Natural Resources Dynamics: Another Look

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Summary

In this paper we study the problem of exhaustible resources and renewable resources in a theoretical endogenous growth framework, under various assumptions. In particular, we consider the hypotheses that those two inputs are or are not technologically perfect substitutes of each other. Moreover, we develop the starting model accounting for the negative externality of waste accumulation. Finally, a comparative analysis is made between Pigouvian tax and waste recycling as an environmental policy to internalize the negative externality represented by refuse accumulation.

Keywords: Economic growth, Endogenous technological progress, Exhaustible resources, Pigouvian taxes, Renewable natural inputs, Technological substitutability

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1 Introduction

In the mists of time our forefathers basically used just renewable resources, like water, wind, and wood, to produce energy. It was only with the industrial revolution and the invention of the internal-combustion engine that we increased the use of non-renewable resources like oil, coke, etc. The cohabitation of both kinds of natural resources has thus become the rule in economic systems all over the world. The increasing use of exhaustible resources creates two kinds of problem: firstly, the price of this type of input is increasing; secondly, a negative externality is generated in terms of pollution discharged into the environment. To off-set the constraint to growth represented by the presence of non-renewable inputs, economic systems have been forced to resort to the so-called "backstop technologies" phenomenon, that is the employment of the same renewable sources of energy as previously, but utilizing new processes (Nordhaus, 1974).

In the real world there has been such a general economic interest in energy technology development over the last few years that venture capital disbursements have risen sharply (The Economist, 2001, p.64). Future scientific improvements will probably allow us to achieve the optimal growth path of the economy: ethanol, for example, derived from a renewable resource (sugarcane), is (or could become) a good substitute for gasoline (Goldember *et al.,* 2001, Anderson, 2001). Roughly speaking, a lot of attention is being paid to technological discoveries regarding the increase in renewable input utilization, such as energy sources and ways to avoid the depletion of non-replenishable inputs. This dynamic substitution process may help to lead economic systems towards more sustainable paths.

Following the seminal paper of Hotelling (1931), since the late nineteen-sixties many theoretical studies have been carried out on exhaustible resources, such as those of Anderson (1972), Barbier (1999), Cummings (1969), Hoel (1978), Kamien and Schwartz (1978), Krautkraemer (1989), Schou (2000), Solow (1974a), Stiglitz (1974), Tahvonen (1997), Vousden (1973).[2] Each of these papers has placed emphasis on some aspects of the issue: the common access to the resource studied, the role of the discount rate, ore quality selection, technological change, the environmental costs of mining exhaustible resources, etc.; none of them, however, takes into account the presence of renewable resources.

Another line of economic literature deals with renewable natural resources: this includes the works of Plourde (1970), Huhtala (1999), Di Vita (2002), Mendelssohn and Sobel (1980), Olson and Roy (1996, 2000), Tahvonen and Kuuluvainen (1993). This current is less substantial, because for this kind of input the main problem is just to ensure its optimal harvest rate. Finally, only a few studies combine renewable and non-replenishable natural resources in the same model (see D'Arge and Kogiku, 1973, Dasgupta and Heal, 1974, Kemp and Van Long, 1980, Smith, 1974, Tahvonen and Salo, 2001). In particular, in all these works of research the kinds of replenishable natural sources of energy considered are eolian, solar, geothermal, biomass, etc.; they do not entertain the

[2] For a detailed survey of this field of literature, see Krautkraemer (1999).

hypothesis of deriving a good substitute for exhaustible resources from agricultural farming (like ethanol from sugarcane).

The latter studies shed light on the relationship between the two kinds of natural resources mentioned here, but they do not take into consideration at least three problems. First, a reproductive function for renewable resources is not explicitly introduced in those models. Second, the problem of substitutability between exhaustible and renewable resources is viewed in terms of costs only and not from the angle of technological possibility. Third, the negative externalities associated with the presence of a non-renewable resource and with waste accumulation is not accounted for. Our paper will try to bridge this gap in economic literature.

Our main intuition is that inserting in our model the hypothesis of a natural input derived from agricultural farming may shed light on the relationship between exhaustible and renewable resources, so it is worth exploring; thus we introduce a logistic function for it in the model. The problem of substitutability between the two kinds of natural resource is at the same time economic and technological, such that endogenous knowledge acquisition plays a fundamental part in our analysis. Finally, we cannot ignore the negative externality represented by waste accumulation, and the possible remedies for this cause of market failure.

This study attempts to answer the following questions: how can the introduction of a parameter representing the degree of technological substitutability between exhaustible and renewable resources change the known results in this field? Is technological change relevant to explain the process of internalization of negative externality represented by refuse accumulation? Is it better to introduce a Pigouvian tax or promote waste recycling, to reduce litter flow to its optimal level?

Our results show that if the two kinds of natural production factors are not perfect substitutes of each other, the economic system cannot achieve the optimal growth path. New scientific discovery has three kinds of spillover: it allows us to alleviate the burden on the economic system represented by exhaustible resources, by removing the obstacles to using renewable natural inputs instead of non-replenishable ones; it increases the amount of waste that may be recycled; and it reduces the price of reproducible resources. Finally, while Pigouvian tax and waste recycling have the same effects when the static first order conditions are considered, secondary materials production causes a positive externality in terms of dynamic efficiency, making it possible to reduce the amount of exhaustible resources mined.

