Ecosystem services, ecosystem disservices, and economic dynamics: is it always worth to conserve natural capital?*

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Abstract

Although several economic growth models have incorporated natural resources and environmental quality into economic dynamics, they have not yet accounted for the ambivalent impacts of ecosystems when modelling economic development.
In this paper, we consider ecosystems as a type of natural capital that enters into a production function and that generates both services and disservices. The economic dynamics of production are set by a representative agent who decides between consuming on the one hand and investing in either man-made or natural capital on the other. We study how different interactions between natural and man-made capitals, including ecosystem disservices, impact economic development. We show that different forms of interactions between the two types of capital can lead to either endogenous growth or a steady state in the long run. In so doing, this paper highlights the impact of the weight of natural capital on economic growth.

Keywords: dynamic control; economic growth; ecosystem disservices; ecosystem services; natural capital.

1 Introduction

Natural capital is a relatively longstanding concept in economic analysis, one that has experienced moments of great interest and moments of obscurity. In the 1990s, natural capital was at the heart of an intense controversy over how to integrate the natural environment into analyses addressing sustainability. Although its first appearance in the economic literature can be traced to the end of the 19th century (Missemer, 2018), the concept of natural capital re-emerged in the early 1970's (Akerman, 2003) as a type of capital that was analogous to other types of productive capitals. This is evidenced in The Fundamentals of Ecology, by E. Odum (5th edition, 1971) and in the well-known collection

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of essays entitled Small is Beautiful, by E.F. Schumacher (1973). Two decades later, the natural environment entered the literature in a more technical way, when natural capital was incorporated in analyses regarding sustainable development (Pearce, 1988; Daly, 1990; Costanza and Daly, 1992; Costanza et al., 1993; Pearce et Atkinson, 1993; Costanza et al., 1997; Jansson et al., 1996; Ekins et al., 2003) and in economic modelling (Van den Bergh and Nijkamp, 1991; Mourmouras, 1993; Berles and Folke, 1994; Clark and Munro, 1994).

The economic literature now contains a number of models of economic growth that take into account the environment. Several decades after the Report to the Club of Rome (Meadows et al., 1972) which called attention to this issue, the analysis of the relationship between economic growth and the natural environment remains rather controversial (Brock and Taylor, 2005; England, 2000; Prieur, 2009). Two main streams of research on the subject exist: studies on the consequences of resource exhaustion (following Nordhaus et al., 1973; Solow, 1974) and studies on pollution as a potential limit to growth (following Keeler et al., 1971; Brock, 1977). However, the issue of limits to growth remains debated (Stokey, 1998); since exhaustible resources are consumed in the production process, they tend to create limits to growth only if substitutes are imperfect, and so too could poorly managed renewable resources that do not regenerate.

A few years ago, Partha Dasgupta (2008) expressed his disappointment over how economists regarded nature, and how they take it into account in growth theories:

"Nature did not appear much in twentieth century economics, and it doesn't do so in current economic modelling. When asked, economists acknowledge nature's existence, but most deny that she is worth much. I have professional colleagues who believe that the services nature provides amount at best to 2-3 % of an economy's output, which is the share of agriculture in the GDP of the United States. Why, they ask, should one incorporate a capital asset of negligible importance in macro-economic models of growth and distribution?"

Nature can, however, be found in the economic literature, most often at the interface of economics and other disciplines (e.g. agronomy, ecology, geography...).

Economics categorizes capital as either stocks or services. With regard to nature, the practical difficulty of measuring natural capital (Ekins et al., 2003) has certainly contributed to the success of the concept of ecosystem services (ES) (Costanza et al., 1997; MEA, 2005; de Groot et al., 2009). Nature, broadly speaking, can be regarded as a stock of natural capital that contributes to the flow of ES (Daily et al., 2000). Costanza et al. (1997), however, point out that ecosystem services are flows of materials, energy, and information from natural capital stocks, and that these flows interact with manufactured and human capitals services to produce human welfare. Thus, it is in fact the interdependencies between ecosystem processes and human activities and choices that constitute what is known as ecosystem services.

Ecosystems contribute to human well-being in many ways that have been classified in different manners according to the aims of specific types of analyses. One fundamental distinction can be drawn between direct services, stemming from ecosystems as direct sources of ecological amenities, and indirect services, which result from interactions between natural and man-made capital. In the first case, the social value of ecosystems depends on both their natural features and on individual preferences regarding these features. In the second, the value of ecosystem services depends on their contribution as factors of production that are complementary to man-made capital. This paper focuses on modelling the role of indirect ecosystem services in the process of economic development. For this purpose, we regard ecosystems as natural capital that provides ecosystem services (as well as disservices, see below), and thus as a non-consumptive factor of production.

The concept of ecosystem services was proposed in order to investigate the extent to which societies depend on functioning ecosystems (Costanza et al., 1997; Daily, 1997; MEA, 2005). Consequently, the literature has primarily considered the positive aspects of the relationship between ecosystems and societies. As such, the negative impacts that certain aspects of ecosystems functioning can have on human well-being, the so-called "ecosystem disservices", are often ignored (Schaubroeck, 2017). This bias against disservices and the fact that the concept remains controversial can be explained by the evidence that, at a sufficiently aggregated level of analysis, the impacts of functioning ecosystems on economies are positive (which makes sense as long as human life is possible without artificial support). Several studies have, however, addressed the potential existence of ecosystem disservices. Zhang et al., (2007) studied the main disservices to agriculture, such as competition for pollination, competition for water, and pest damage to agriculture. Lyytimaki and Sipila (2009) investigated the various nuisances and losses produced by ecosystem functions in urban territories, and their consequences for green urban management. Dunn (2010) proposed a global mapping of ecosystem disservices in terms of their impacts on health and mortality, but without considering with their economic impacts. Escobedo et al. (2011) used the concept of ecosystem services and disservices in order to assess the efficacy of using urban forests for mitigating pollution. Campagne et al. (2018) assess ecosystem disservices in a regional natural park using expert judgments and analyze their correlation with ecosystem services, showing that both services and disservices can be associated with the same ecological processes.

