ecological Economics 15, 157–164.
Hinterberger, F., Luks, F., Schmidt-Bleek, F., 1997. Material flows vs. 'natural capital.' What makes an economy sustainable? Ecological Economics 23, 1–14.
Hofbauer, J., Sigmund, K., 1998. Evolutionary Games and Population Dynamics. Cambridge University Press, Cambridge.
Kaufmann, R.K., 1995. The economic multiplier of environmental life support: can capital substitute for a degraded environment? Ecological Economics 12, 67–79.
Keil, T., 1998. Substitution or technical progress: a production theoretic perspective on the sustainability debate. Global Network of Environmental Economists, Working Paper.
Kolstad, C.D., Toman, M., 2001. The economics of climate policy. Resources for the future. Discussion Paper 00-40REV.
Kraev, E., 2002. Stocks, flows and complementarity: formalizing a basic insight of ecological economics. Ecological Economics 43, 277–286.
Krebs, C.J., 1994. Ecology, 4th ed. Addison Wesley Longman, New York.
Levin, S., 1999. Fragile Dominion. Perseus Books, Reading, MA.
Lieb, C.M., 2001. The environmental Kuznets curve and flow versus stock pollution—when abatement increases pollution. 11th Annual Conference of the European Association of Environmental and Resource Economists, Southampton.
Löschel, A., 2002. Technological change in economic models of environmental policy: a survey. Ecological Economics 43, 105–126.
Lucas, R., 1988. On the mechanics of economic development. Journal of Monetary Economics 22 (1), 3–42.
Luzzati, T., 2002. Growth theory and the environment: how to include matter without making it really matter. In: Salvatori, N. (Ed.), The Theory of Economic Growth: A "Classical" Perspective. Edward Elgar.
Martínez-Alier, J., 1995. The environment as a luxury or "too poor to be green"? Ecological Economics 13, 1–10.
Nelson, R.H., 1997. In memoriam: on the death of the 'market mechanism'. Ecological Economics 20, 187–197.
North, D.C., 1990. Institutions, Institutional Change and Economic Performance. Cambridge University Press, New York.
Odum, E.P., 1969. The strategy of ecosystem development. Science 164, 262–270.
Parker, P., 2000. Physioeconomics—the Basis for Long-Run Economic Growth. MIT Press, Cambridge.
Peters, R.H., 1991. A Critique for Ecology. Cambridge University Press, Cambridge.
Rabl, A., 1996. Discounting of long-term costs: what would future generations prefer us to do? Ecological Economics 17, 137–145.
Rebelo, S., 1991. Long-run policy analysis and long-run growth. Journal of Political Economics 99, 500–521.
Rothman, D., 1998. Environmental Kuznets curves—real progress or passing the buck? A case for consumption based approaches. Ecological Economics 25, 177–194.
Schneider, E.D., Kay, J.J., 1994. Life as a manifestation of the second law of thermodynamics. Mathematical and Computer Modelling 19, 25–48.
Serageldin, I., Steer, A., 1994. Epilogue: expanding the capital stock. In: Serageldin, I., Steer, A. (Eds.), Making Development Sustainable: from Concepts to Action. The World Bank, Washington, D.C.
Solow, R., 1974. Intergenerational equity and exhaustible resources. Review of Economic Studies, 29–45.
Stern, D.I., 1997. Limits to substitution and irreversibility in production and consumption: a neoclassical interpretation of ecological economics. Ecological Economics 21, 197–215.
Stiglitz, J.E., 1997. Georgescu-Roegen versus Solow–Stiglitz—reply. Ecological Economics 22, 269–270.
Torras, M., Boyce, J.K., 1998. Income, inequality and pollution: a reassessment of the environmental Kuznets Curve. Ecological Economics 25, 147–160.
Ulanowicz, R.E., 1986. Growth and Development. Springer-Verlag, New York.
van den Bergh, J., Hofkes, M.W., 1997. A survey of economic modelling of sustainable development. Discussion Paper, vol. 97-107. Tinbergen Institute.
van den Bergh, J., Verbruggen, H., 1999. Spatial sustainability, trade and indicators: an evaluation of the "ecological footprint". Ecological Economics 29, 61–72.
Vitousek, P.M., Mooney, H.A., Lubchenco, J., Melillo, J.M., 1997. Human domination of Earth's ecosystems. Science 277, 494–499.
Wackernagel, M., Rees, W.E., 1997. Perceptual and structural barriers to investing in natural capital: economics from an ecological footprint perspective. Ecological Economics 20, 3–24.