The problem of imperfect substitutability between exhaustible and renewable natural input is well known in economic literature (Dasgupta and Heal, 1974), but has not been fully explored. Solow (1974b) affirms:"... *As you would expect, the degree of substitutability is also a key factor. If it is very easy to substitute other factors for natural resources, then there is in principle 'no problem'. ...* ". Under the hypothesis of perfect substitutability, there is some 'back-stop technology', such that production is not limited by the exhaustible resource; if there is no substitute for the non-replenishable input, on the other hand, catastrophe is unavoidable. Solow suggests that there is a wide range of cases in between, in which the question is real, interesting and not foreclosed; he thus emphasizes the role of elasticity of substitution between the two inputs.

In this paper we formally introduce the assumptions that the two kinds of resources may or may not be technologically perfect substitutes of each other. The negative externality represented by litter accumulation is accounted for in formal analysis. Finally, we try to find solutions to the problem of using waste recycling or Pigouvian tax to internalize the negative externality represented by refuse. These are problems that have been ignored in previous research.

Our endogenous growth model consists basically of two sectors. The final output is produced in the first, while knowledge is accumulated in the second. When the waste recycling process is considered, there are three industries involved. A standard Cobb-Douglas production function is assumed. Among other inputs, we consider two natural resources, one exhaustible and the other replenishable. The condition that the two natural resources used here are perfect substitutes of each other makes analysis simple, but could be unrealistic, because in this case it could be difficult to see the problems involved in using one natural input instead of another. Thus it is interesting to see what happens when the hypothesis of imperfect substitutability is considered. Physical capital is accrued by means of net investment. The dynamics of technology stock is the same as in Romer (1990). New scientific discoveries are neither exogenous nor costless, but depend on the labor time allotted to this aim (Kamien and Schwartz, 1978). The amount of exhaustible resources available declines at the same rate as that of extraction. A logistic function describes the behavior over time of the renewable natural resources stock. The utility level depends on consumption and on the amount of waste accumulated. This is a quite widely accepted assumption, in models dealing with growth and pollution.

The optimal growth path is constrained by the amount of labor time available in our economy, that we assume constant for the sake of simplicity.

In section three, we consider the possibility that the waste derived from exhaustible resources can be recycled: this reduces not only the amount of litter discharged into the environment but also the flow of this kind of natural input extracted from the world's crust. For renewable resources, the main problem is to find the optimal rate of harvest, thus the problem of recycling the waste derived from this kind of input may be ignored.

To simplify the reading of the paper we denote the parameters with greek letters: lambda represents the dynamic multipliers, the capital letters are the stock variables and the small letters are the flow variables; finally, asterisks indicate the optimal values.

The remainder of the paper is as follows. After the description of the model, we derive the first order conditions. Section 3 is devoted to extending the model and making some comparative analysis. Conclusive remarks and implications for environmental political economy are the subject of the last section.

We confine the mathematical details to the appendix.

2 A Model with Exhaustible and Renewable Resources

We start by presenting a simple theoretical framework, in which both kinds of natural resource are considered. The production function of the final output y depends on five inputs: physical capital K, stock of technology A, labor time devoted to final output production l_1, rate of use of exhaustible resources e, amount of renewable resources harvested r. The total number of skilled workers N is assumed constant and normalized to one. Labor may be used not only to produce the final output but also in R&D activity l_2, such that $1 = l_1 + l_2$. In what follows we are interested only in interior solutions, in which $l_i > 0$, for $i = 1, 2$. Technology (or knowledge) is accumulated as a consequence of the labor time allotted to this purpose (Romer, 1990). In other words, technological change is at the same time costly and not fortuitous: it depends on the effort devoted to this aim and is an outcome of a sector of our economy (Kamien and Schwartz, 1978, Romer, 1990). All the variables considered in the model are functions of the time t; just to make the reading of the paper easier we will suppress the subscript (t) in the ensuing discussion.

The production function is

$$[1] \quad y = f(K, A, l_1, e, r) = K^{\alpha_1} (Al_1)^{\alpha_2} (e + \psi r)^{\alpha_3}, \quad \sum_{i=1}^{3} \alpha_i = 1,$$

where ψ is a parameter describing the kind of technological substitutability between exhaustible and renewable resources. In this way, if $\psi = 1$, we may use e or r indiscriminately. If this condition is not satisfied (i.e. $0 < \psi < 1$) we are in a case of imperfect substitutability, for which the marginal productivity of e and r will be not the same, and the elasticity of substitution between those two inputs will be lower than in the hypothesis in which $\psi = 1$.

The law motion of physical capital is

$$[2] \quad \dot{K} = y - c, \text{ where } K(0) = K_0 \text{ and } K(t) \geq 0.$$

[2] is a constraint which considers the change of physical capital over time. For the sake of simplicity, depreciation in K is not considered here. Aggregate consumption is denoted by $c = xy$, with $0 < x \leq 1$. Per capita consumption is represented by $c = c/N$. Aggregate saving is $s = zy = \dot{K}$, where $0 \leq z < 1$, and $z = (1 - x)$.

$$[3] \quad \dot{A} = \xi l_2 A, \text{ where } A(0) = A_0 > 0, \text{ and } A(t) \geq 0.$$

Equation $[3]$, which is of an endogenous nature, describes the stock of technology accumulated, where $\xi > 0$ is a productive parameter of scientific research (Romer, 1990).

$$[4] \quad \dot{E} = -e, \text{ where } E(0) = E_0 > 0, \; E(t) \geq 0.$$

$\dot{E}$ considers the dynamics of the exhaustible resource stock E as a function of the flow of virgin ores extracted from the world's crust (for a similar specification see Vousden, 1973).