This paper introduces an economic perspective to the issue by modelling the dynamics of the interaction between economic production and ecosystem conservation that takes into account the presence of ecosystem services as well as disservices. We consider an economy governed by the choices of a representative agent whose production and well-being depend on both productive capital and the state of the ecosystems on which production depends. The novelty of our approach lies mainly in the fact that we consider the environment as a type of natural capital that acts both as a factor of production as well as a limit to growth. In doing so, we focus on a number of specific aspects of the relationship between man-made and natural capitals. We use the term "man-made capital" as a proxy for a composite asset of manufactured and human capital, without loss of generality. Ecosystems are considered to be a natural resource that is not consumed in the process of production; production depends on the services provided by the ecosystems but does not involve their consumption, and so production does not have a direct impact on the level of natural capital. On the other hand, there is no inherent dynamic of natural capital: although some ecological processes tend to produce biomass, other processes destroy it. Thus, in the model, only investment in restoration can increase in the stock of natural capital.

The purpose of this paper is twofold: first, we analyze how the interactions between production factors affect growth and, second, we highlight the role that the weight given to ecosystems plays in the production function, in the consumption of goods, and in growth. The rest of the paper is organized as follows. In the first section, we present the model. The second section, we present the results. In a first subsection of the results, we assume that the depreciation of man-made capital and the disservices produced by nature are independent of each other. In a second subsection, we assume that the man-made capital depreciation rate is a function of the stock of natural capital. The last section is devoted to a discussion of the results.

2 The model

We consider an economy in which production depends on two types of capital: natural capital N and man-made capital K. The representative agent makes use of each type of capital in a production function, the output of which is used for consumption, generating welfare for the agent, and investments, which are put towards the maintenance of the two capitals. Note that N and K are not expressed in terms of physical units but in terms of value, where currency is the unit of final production. Therefore, when the agent invests in K or in N, it is indifferent whether it is a direct investment in this form of capital (either the accumulation of K or the restoration of N), or if it is investment in being able to better value the capital concerned.

Natural capital represents the ecosystems and the biodiversity they contain. We assume that the services that the agent derives from these ecosystems do not themselves consume natural capital (i.e. we do not consider them to be a natural resource), but we do assume that natural capital is impacted by investment in man-made capital. We also assume no depreciation of natural capital, which, unlike man-made capital, does not deteriorate over time. Natural capital does not, however, renew spontaneously when it has been degraded by the agent's productive investments. In most cases, investments in man-made capital artificialize natural environments in a lasting way and species that disappear in an ecosystem are permanently lost. Investing in natural capital can take the form of either financing ecosystem restoration or of making better (more environmentally-friendly) use of existing ecosystems.

Man-made capital can be defined as a stock of investments, such as farm equipment, industrial activities, or recreational development that renders natural areas more artificial. The agent combines natural and man-made capitals in order to produce value that will be either consumed or invested.

We formalize the agent's optimization process.

We begin with the production technology that links the factors of production to their output. Final goods and services are obtained from a homogeneous Cobb-Douglas production function of degree one:

$$F(N, K) = N^{\alpha} K^{1-\alpha}.$$

As explained above, no depreciation of natural capital N occurs. However, natural capital suffers degradation due to investment in man-made capital, which is proportional to the level of K. This degradation results from the impact of man-made capital on natural ecosystems, and as such it is a stock externality. Natural capital N can be restored by an investment $I_N(t) = I_N$ made by the representative agent. The dynamics of N are given by:

$$\dot{N} = I_N - \gamma K.$$

Man-made capital K increases with an investment $I_K(t) = I_K$ by the representative agent. It depreciates with time (capital erosion) proportional to the level of man-made capital ($\delta_1 K$). Man-made capital is also negatively impacted by natural capital, and the greater the stock of natural capital, the stronger this impact. It is well known that infrastructures, such as roads, railroads, bridges or ports, must be regularly protected against deterioration from a number of plant species (Pimentel et al., 2005). Infrastructures can also deteriorate due to the activity of certain animal species, such as insects or some molluscs (Connelly et al., 2007; Bradshaw et al., 2016). This activity can be interpreted as an ecosystem disservice: natural ecosystems tend to accelerate the depreciation of man-made capital, proportional to the level of natural capital stock ($\delta_2 N$). Sometimes, the intensity of disservices depends not only on the level of man-made capital and of natural capital separately, but on a negative interaction between them: the ecosystem stock limits the productive efficiency of man-made capital to a greater degree when the level of man-made capital rises. This reflects the fact that the higher the level of man-made capital, the greater the extent to which ecosystems are disturbed and the more they tend to limit the productive value of man-made capital. This can be illustrated by a number of real-world examples described in the literature. Highly disturbed ecosystems no longer provide certain basic services, such as invasive species regulation (Didham et al., 2005; Teyssèdre and Barbault, 2009; Airoldi and Bulleri, 2011), pest control for agricultural production (Zhang et al., 2007; Vandermeer et al., 2010), control of certain biological epidemics (Chivian and Bernstein, 2008; Keesing et al., 2010; Sala et al., 2012) and more generally, compromised ecosystems contribute less effectively to animal and human health (Sandifer et al. 2015; Morand and Lajaunie, 2017). We will describe this kind of effect as a negative KN interaction in the dynamic of K. We suppose that fragmented ecosystems (the KN interaction) tend to experience more disservices, such as biological invasions, that can degrade the economic value of man-made capital K.