$$[5] \quad \dot{R} = f(R) - \rho R = \sigma \left(1 - \frac{R}{\pi}\right) R - r, \text{ where } R(0) = R_0,\ R(t) \geq 0.$$

Equation [5] expresses the behavior over time of the renewable resource stock R. We assume that $f(R)$ is the growth function, with properties $f(R) \geq 0$, for $0 \leq R \leq \pi$, $f^{'}(R) > 0$ for $0 \leq R \leq \bar{R}$, $f^{'}(\bar{R}) = 0$ and $f^{'}(R) < 0$ for $\bar{R} \leq R \leq \pi$, where $\bar{R}$ is the maximum sustainable yield stock level of our renewable resource, and π is the ecological carrying capacity (Hanley *et al.*, 1997, Li and Löfgren, 2000). σ denotes the intrinsic growth rate of renewable resources, while r, equal to ρR, is the harvest flow of this natural input, ρ being the rate of use of R (where $0 \leq \rho \leq 1$). The assumption regarding the first derivative of the natural production function $f^{'}(R)$, is justified by the fact that this kind of resource has a maximum point and then decreases to zero. Thus there is a maximum sustainable yield, that in equilibrium should be equal to the highest possible harvest rate (Clark, 1999).

$$[6] \quad \dot{J} = d - \gamma J = (e + r) - \gamma J,\ J(0) = J_0,\ J(t) \geq 0.$$

This is the motion equation of the waste stock J (Smith, 1972); it is a function of the litter flow d produced in the economy (as a by-product of the transformation of inputs into outputs), minus the amount of J that the ecosystem is capable of absorbing by biodegradation. $0 \leq \gamma < 1$ is a parameter representing the capacity of the environment to assimilate waste (Huhtala, 1999, Plourde, 1972). As the forerunners of waste management analysis observed, the conservation of matter principle makes it possible to affirm that, in a closed system, the tonnage of raw materials utilized by an economy is approximately equal to the weight of waste generated (D'Arge and Kogiku, 1973). In formal terms $d = e + r$. This specification of waste stock dynamics reflects the materials balance approach, for which any material input will be returned to the environment in some kind of waste (Ayres, 1999, Huhtala, 1999, Radetzki and Van Duyne, 1985).

The welfare of society, at any point in time, is a function of the per capita flow of consumption and the stock of waste (D'Arge and Kogiku, 1973, Hoel, 1978, Huhtala, 1999, Keeler *et al.*, 1971, Lusky, 1976, Plourde, 1972, Smith, 1972, Tahvonen, 1997). The inclusion of J in our utility function indicates that we will pay a price to reduce the amount of residuals accumulated. The instantaneous utility function can be indicated by

$$[7] \quad u = u(c, J) = \frac{c^{1-\theta} - 1}{1 - \theta} - \frac{J^{1+\omega} - 1}{1 + \omega}, \text{ with } \theta, \gamma, \omega > 0.$$

[7] has continuous first and second partial derivatives, with $u_c > 0$, $u_{cc} < 0$, $u_J < 0$, $u_{JJ} < 0$ and $U_{cJ} = 0$. It is assumed that for $c \to 0$, $u_c \to +\infty$, where θ and ω are two more parameters, representing the elasticity of marginal utility with respect to consumption and waste stock.

Assuming that the case of $\psi = 1$ prevails, the current-value Hamiltonian $\aleph$ for the problem is:

$$[8] \quad \aleph = \frac{c^{1-\theta}-1}{1-\theta} - \frac{J^{1+\omega}-1}{1+\omega} + \lambda_1 \left\{ \left[K^{\alpha_1} \left(A l_1 \right)^{\alpha_2} \left(e+r \right)^{\alpha_3} \right] - C \right\} + \lambda_2 \left[\xi l_2 A \right]$$
$$- \lambda_3 e + \lambda_4 \left[\sigma \left(1 - \frac{R}{\pi} \right) R - r \right] - \lambda_5 \left[\left(e+r \right) - \gamma J \right] + \lambda_6 \left(1 - l_1 - l_2 \right),$$

where λ_i, $i = 1, 2, 3, 4, 5, 6$, are the dynamic multipliers of the stock variables. Note that we consider the shadow price of waste to be negative, because it generates disutility.

First order conditions for an optimal solution, together with the usual transversality constraints, are confined to Appendix A.[3] Here it is assumed that all the conditions in Theorem 9 of Seierstad and Sydæter (1997, p. 217), together with the concavity on the maximized Hamiltonian, are satisfied.

3 Investigating the Model Behavior Under Different Hypotheses

In what follows, we shall use the theoretical framework outlined in the previous paragraph to analyse the relationship between exhaustible and renewable resources. First of all, we assume perfect substitutability in the production function between these two natural inputs; we then introduce some complication into the model, to take into account the hypothesis of imperfect substitutability. Further on, we extend the model to consider what happens when waste recycling occurs, in cases where it is not indifferent whether secondary materials are used instead of one or both of the natural resources considered. Finally, the use of Pigouvian tax to internalize the negative externality represented by waste accumulation is evaluated here. We conclude this paragraph by making a comparison between waste recycling and Pigouvian tax, as instruments to increase welfare and achieve the optimal amount of litter discharged into the environment.

3.1 The Basic Model

The first question that we should tackle is: how does the presence of a renewable natural input influence the dynamics of the exhaustible resources stock? To this aim we may use [$A3$]; after putting in evidence e, and substituting in [4], the result is

$$[9] \qquad \dot{E} = \frac{\lambda_1 \alpha_3 y}{\lambda_4 + \lambda_5} - r.$$

From the equation above we may see that an increase in the rate of use of renewable resources allows us to reduce the extraction of e by the same amount, and that a negative relationship exists between $\dot{E}$ and λ_4. In other words, under a condition of perfect substitutability between the two natural resources

[3] For expositional reasons, the demonstration that the model exhibits a unique optimal saddle point is omitted. It was derived following a standard procedure similar to that of Schou (2000). The formal proof is available, upon request, from the author.

taken into account here, the first step to off-set the constraint to growth due to exhaustible resource consumption is to increase the use of renewable natural input.

Now the problem is to define the role played by technological change in alleviating the constraint to growth represented by non-replenishable resources. To answer this question we use $[A2]$, [3] and the condition $l_1 + l_2 = 1$.

After some algebra, and calculating the implicit derivative of e^* with respect to ξ, we obtain

$$[10] \qquad \frac{\partial e^*}{\partial \xi} = -\frac{(e+r)\,\xi\alpha_2 g_A}{(\xi-1)\left[\xi^2(\alpha_3-1)\right]} < 0.$$

Thus we may say that there is an inverse relationship between the rate of use of the exhaustible resource and changes in knowledge accumulation, represented by the parameter of productivity in this sector of our economy (where g_A is the growth rate of stock of technology). An increase in knowledge allows us to reduce the pressure on the environment in different ways: improving the efficiency of the use of inputs through the new production process; diminishing dependence on the non-replenishable input; increasing the possibility of using other inputs in place of the exhaustible ones.

So far we have dealt only with the first order static conditions, from which we can say that one more unit of renewable input allows us to reduce consumption of exhaustible resources by the same amount, and that technological progress reduces the quantity of e extracted from the earth's crust. It is worth taking a look at the first order dynamic conditions. Starting from $[A14]$, putting in evidence δ and substituting in $[A13]$, we obtain

$$[11] \qquad g_{\lambda_3} = g_{\lambda_4} + \sigma\,(1 - 2R/\pi) - \rho,$$

such with an increase in the rate of use of the renewable resource ρ, the growth rate of the shadow price of exhaustible resource decreases. In the stationary growth path, however, it always proves that $g_{\lambda_3} = g_{\lambda_4}$, such that $\sigma\,(1 - 2R/\pi) - \rho = 0$. During transitional dynamics an increased use of renewable resources allows us to reduce pressure on the exhaustible natural input and its price.

To investigate how technology influences the dynamics of λ_3, we may put in evidence δ in $[A11]$ and then substitute in $[A13]$, to find

$$[12] \quad g_{\lambda_3} = g_{\lambda_1} + \alpha_3 K^{\alpha_1 - 1}\left(A - \frac{\dot{A}}{\xi}\right)^{\alpha_2}(e+r)^{\alpha_3}.$$

From [12] it is clear that the greater the changes in technological stock over time, the lower g_{λ_3} will be. An increase in the absolute accumulation rate of knowledge diminishes the demand for exhaustible resources and mitigates the dynamics of λ_3.

Using the model described in the last section, and the first order conditions, we may say that the shadow prices of both natural inputs will be the same in the stationary growth path. The shadow prices of e and r will grow at the same rate in the steady state equilibrium, such that Hotelling's rule is verified also for renewable resources. This result holds if and only if $\sigma(1 - 2R/\pi) - \rho = 0$. In other words Hotelling's rule is verified for renewable resources only in the case of $\partial\dot{R}/\partial R = 0$; this implies that in the optimal path, the effective growth rate of renewable resource should be equal to its rate of use.

3.2 Imperfect Substitutability Between Exhaustible and Renewable Resources

The assumption employed in the previous section, for which it is possible to use one natural input instead of another indifferently in the production function, makes analysis simple, but may not always prove realistic. Thus it is worth highlighting what happens if the two resources are not perfect substitutes of each other. We assume this condition because historically, while exhaustible resources generally offer a greater productivity than renewable ones, the latter do not represent a constraint to growth, because the main problem is merely to harvest them at the optimal rate.

To extend the model to a case in which we assume imperfect substitutability between exhaustible and renewable resources, we have to consider the parameter ψ, under the hypothesis that $0 < \psi < 1$, in our production function and Hamiltonian. In this case only two first order conditions change with respect to the case in which $\psi = 1$; the others remain unaltered, in particular the derivative of $\aleph$ with respect to e and r, that is easy to calculate. Using $\partial\aleph/\partial e$, and [3] we obtain

$$[13] \qquad \dot{E} = \frac{\lambda_1 \alpha_3 y}{\lambda_3 + \lambda_5} - \psi r.$$

Comparing [9] with the equation above, it is evident that in cases of imperfect substitutability we will extract more exhaustible resources from the world's crust. When $\psi = 1$, in fact, one more unit of renewable natural input allows us to save the same amount of non-replenishable ones. Thus we can affirm that the hypothesis of perfect substitutability between the two natural resources considered is better for the environment.

It is interesting to see whether the effects of technological change on the rate of use of exhaustible resources, in a case of imperfect substitutability between e and r, are the same as in case ψ. To this aim we again use $\partial\aleph/\partial e$, [3] and the constraint $l_1 + l_2 = 1$.