$$\dot{K} = I_K - \delta_1 K - \delta_2 N - \delta N K.$$

The agent distributes the value of final output between consumption of the final good C and investment I_N, towards the renewal of natural capital, and I_K, towards the renewal of man-made capital.

$$F(N, K) = C + I_N + I_K.$$

The representative agent chooses C, I_N, I_K so as to maximize the utilitarian discounted utility function with discount rate ρ. The instantaneous utility function $U(C)$ is increasing and concave with $U'(C) > 0$ and $U''(C) < 0$, and the inter-temporal elasticity of substitution in consumption $\eta = -\frac{U'(C)}{U''(C)C}$ is constant.

$$\max_{C \geq 0, I_N \geq, I_K \geq 0} \int_0^\infty e^{\rho t} U(C) dt,$$

$$\dot{N} = I_N - \gamma K, \quad \dot{K} = I_K - \delta_1 K - \delta_2 N - \delta N K, \quad N_0, K_0, \text{given},$$
$$F(N, K) = C + I_N + I_K.$$

3 Model resolution

This section is dedicated to the resolution of the model in the long run. For simplicity, we focus on two particular cases. First, we consider the case in which there is no interaction effect ($\delta = 0$). Second, we consider the case in which there is only an interaction effect ($\delta_1 = \delta_2 = 0$). Interpretations for each of these cases are explained above.

3.1 The linear case ($\delta = 0$)

In this case, the depreciation rate of physical capital, δ_1, and the depreciation rate of ecosystem disservices, δ_2, are separable, and their effects are additive. For clarity of exposition, all proofs can be found in the appendix. The following proposition gives the necessary conditions for the long run solution.

Proposition 1 *i) If* $\left(\frac{\rho+\delta_2}{\alpha}\right)^{1/(1-\alpha)} = \left(\frac{\rho+\delta_1+\gamma}{1-\alpha}\right)^{-1/\alpha}$*, then there exists a steady state.*

ii) When endogenous growth exists, it is given by:

$$\frac{K}{N} = x, \text{ solution of } \alpha x^{1-\alpha} - (1-\alpha)x^{-\alpha} + a = 0, \quad a = \delta_1 + \gamma - \delta_2,$$

$$r := \frac{\dot{C}}{C} = \frac{\dot{K}}{K} = \frac{\dot{N}}{N} = \eta(-\rho + \alpha x^{1-\alpha} - \delta_2),$$

$$\frac{I_N}{N} = r + \gamma x, \quad \frac{I_K}{N} = rx + \delta_1 x + \delta_2, \quad \frac{C}{N} = x^{1-\alpha} - \frac{I_N}{N} - \frac{I_K}{N}.$$

In the above proposition, $a = \delta_1 + \gamma - \delta_2$, can be regarded as an indicator of the importance of K relative to N in the dynamics of the capital stocks. When a is high (and positive), the stock K is the main factor that constrains both dynamics. When a is low (or negative), N is the predominant constraint.
In order to insure positive endogenous growth, we must prove that K/N , r and C/N are positive. Each of these points will be dealt in the following propositions.

Proposition 2 (Existence and properties of K/N) *There exists a unique* $\frac{K}{N} = x > 0$*. Moreover:*

$$\alpha < \frac{1-a}{2} \implies x > 1, \quad \alpha > \frac{1-a}{2} \implies 0 < x < 1, \quad \frac{\partial x}{\partial \alpha} = -\frac{x^{1-\alpha} + x^{-\alpha} + \ln(x)a}{\alpha(1-\alpha)(x^{-1-\alpha} + x^{-\alpha})}.$$

This result can be explained by two effects related to α and a. When α is small, the weight of N in the production function is small. It is therefore reasonable that $K > N$. However, the tipping point is not symmetric in $\alpha = 1/2$ because of the interactions in the dynamics of K and N. For example, when $a = \delta_1 + \gamma - \delta_2$ is positive, K tends to constrain the dynamics and α must be less than $1/2$ in order to allow for $K > N$ in the growth path. We can interpret the case where $K < N$ and $a < 0$ in the same way.

Proposition 3 (Sign and properties of the growth rate r) *If we call* $z = \rho + \delta_2$ *and* $y = \rho + \delta_1 + \gamma$*, then*

i) If $z - \alpha\left(\frac{1-\alpha}{y}\right)^{(1-\alpha)/\alpha} = 0$*, a steady state exists.*

ii) If $z - \alpha\left(\frac{1-\alpha}{y}\right)^{(1-\alpha)/\alpha} < 0$*,* $r > 0$*.*

iii) If $z - \alpha\left(\frac{1-\alpha}{y}\right)^{(1-\alpha)/\alpha} > 0$*,* $r < 0$*. Note that in this case, in the long run: state variables, endogenous prices, and consumption go to 0.*

iv) r is decreasing in $(0, \frac{1-a}{2})$ *and increasing in* $(\frac{1-a}{2}, 1)$.

Note that proposition 3 means that a positive growth path does not always exist. Next, we discuss possible parameter values that ensure positive or negative growth.
When $y = \rho + \delta_1 + \gamma < 1$ (which is the case for any realistic parameter values), we have:

a) For small values of α, case ii) is true. This is reasonable because production depends on natural capital, which is less important here; thus N is not a limit to growth;

b) If $z + y < 1$, case ii) is also true; in this case, the extent of disservices is limited, and K and N grow in a balanced way;

c) If $z + y > 1$, and $z < 1$, case iii) is true for intermediate values of α; in this case, K puts pressure on N and, given the complementarity of K and N in production, this pressure disrupts the growth dynamics and results in negative growth;

d) If $z > 1$, there exists an α^* such that for that all $\alpha > \alpha^*$, $r < 0$ (case iii)).

Proposition 3 also shows that r is U-shaped with a minimum of $\alpha = (1-a)/2$. The growth rate is then maximal for extreme values of α and minimal for $\alpha = (1-a)/2$. This result reflects a situation in which growth is stronger for production functions that rely mainly on one type of capital rather than a more balanced mix of man-made and natural capitals. In the real world, this could be interpreted to suggest that economies develop in two primary ways: "green growth" based mainly on the sustainable development of natural capital, and "grey growth" based mainly on the accumulation of man-made capital. In the model, this can be traced to the marginal productivity of the factors of production, which depends on both the form chosen for the production function and the dynamics of the interaction between the two types of capitals.

Proposition 4 (Positivity of $\frac{C}{N}$)

- $\frac{C}{N} > 0 \quad \iff r < \alpha x^{1-\alpha} - \delta_2$.
- *If* $\eta \leq 1$ *then* $r < \alpha x^{1-\alpha} - \delta_2$. *and the positivity of* $\frac{C}{N}$ *is guaranteed.*

Remark 1 *Propositions 2, 3 and 4 give the conditions which guarantee the existence of a positive growth path:*

$$\frac{K}{N} = x, \text{ solution of } \alpha x^{1-\alpha} - (1-\alpha)x^{-\alpha} + a = 0, \quad a = \delta_1 + \gamma - \delta_2,$$

$$\rho + \delta_2 - \alpha \left(\frac{1-\alpha}{\rho + \delta_1 + \gamma} \right)^{(1-\alpha)/\alpha} < 0, \quad r = \eta(-\rho + \alpha x^{1-\alpha} - \delta_2) < \alpha x^{1-\alpha} - \delta_2.$$

For example, sufficient conditions that satisfy all of these properties are $\rho + \delta_1 + \gamma < 1$, α *small and* $\eta \leq 1$.

Analytical results are not informative regarding several points that can be illustrated with numerical simulations. However, the case in which $a = 0$ does provide an analytical solution for $\frac{K}{N} = \frac{1-\alpha}{\alpha}$, and the remaining quantities follow from proposition 1. See figure 1 for the following parameter values $\delta_1 = 0.1, \delta_2 = 0.16, \gamma = 0.06, \rho = 0.04$, $\eta = 1$.

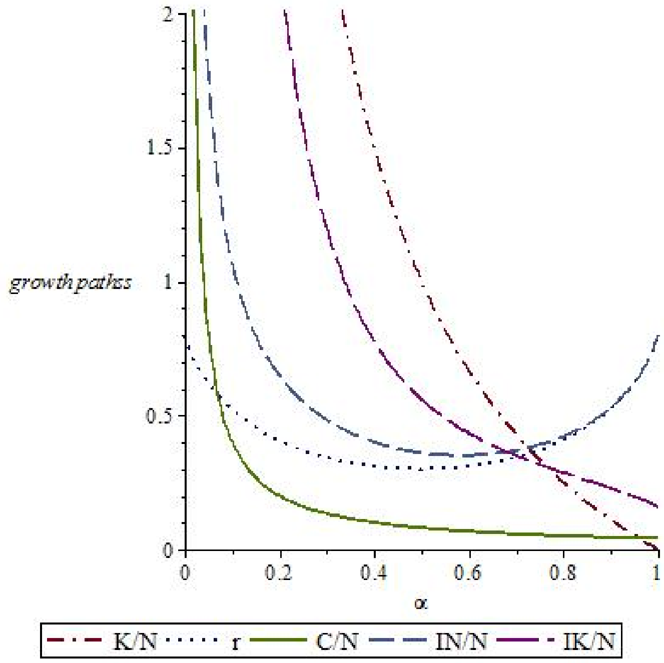

Figure 1: Growth paths when $a = 0$

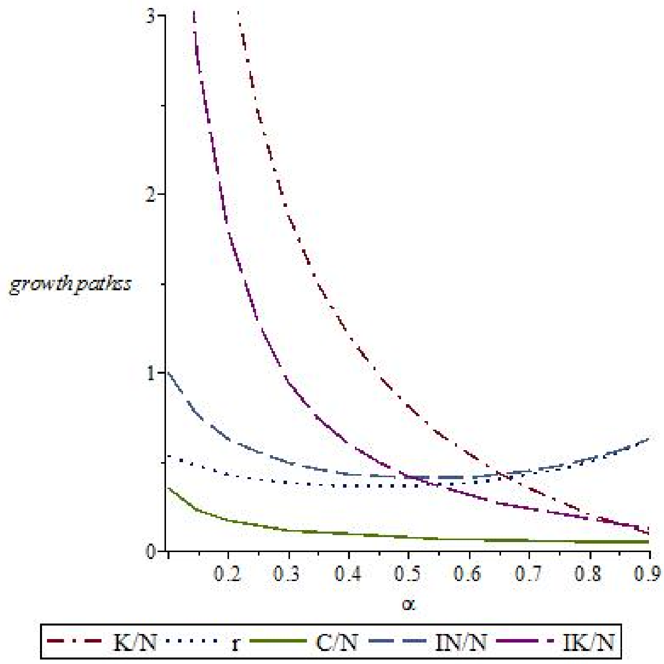

Figure 2: Growth paths when $a = 0.11$

We also present the results of simulations using the following parameter values: $\delta_1 = 0.1, \delta_2 = 0.05, \gamma = 0.06, \rho = 0.04$, $\eta = 1$, $a = 0.11$, $(1-a)/2 = 0.445$, (See figure 2). The simulation results in this figure are consistent with proposition 3 and show a decreasing growth rate r when $\alpha \in (0, \frac{1-a}{2})$ and an increasing growth rate r when $\alpha \in (\frac{1-a}{2}, 1)$. They are also consistent with proposition 4, which specifies that consumption is positive when $\eta \leq 1$. Moreover, when α goes to 0, N plays a negligible role in production and K drives economic growth. In this situation, the equations that determine the dynamics of K and N create incentives for the maximizing agent to invest in K and pursue a high rate of economic growth based on the accumulation of artificial capital. Symmetrically, when α goes to 1, K plays a negligible role in production and N drives economic growth.