Using some simple algebra and evaluating the implicit derivative of e with respect to ξ, the result is

$$[14] \qquad \frac{\partial e}{\partial \xi} = -\frac{(e + r\psi)\,\xi\alpha_2 g_A}{(\xi - 1)\left[\xi^2(\alpha_3 - 1)\right]} < 0.$$

By means of [10], it is easy to see that in this case, under *ceteris paribus* conditions, the reduction of the rate of use of non-replenishable natural inputs will be smaller than in the case where the two natural inputs are perfect substitutes of each other.

The first order dynamic conditions remain formally unaltered, under the hypothesis of imperfect substitutability between e and r.

In cases where $\psi < 1$, the shadow prices of exhaustible and renewable resources will be different in the stationary growth path. This implies that Hotelling's rule will also be satisfied if and only if $\sigma(1 - 2R/\pi) - \rho = 0$. But, unlike that obtained under the assumption $\psi = 1$, this is not an implicit result of the model, because $[A19]$ does not hold if $\psi < 1$. Thus, combining $[A14]$ with $[A20]$, we may obtain three possible results

$$[15] \qquad g_{\lambda_3} \begin{cases} > g_{\lambda_4} \text{ if } \sigma(1 - 2R/\pi) > \rho \\ = g_{\lambda_4} \text{ if } \sigma(1 - 2R/\pi) = \rho \\ < g_{\lambda_4} \text{ if } \sigma(1 - 2R/\pi) < \rho \end{cases} .$$

In the case where $g_{\lambda_3} = g_{\lambda_4}$, corresponding to the middle row of [15], the system is at its optimal growth path; in the other hypotheses the economic system runs the risk of diverging from its optimal growth path. If we are under-utilizing renewable resources (i.e. $\sigma(1 - 2R/\pi) > \rho$), the growth rate of λ_3 will be higher than its optimal value, thus over-exploiting the exhaustible natural input. Vice-versa, when the growth rate of the shadow price of the exhaustible resource is lower than its optimal value (i.e. $\sigma(1 - 2R/\pi) < \rho$) we are over-sweating the renewable natural input. In the first case there is a risk of depleting exhaustible resources, while in the second hypothesis the danger is of using up the replenishable resource. In both cases the economic system is addressed toward an unsustainable growth path.

3.3 Waste Recycling Under Imperfect Substitutability between Natural Resources

In the simple version of the model there are two forces at work that may off-set the constraint to growth represented by exhaustible resources: the increasing use of renewable natural inputs and technological progress. The results of the previous section show that when natural resources are not perfect substitutes of each other, the scarcity of non-replenishable resources may bring the system to exploit both natural inputs. This suggests that we should look for another channel to move the economic system towards more environmentally friendly behavior. Thus we want to extend our model further, to include the recycling of waste derived from non-renewable resources, and see what happens in this hypothesis.

The process of transforming litter into secondary input is considered both a good pollution abatement technology and a system to off-set the scarcity of exhaustible resources (Di Vita, 2002, Huhtala, 1999, Lusky, 1976, Smith, 1974). In this case we assume that there is another production process inside the economic system, transforming waste into a substitute input by using the refuse derived from exhaustible resources. We do not consider the possibility of transforming litter from reproducible natural input into secondary materials, because for this kind of input the main problem is to achieve their optimal harvest rate. Indeed, the environment has a greater capacity to absorb waste derived from renewable resources.

To produce the secondary material m it will be necessary to devote some labor time to the third sector of our economy l_3. In cases where waste recycling occurs the constraint on labor time will be $l_1 + l_2 + l_3 = 1$.

The Cobb-Douglas production function of secondary materials is

[16] $\quad m = f(e, l_3) = e^{\mu_1} l_3^{\mu_2}$, with $\mu_1 + \mu_2 = 1$,

that exhibits constant returns to scale. In continuous time we may overlook the temporal lag between extraction, use and recycling of the exhaustible resource, because the differences are not so important as for the flows in the previous period (Hoel, 1978). In particular, with regard to the process of transformation of refuse into input, the most relevant phenomenon in magnitude is the so-called "closed-loop" (i.e. the recycling of new scrap inside the production process). For example, pyro-processing R&D was part of the U.S. Integrated Fast Reactor development program, which proposed that a reprocessing and fuel-recycling plant be integrated into each reactor complex (van Hippel, 2001). This means that transformation of residuals into input has more and more frequently become another stage in the production process. In other words, recycling increases the effective long-term supplies of the resources that are being reused (Solow, 1974b, Tietenberg, 1992, Weinstein and Zeckhauser, 1974). Finally, it is worth noting that it is cheaper to recycle the current flow of waste than previously stored residuals.

The motion equation of waste stock becomes

[17] $\quad \dot{J} = d - m - \gamma J = (e + r) - e^{\mu_1} l_3^{\mu_2} - \gamma J$, where $J(0) = J_0$, and $J(t) \geq 0$,

where the accumulation of litter is reduced as an effect of the recycling process. It is interesting to note that if $l_3 = 0$, [17] is the same as [6]. Moreover, while the shadow price of waste is negative, because litter reduces the welfare level, the dynamic multiplier of secondary materials will be the same as that of an exhaustible resource, because in our model they are perfect substitutes of each other.