When $a > 0$, r is higher when α tends to 1; when $a < 0$, r is higher when alpha tends to 0. The meaning of this result is rather straightforward since the sign of $a = \delta_1 + \gamma - \delta_2$ can be interpreted as an indicator of the relative importance of the impacts of K on N and of N on K.

The positivity of a implies that the impact of nature on man-made capital is weaker than the impact of man-made capital on nature and the depreciation of man-made capital together. This means that the main drivers of the dynamics is man-made capital, which depreciates at a high rate and/or degrades natural capital. It follows that economic growth is stronger when α is high (i.e. when production is mainly dependent on natural capital). The negativity of a implies that the impact of N on K is stronger than the impact of K on N. The dominant driver of this dynamic is the fact that nature damages man-made capital. It follows that growth is stronger when α is small (i.e. when production is mainly dependent on man-made capital).

We therefore consider that different production functions are not equally adapted to different natural environments. It follows that when α varies, the ratio I_N/N passes through a minimum for intermediate values, which corresponds to the lowest growth rates (i.e. when the economy does not generate enough capacity to invest). For low values of α, the ratio is high in order to maintain a minimum level of N that is destroyed by a very high level of K (while the level of N remains low). For high values of α, the ratio is also high, but here this results from the necessity of maintaining a very high level of N, which is the main factor of production. On the other hand, I_K/N always decreases when α increases. For low values of α, the agent is encouraged to invest heavily in K, the main factor of production, which is not the case for high values of α. The asymmetry between these two curves is explained by the fact that the interactions between the two forms of capital are not symmetrical.

3.2 Second case: when $\delta_1 = \delta_2 = 0$

In this scenario, we assume that the levels of K and N jointly impact the dynamics of K. The intuition here is that natural capital tends to accelerate the depreciation of man-made capital to a greater extent when ecosystems have already been perturbed by a high level of man-made capital. In other words, natural capital tends to generate more disservices when its natural dynamics have been significantly disrupted. In this case, the rate at which man-made capital is depreciated is not constant. Rather, it is a function of natural capital $H(N)$, and we consider a linear function where $H(N) = \delta N$.

In this case, we have the following results:

Proposition 5 (Growth paths and steady state) . *The necessary conditions for the existence of a steady state are given by:*

$$K > 0, \quad \text{solution of } (\rho+\gamma)(\delta K+\rho)^{1/(1-\alpha)} - (1-\alpha)\alpha^{\alpha/(1-\alpha)}(\delta K+\rho) + \delta K\alpha^{1/(1-\alpha)} = 0,$$

$$I_N = \gamma K, I_K = \delta NK, N = \frac{K\alpha^{1/(1-\alpha)}}{(\delta K+\rho)^{1/(1-\alpha)}}.$$

The sufficient conditions for a positive steady state are:

$$C = N^\alpha K^{1-\alpha} - \gamma K - \delta NK > 0, \ (\rho+\gamma)\rho^{1/(1-\alpha)} - (1-\alpha)\alpha^{\alpha/(1-\alpha)}\rho \leq 0.$$

To illustrate proposition 5, we study two specific cases: $\alpha = 1/2$ and $\rho = 0$. The case where $\rho = 0$ corresponds to the limit of a very patient agent who maximizes utility at the steady state. We find the following:

Proposition 6 *When $\alpha = 1/2$ we have*

$$K = \frac{\sqrt{\frac{\rho}{\rho+\gamma}} - 2\rho}{2\delta}, \quad N = \frac{K}{4(\rho+\delta A)^2}, \quad \text{when } K > 0 \text{ then } C > 0.$$

Note that $K > 0 \iff \rho < \frac{1}{2}(-\gamma + \sqrt{\gamma^2+1})$.

Figure 3, shows K, N, and C as a function of ρ for $\gamma = 0.1$ and $\delta = 0.001$. Positivity of K, N, and C is guaranteed for $\rho < 0.45$.
When $\rho = 0$ the problem to solve is:

$$\max_{K,N} N^\alpha K^{1-\alpha} - \gamma K - \delta KN, \quad \dot{K} = \dot{N} = 0.$$

We have the following proposition:

Proposition 7 *When $\rho = 0$, the behavior in the long run is the following:*

a) When $\alpha < 1/2$, there exists a steady state,

b) When $\alpha = 1/2$, then K goes to zero, N to $+\infty$, and C is constant,

c) When $\alpha > 1/2$, then K goes to zero and N and C go to $+\infty$.

As far as $\alpha \leq 1/2$ (when production is more dependent on K than on N), K remains positive in the long run. This means that giving an equal weight to all future generations and a production function that is less dependent on natural capital could lead to the preservation of the two capitals.
When $\alpha > 1/2$, K tends to disappear. Our model, which implies that production depends on two types of capital and especially natural capital, leads to the disappearance of K, but can nonetheless maintain a non-zero level of consumption because K disappears at a rate compensated for by the accumulation of N. In fact, the interactions between the two capital forms in the model tend to create an economy in which production in the long run

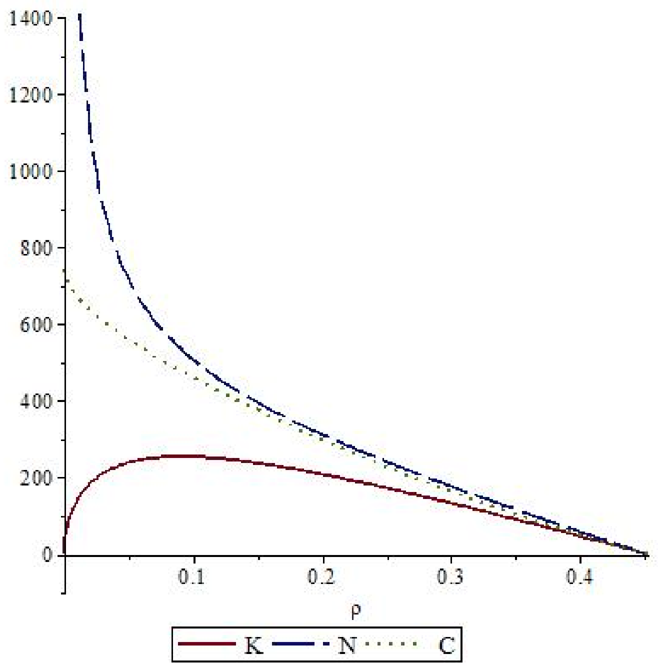

Figure 3: $K(\rho)$, $N(\rho)$, $C(\rho)$ at the steady state when $\alpha = 1/2$.

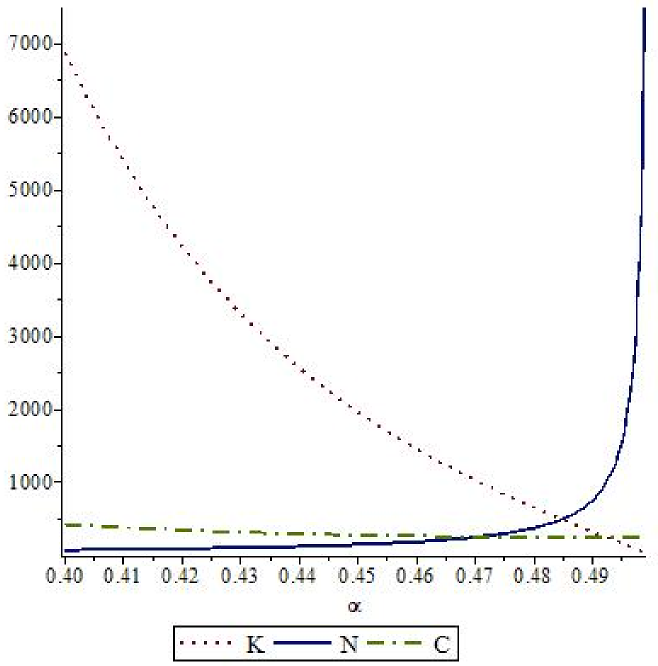

Figure 4: $K(\alpha)$, $N(\alpha)$, $C(\alpha)$ at the steady state when $\rho = 0$, $\alpha < 1/2$.

relies more and more on natural capital and is more and more efficiently exploited despite the gradual disappearance of K.

Figure 4 is an example of proposition 7 for $\alpha < 1/2$, $\delta = 0.001$, $\gamma = 0.03$. Figure 3 shows the behavior in item c) of proposition 7 when ρ goes to zero.

From propositions 5 and 7 we conjecture that for any ρ, the behavior at infinity when there is no steady state is similar to the case where $\rho = 0$.

4 Discussion

The main objective of this work was to use a formalized framework to study the characteristics of an economy as it relates to the ecosystems that influence the existence, pace and shape of economic growth. The models we develop clearly point to the importance of the interaction between the evolution of natural and man-made capital. The primary result is that, according to the form of these interactions, we observe either endogenous growth or a steady state in the long run. These results are not a given, however, and depend on the value of the technical coefficients that parameterize these interactions.

In the linear case ($\delta = 0$), we observe endogenous growth. Nevertheless, the growth rate can be negative and the dynamics go to 0. Which outcome prevails depends mainly on the level of negative interactions (the disservices of N and the environmental impacts of K) that each type of capital imposes on the other, and thus on the value of parameters $(\rho, \gamma, \delta_1, \delta_2)$. A small negative impact resulting from man-made capital K (δ_1 and γ) leads to the balanced growth of all variables K, N, C, I_K, I_N. If man-made capital is greatly degraded by nature (δ_2), this degradation disrupts the dynamics of economic growth and may result in degrowth (proposition 3, iii).

The growth rate r varies with α. It decreases from 0 to $(1 - a)/2$ and increases when $\alpha > (1-a)/2$. The lowest growth rate corresponds to the situation in which $\alpha = (1-a)/2$. For high values of α, natural capital increases faster than man-made capital and investment in N is greater than that in K. The growth dynamic relies mainly on N and achieves what can be regarded as green growth. In others words, when natural capital is weighted to a greater degree in the production function, the growth dynamic is not disrupted and capital stocks do not collapse as in Gylfason and Zoega (2006). However, this result is due to the fact that, in contrast to studies with exhaustible resources, natural capital is not consumed in our model.

We note that a high level of capital depreciation, as in the case where the depreciation of man-made capital depends on natural capital, disrupts the growth path and generally leads to a steady state. Particular cases considered give interesting results in this regard. When the agent is very patient and values the future more than the present (ρ near to zero), K is positive if and only if the weight of N in the production function is inferior of that of K ($\alpha < 1/2$), and a steady state exists for K, N and C. When $\alpha > 1/2$, no steady state exists because, even though K is null, N always tends to infinity and C is either positive and constant or tends to infinity, as well. A preference for future consumption could facilitate more sustainable ecosystems management by encouraging the preservation of both natural and man-made capital.

We developed a framework to address this issue and, as noted by Dasgupta (2008), we discovered a very limited literature offering insights regarding this framework. Representing nature as a capital stock that is neither consumed when involved in production, nor has a inherent regenerative dynamic of its own, may be criticized. However, after many different attempts, these assumptions appeared to be the most appropriate way to concisely incorporate nature into a model of economic production. Indeed, in the long run, the relation between economic dynamics and ecosystems is not - at least not only - an issue of (renewable) resource provision, but of ecosystem services and disservices that can either boost or hamper economic development. It is indeed evident that ecosystems, when properly preserved, can play an important role in economic growth.