Under these new conditions and using the constraints expressed in equations [2] - [5], the suitable Hamiltonian expressed at current values is

[18] $$\aleph = \frac{c^{1-\theta} - 1}{1 - \theta} - \frac{J^{1+\omega} - 1}{1 + \omega} + \lambda_1 \left\{ \left[K^{\alpha_1} (A l_1)^{\alpha_2} (e + \psi r)^{\alpha_3} \right] - C \right\} + \lambda_2 [\xi l_2 A] - \lambda_3 e + \lambda_4 \left[\sigma \left(1 - \frac{R}{\pi} \right) R - r \right] - \lambda_5 \left[(e + r) - e^{\mu_1} l_3^{\mu_2} - \gamma J \right] + \lambda_6 (1 - l_1 - l_2 - l_3).$$

In this case few first order conditions change with respect to the case where waste recycling is not considered. In particular, $\partial \aleph / \partial e$ becomes

[19] $$\frac{\partial \aleph}{\partial e} = \frac{\lambda_1 \alpha_3 y}{e + \psi r} - \lambda_3 - \lambda_5 \left[1 - \mu_1 \frac{m}{e} \right] = 0,$$

and we have to consider the marginal productivity of labor employed in the third sector of our economy (i.e. secondary materials production).

[20] $$\frac{\partial \aleph}{\partial l_3} = \lambda_5 \mu_2 \frac{e^{\mu_1} l_3^{\mu_2}}{l_3} - \lambda_6 = 0.$$

The above equation is the standard first order condition for optimal employment of labor in transforming litter into substitute inputs. The other first order and dynamic conditions are the same as in the previous version of the model.

[19] is worthy of some comment, because the addend $\lambda_5 \mu_1 (m/e)$ represents the positive effects of waste recycling. It is none other than the value of the marginal productivity of refuse derived from exhaustible resources transformed into substitute input.

To understand the effect on the rate of extraction of exhaustible resources, of transforming refuse (from non-reproducible natural input) into secondary materials, we may use [19]; we calculate the partial derivative of e with respect to μ_1 (that is a coefficient that measures the productivity of non-replenishable input, in the process of transforming waste into secondary materials), to get

[21] $$\frac{\partial e}{\partial \mu_1} = -e \frac{\ln e}{\mu_1} < 0.$$

This means that an increase in the marginal productivity of waste recycling reduces the amount of exhaustible resources taken from the earth's crust.

Using $\partial \aleph / \partial r$, in cases where $\psi < 1$, and [19], after some little algebra we get

[22] $$\frac{\lambda_1 \alpha_3 y}{e + \psi r} (1 - \psi) + \lambda_5 \mu_1 \frac{m}{e} = \lambda_3 - \lambda_4.$$

The above equation implies that the two shadow prices will never be the same under the assumption $\psi < 1$, such that λ_3 will be always greater than λ_4. Where the first addend on the left side of the equation measures the loss of marginal productivity due to imperfect substitutability, the second addend accounts for the positive effects of waste recycling. In other words, the litter recovery process increases the difference between λ_3 and λ_4.

Putting in evidence λ_4 in [22] and calculating the partial derivative of the shadow price of renewable resources with respect to μ_1, we obtain

[23] $$\frac{\partial \lambda_4}{\partial \mu_1} = -\lambda_5 \mu_2 e^{\mu_1 - 1} (\ln e) \, l_3^{\mu_2} < 0,$$

such that we may affirm that a rise in productivity of the waste recycling activity allows us to reduce the price of r.

Starting from [19] , under the assumption for which $A = \dot{A}/l_2 \xi$, we may calculate the partial derivative of m with respect to ξ, to investigate the effects of an increase in the efficiency of knowledge accumulation on the process of transforming refuse into substitute inputs

[24] $$\frac{\partial m}{\partial \xi} = -\frac{\lambda_5 \frac{\mu_1}{e}}{(e + \psi r)^{\alpha_3 - 1} K^{\alpha_1} \left[\frac{A}{z}\right]^{\alpha_2 - 1} \alpha_2 \left[-\frac{A}{z^2}\right]} > 0.$$

Thus we may affirm that technological improvement allows us to increase the amount of secondary materials produced.

To examine how secondary materials production modifies the dynamics of the exhaustible resources' shadow price, we put in evidence λ_3 in [19] and substituting in $[A8]$, deriving with respect to μ_1, we obtain

$$[25] \qquad \frac{\partial \dot{\lambda}_3}{\partial \mu_1} = \delta \lambda_5 e^{\mu_1 - 1} l_3^{\mu_2} (1 + \ln e) > 0.$$

This means that waste recycling increases by λ_3 over time, such that this process sends the right message to the economic system, diminishing the opportunity cost of using renewable resources instead of non-replenishable ones.

To take into account the effects of secondary materials production upon the behaviour over time of the dynamic multiplier of r, we combine [19] with $\partial \aleph / \partial r$ in cases where $\psi < 1$; substituting in $[A9]$ and partially deriving with respect to μ_1 we obtain

$$[26] \qquad \frac{\partial \dot{\lambda}_4}{\partial \mu_1} = -\left[\delta \lambda_5 e^{\mu_1 - 1} l_3^{\mu_2} (1 + \ln e)\right] \left[\delta + \left(\frac{2\sigma R}{\tau} - \sigma + \rho\right)\right] < 0$$

This means that the production of secondary materials reduces the dynamics of the shadow prices of renewable natural resources.