This work therefore provides new arguments regarding why greater attention should be paid to the impacts that productive investment, including the land development, has on ecosystems. In particular, it suggests that the type of interactions between natural and man-made capital can hinder growth when ecosystems are already compromised and are no longer able to provide fundamental regulatory services. One might note that this result is only the consequence of our modelling assumptions, the economic significance of which can be debated or considered to be relevant only to specific contexts. However, as we point out, these choices were based on a literature, increasingly important in conservation sciences, that demonstrates that such types of relationships between natural and man-made capital do in fact exist.

5 Conclusion

The purpose of this work was to study the implications of explicitly taking into account the relationship between economic activity and ecosystems in a dynamic context. Preliminary motivations for the work were that this type of analysis is undeveloped in the literature to date and that there is considerable evidence that the diversity of interactions between nature and society are poorly taken into account in natural resource models. In order to better understand this diversity, we chose not to represent ecosystems as a resource but as a stock of natural capital that is necessary for economic production (hence the choice of a Cobb-Douglas production function), and which is not directly consumed in the production process. An important objective therein was modeling not only the positive contributions of ecosystems to production - "ecosystem services" - but also the fact that they can constrain economic activity and human welfare, i.e. that they can also constitute "disservices". Modelling ecosystem services as benefits derived from natural capital is a rather standard approach and appears to be the more appropriate way to analyze growth issues in a finite world, though this does not imply that human welfare is limited. The results yielded by our modelling choices appear to lend them some validity. On the one hand, we found a set of effects are to be expected in this type of exercise. The weight of the two types of capitals lead to growth patterns that rely on the factor that contributes the most to production, and the rational representative agent invests in this type of capital.

On the other hand, we also obtain less expected results. The duality between the existence of a stationary state and endogenous growth was undoubtedly predictable, but our model makes it possible to study the conditions that determine which outcome will prevail. At the beginning of this work, we primarily considered comparing steady state levels and the choice of a production function with constant returns to scale for the purposes of simplicity. Our model does not allow for explicit technical progress, and economic growth results directly from capital accumulation. The mechanism involved in this dynamic is quite trivial, and it did not seem obvious that the agent could - depending on the conditions - be encouraged to invest in anything besides the maintenance of capital stock. An unexpected result was that, under certain conditions and with a production function mainly reliant on natural capital ($\alpha > 1/2$), the long-term dynamic moves towards growth based solely on improving the development of ecosystems services. This result is likely to be fragile (no discounting or weak ρ), but the idea that an economy may depend essentially on nature is not unrealistic, especially if we consider recent global assessments regarding the economic value of ecosystem services (Costanza et al., 2014). The indefinite increase in the value of the ecosystem stock can be interpreted as reflecting implicit technical progress. We hope that this modeling approach and the results herein will stimulate further reflection regarding the nature of the relationship between the environment and the economy.

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Appedix

The Hamiltonian of the problem is

$$H(C,K,N,\lambda_N,\lambda_K) = U(C) + \lambda_N(I_N - \gamma K) + \lambda_K(I_K - \delta_1 K - \delta_2 N - \delta KN).$$

The first order conditions at the steady state are:

$$\frac{\partial H}{\partial I_N} = -U'(C) + \lambda_N = 0, \tag{1}$$
$$\frac{\partial H}{\partial I_K} = -U'(C) + \lambda_K = 0, \tag{2}$$
$$\dot{\lambda_N} = \rho\lambda_N - U'(C)\alpha(K/N)^{1-\alpha} + \lambda_K(\delta_2 + \delta K) = 0, \tag{3}$$
$$\dot{\lambda_K} = \rho\lambda_K - U'(C)(1-\alpha)(N/K)^{\alpha} + \lambda_K(\delta_1 + \delta N) + \gamma\delta N = 0, \tag{4}$$
$$\dot{N} = I_N - \gamma K = 0, \quad \dot{K} = I_K - \delta_1 K - \delta_2 N - \delta NK = 0. \tag{5}$$

Proofs of propositions 1, 2, 3 and 4

From the first order conditions 1 and 2 we have:

$$U'(C) = \lambda_N = \lambda_K. \tag{6}$$

Equations 3 and 4 are two equations with a unique unknown K/N, so there is no steady state unless

$$\left(\frac{\rho+\delta_2}{\alpha}\right)^{\frac{1}{1-\alpha}} = \left(\frac{\rho+\delta_1+\gamma}{1-\alpha}\right)^{-\frac{1}{\alpha}}.$$

Now we consider the existence of a growth path. By deriving equations 1 and 2 we have:

$$\frac{\dot{\lambda_N}}{\lambda_N} = \frac{\dot{\lambda_K}}{\lambda_K} = -\frac{1}{\eta}\frac{\dot{C}}{C},$$

with $\eta = -\frac{U'(C)}{U"(C)C}$ as the inter-temporal elasticity of substitution of consumption. From 3, 4 and 6 we have:

$$\rho - (1-\alpha)\left(\frac{N}{K}\right)^{\alpha} + \delta_1 + \gamma = \rho - \alpha\left(\frac{K}{N}\right)^{1-\alpha} + \delta_2. \tag{7}$$

Now, we prove that there exists a solution $x = K/N$ of equation 7. We seek the existence of $x \in (0,\infty)$ such that

$$f(x) = \alpha x^{1-\alpha} - (1-\alpha)x^{-\alpha} + a = 0, \quad a = \delta_1 + \gamma - \delta_2.$$

As $\lim_{x\to 0} f(x) = -\infty, \quad \lim_{x\to\infty} f(x) = \infty, \quad f'(x) = \alpha(1-\alpha)(x^{-\alpha} + x^{-\alpha-1}) > 0$, then there exists a unique solution of $f(x) = 0$ with $x > 0$.

- As $f(1) = -1 + 2\alpha + a$,

$$\alpha < \frac{1-a}{2} \Longrightarrow x > 1, \quad \alpha > \frac{1-a}{2} \Longrightarrow 0 < x < 1.$$

- Moreover

$$\frac{\partial x}{\partial \alpha} = -\frac{x^{1-\alpha} + x^{-\alpha} + \ln(x)a}{\alpha(1-\alpha)(x^{-1-\alpha} + x^{-\alpha})}$$

Since K/N is constant, we have $\frac{\dot{N}}{N} = \frac{\dot{K}}{K} := r$. From the dynamics of the model $\dot{N} = I_N - \gamma x N, \quad x\dot{N} = I_K - \delta_1 x N - \delta_2 N$, then

$$\frac{\dot{N}}{N} = \frac{I_N}{N} - \gamma x, \quad x\frac{\dot{N}}{N} = \frac{I_K}{N} - \delta_1 x - \delta_2.$$

and

$$\frac{\dot{I_N}}{I_N} = \frac{\dot{I_K}}{I_K} = r.$$

taking into account that $F(N, K) = C + I_N + I_K$, we have

$$x^{1-\alpha} = \frac{C}{N} + \frac{I_N}{N} + \frac{I_K}{N},$$

and

$$\frac{C}{N} = x^{1-\alpha} - (r + \gamma x) - (rx + \delta_1 x + \delta_2)$$

Moreover,

$$r := \frac{\dot{C}}{C} = -\eta(\rho - \alpha x^{1-\alpha} + \delta_2).$$

To establish a sign for r we must study $t(\alpha) = z - \alpha \left(\frac{1-\alpha}{y}\right)^{\frac{1-\alpha}{\alpha}}$. This function has the following properties.

$$\lim_{\alpha \to 0} t(\alpha) = -\infty, \text{ if } y < 1, \quad \lim_{\alpha \to 0} t(\alpha) = z, \text{ if } y \geq 1, \quad \lim_{\alpha \to 1} t(\alpha) = z - 1,$$

and

$$t'(\alpha) = 0 \iff \alpha = 1 - y, \quad t(1-y) = z + y - 1.$$

Some properties of r

- Variation with respect to α

$$\frac{\partial r}{\partial \alpha} = -\eta \left[x^{1-\alpha} + \alpha x^{1-\alpha} \left(-\ln(x) + (1-\alpha)x^{-1}\frac{\partial x}{\partial \alpha} \right) \right].$$

  taking into account the formula of $\frac{\partial x}{\partial \alpha}$ and replacing a,

$$\frac{\partial r}{\partial \alpha} = -\eta x^{1-\alpha} \left[1 + \alpha \left(-\ln(x) - \frac{x^{1-\alpha} + x^{-\alpha} + \ln(x)a}{\alpha(x^{-\alpha} + x^{1-\alpha})} \right) \right] = \frac{\eta x^{1-\alpha} x^{-\alpha} \ln(x)}{x^{1-\alpha} + x^{-\alpha}},$$

  then

$$\alpha < \frac{1-a}{2} \iff \frac{\partial r}{\partial \alpha} < 0.$$

- Variation with respect to a

$$\frac{\partial r}{\partial a} = \frac{x^{1-\alpha}}{x^{1-\alpha} + x^{-\alpha}} > 0.$$

Proof of proposition 5 and 6

From equations 1, 2 and 5 we have:

$$U'(C) = \lambda_N = \lambda_K, \quad I_N = \gamma K, \quad I_K = \delta N K.$$

Equations 3 and 4 are:

$$\dot{\lambda_N} = \rho - \alpha \left(\frac{K}{N}\right)^{1-\alpha} + \delta K = 0,$$

$$\dot{\lambda_K} = \rho - (1-\alpha)\left(\frac{N}{K}\right)^{\alpha} + \delta K + \gamma = 0.$$

from the first equation

$$N = \frac{K\alpha^{1/(1-\alpha)}}{(\delta K + \rho)^{1/(1-\alpha)}},$$

and replacing this in the second one, K is the solution of

$$f(K) = (\rho+\gamma)(\delta K + \rho)^{1/(1-\alpha)} - (1-\alpha)\alpha^{\alpha/(1-\alpha)}(\delta K + \rho) + \delta K \alpha^{1/(1-\alpha)} = 0.$$

If $F(0) = (\rho+\gamma)\rho^{1/(1-\alpha)} - (1-\alpha)\alpha^{\alpha/(1-\alpha)}\rho \leq 0$ as $lim_{K\to\infty} f(K) = +\infty$, there exist a solution K $>$0 of the problem.
The particular case of $\alpha = 1/2$ follows easily, appearing in the last equations.

Proof of proposition 7

The problem is

$$\max_{N\geq 0, K\geq 0} \pi(N,K) := N^{\alpha}K^{1-\alpha} - \delta K N - \gamma K.$$

The first order conditions give

$$K = 0, \quad \text{or} \quad N^* = \left(\frac{\delta K^{\alpha}}{\alpha}\right)^{1\alpha - 1};$$

and if $K > 0$

$$K^* = \frac{\alpha}{\delta}\left(\frac{1-2\alpha}{\gamma}\right)^{\frac{1-\alpha}{\alpha}}.$$

Then $K > 0 \iff \alpha < 1/2$. When $\alpha > 1/2$,

$$\pi(N^*, K^*) = \left(\left(\frac{\alpha}{\delta}\right)^{\frac{1-\alpha}{\alpha}} - \delta\left(\frac{\alpha}{\delta}\right)^{\frac{1}{\alpha}}\right) G^{2-1/\alpha} - \gamma\left(\frac{\alpha}{\delta}\right)^{\frac{1}{\alpha}} G^{1-1/\alpha},$$

goes to $+\infty$ when N goes to ∞.