Moreover, it is worth considering waste recycling in our analysis not only because this process increases the efficiency of exhaustible resource use (Weinstein and Zeckhauser, 1974), but also because it improves the standard of welfare. It is possible to ignore the refuse discharge problem as long as J has no major effects on social welfare, but when, as a result of an increase in income, the stock of scrap goes beyond a certain threshold level (i.e. $d > \gamma J$), we can affirm that accumulation creates a loss of utility, measured by λ_5; this is the negative shadow price of waste, and represents an externality cost of the use of both kinds of natural inputs considered in this model. Without an environmental policy, therefore, the dynamic multipliers of e and r will be higher than their optimal values, in cases where the externality is fully internalized. This is why the economic system is led to over-use both kinds of natural resources.

By means of $[A2]$, calculating the partial derivative of λ_5 with respect to α_3, we are able to show that the negative externality represented by waste discharged into the environment is increasing with natural resource use

$$[27] \qquad \frac{\partial \lambda_5}{\partial \alpha_3} = \frac{Y}{e + \psi r} \left[\lambda_1 + \alpha_3 \ln (e + \psi r)\right] > 0.$$

If no pollution abatement policy is adopted, growth increases consumption but also reduces welfare as a consequence of waste accumulation. The net result on the welfare level of those two opposite effects is not immediately evident: at the moment, by using $\partial \aleph / \partial e$ for $\psi < 1$ and $[A1]$, and knowing that $u_J = \lambda_5$ (derived from $\partial \aleph / \partial J = 0$), it is just possible to affirm that the marginal utility of consumption is sub-optimal high, because the negative effects of waste accumulation are not taken into account.[4]

[4]Note that at an individual level the utility function is $u(c)$, because consumption is rivalrous and excludible, while the negative effects of waste stock accumulation are a public bad, such that consumers do not take the latter into consideration in their decisions (for the difference between centralized and market choices in a similar environment, see Lusky, 1975).

[28] $$u_C = \frac{(\lambda_3 + \lambda_5)(e + \psi r)}{\alpha_3 y}$$

From the point of view of the benevolent social planner, it is necessary to follow some environmental policy to internalize the negative externality. Here we consider two possible instruments: waste recycling and Pigouvian taxes. In the following part of this section we shall deal with the first.

The best way to ensure that the optimal amount of waste is recycled is to make the marginal disutility of litter $\partial U/\partial J$ equal to the value of an increase in secondary materials production, due to the recycling of one more unit of refuse derived from the exhaustible resource $\lambda_5 \partial m/\partial e$. [5]

Remember that we have assumed secondary materials to be perfect substitutes of exhaustible resources, such that the condition regarding the optimal amount of waste recycled implies that the shadow price of exhaustible resource should be equal to its marginal productivity.

Calculating the first order condition of the Hamiltonian with respect to the waste stock, we get

[29] $$\partial\aleph/\partial J = -\gamma J^{\omega} + \gamma\lambda_5 = 0 \text{ or } J^{\omega} = \lambda_5,$$

where $u_J = -\gamma J^{\omega}$. Considering that $\lambda_5 \partial m/\partial e = \lambda_5 \mu_1 (m/e)$, using the condition for the optimal level of waste recycling $u_J = \lambda_5 \partial m/\partial e$, and rewriting [19] as

[30] $$\lambda_5 \left[1 - \mu_1 \frac{m}{e}\right] = \frac{\lambda_1 \alpha_3 y}{e + \psi r} - \lambda_3,$$

we observe that the optimal level of refuse recycled ensures that the value of the marginal productivity of exhaustible resources is equal to its own shadow price, thus fully internalizing the negative externality represented by refuse production. It is worth noting that the result above holds if and only if $\lambda_5 = 0$.

Now we are able to take into account the problem regarding the net effect of growth on welfare, by means of its net changes Δw

[31] $$\Delta w = \partial u/\partial c - \partial u/\partial J,$$

by using $\partial\aleph/\partial e$ for $\psi < 1$ and $[A1]$, and knowing that $u_J = \lambda_5$, without the waste recycling process, the result is

[32] $$\Delta w = \partial u/\partial c - \partial u/\partial J = \frac{\lambda_3 (e + \psi r)}{\alpha_3 y} + \lambda_5 \left[\frac{(e + \psi r)}{\alpha_3 y} - 1\right].$$

We may compare this with the net effects on welfare when secondary materials production is at its optimal level ΔW^*

[33] $$\Delta w^* = \frac{\lambda_3 (e + \psi r)}{\alpha_3 y}.$$

It is immediately clear that $\Delta w^* > \Delta w$, for $(e + \psi r)/\alpha_3 y < 1$ (this result comes from $\partial\aleph/\partial e$, when $\psi < 1$). In other words the optimal amount of waste recycling ensures the maximum level of welfare.

[5] In other words, $\lambda_5 (\partial m/\partial e)$ is none other than the value of the reduction in loss of total utility, in one more unit of waste not discharged into the environment.

3.4 Pigouvian Taxes as an Instrument to Achieve the Maximum Level of Welfare

As an alternative to the waste recycling process we may internalize the negative externality represented by litter accumulation by imposing a Pigouvian tax τ on both the shadow prices of natural resources. In cases of both perfect and imperfect technological substitutability between exhaustible and renewable resources, τ^* should be equal to λ_5, such that both shadow prices of natural inputs will be equal to their own marginal productivity and the negative externality upon the utility function wil be fully internalized. First of all we have to say something about cases in which waste recycling is used, because in this hypothesis we have levied a Pigouvian tax on the waste derived from replenishable resources. After this clarification, we may deal with the case in which the aim to internalize the negative externality is reached by resorting to Pigouvian tax. In the latter situation, using $[A2]$ and $[A3]$, the shadow prices of resources become

[34] $$\lambda_3 = \lambda_1 \alpha_3 \frac{y}{e+r},$$

and

[35] $$\lambda_4 = \lambda_1 \alpha_3 \frac{y}{e+r}.$$

When τ^* is levied on both prices of natural inputs, this ensures that the shadow prices of both natural resources considered will be equal to their marginal productivity; this is also true for $\psi < 1$.

To account for the effect of Pigouvian tax on the changes over time of λ_3 and λ_4 we may use $[A8]$ and $[A9]$ and substituting, respectively, for both dynamic multipliers $[A2]$ and $[A3]$, we get

[36] $$\dot{\lambda}_3 = \delta \frac{\lambda_1 \alpha_3 y}{e + \psi r},$$

and

[37] $$\dot{\lambda}_4 = \left[\frac{\psi \lambda_1 \alpha_3 y}{e + \psi r}\right] \left[\delta + \left(\frac{2\sigma R}{\tau} - \sigma + \rho\right)\right].$$

In this case there are no effects on the behavior over time of both shadow prices of natural inputs.

By means of [31] we may see that when a Pigouvian is levied, the net effect of growth on welfare, by means of net changes Δw^T,is

[38] $$\Delta w^T = \partial u/\partial c - \partial u/\partial J = \frac{\lambda_3 (e + \psi r)}{\alpha_3 y},$$

that is the same as in the case of waste recycling.

Now, what can we say about the question whether the mixed regime (waste recycling and Pigouvian tax) is better than the pure regime in which τ^* is levied on both prices of natural resources? From static first order conditions, it is just possible to say that the performances of the economy represented in our model are the same; no differences emerge. The problem is the dynamics. In cases where only Pigouvian tax is applied there are no effects on technology accumulation, and on the behavior during time of both prices of natural resources. The previous results regarding the dynamic effects of waste recycling could be questionable because referred to the single differential equation. Thus it could be interesting to make a sensitivity analysis on the Hamiltonian as a whole to derive more general insights.

3.5 A Comparison Between Waste Recycling and Pigouvian Taxes (Sensitivity Analysis)

In section 3.3 we were dealing with a model in which waste recycling was considered: we may conclude that this process off-sets the constraint to growth represented by exhaustible resources and reduces the environmental burden. On the other hand, we know that to produce secondary materials we have to divert the labor force from other sectors to recycling, and also that we may internalize the externality represented by the sub-optimal accumulation of waste by introducing a Pigouvian tax. To make a comparison between the mixed regime and that in which we use only a fiscal measure, we make a sensitivity analysis on the Hamiltonian as a whole (Kamien and Schwartz, 1991, Malanowski, 1984, Seierstad and Sydæter, 1997), calculating its partial derivative with respect to a parameter, representing an improvement in the waste recycling process, or the Pigouvian tax, respectively. Here we are interested just in a quality analysis because there are too many variables and parameters to make a numerical calculus. Using $\aleph$ from [19] and calculating its partial derivative at the optimal level $\aleph^*$ with respect to μ_1, we obtain

$$[39] \qquad \frac{\partial \aleph^*}{\partial \mu_1} = \lambda_5^* e^{*\mu_1} (\ln e^*) \, l_3^{*\mu_2} > 0.$$

This means that an improvement in the secondary materials production process increases the value $\aleph^*$, that is none other than the constrained optimal welfare level (for an economic interpretation of the Hamiltonian see Dorfman, 1969).

In the Hamiltonian there is no parameter accounting for a change in Pigouvian tax, thus we may substitute τ in [19] for λ_5 when $l_3 = 0$ (i.e. no waste recycling occurs), and calculating the partial derivative, the result is

$$[40] \qquad \frac{\partial \aleph^*}{\partial \tau} = -\left[(e^* + r^*) - \gamma J^*\right] < 0.$$

In this case it is evident that an increase in Pigouvian tax reduces the value of $\aleph^*$, such that efficient management of refuse shows a better outcome in dynamics than τ. This result confirms our findings in the previous paragraph.

4 Final Remarks

Few words are necessary to conclude our paper. In cases of imperfect substitutability between exhaustible and renewable resources the economy shows a worse performance than in cases where it is possible to use one natural input instead of another indifferently in the production function. Technological progress allows us to off-set the constraint to growth represented by exhaustible resources by means of four different channels: firstly, by improving substitutability between the resources; secondly, by reducing the amount of exhaustible natural input drawn from the earth's crust; thirdly, by increasing the amount of secondary materials that we are able to produce; fourthly, by sending the right message to the system regarding the behavior over time of the prices of both kinds of natural resource. Finally, the waste recycling process permits us to achieve two results at the same time: to improve the marginal productivity of exhaustible resources and to internalize fully the negative externality represented by waste stock accumulation. Using the first order conditions, the same results are shown by the economy in both regimes, secondary materials production and pure Pigouvian tax, but in the dynamics the former environmental policy ensures greater positive effects on the constrained optimal level of welfare.

These are the results of our theoretical framework; at the moment no empirical analyses have been carried out on this issue. We think that it could be a good topic for further applied studies.

Appendix

A. First Order and Transversality Conditions

The first order conditions are

[A1] $$\frac{\partial \aleph}{\partial c} = c^{-\theta} - \lambda_1 = 0, \text{ or } \lambda_1 = c^{-\theta},$$

[A2] $$\frac{\partial \aleph}{\partial e} = \lambda_1 \alpha_3 \frac{y}{e+r} - \lambda_3 - \lambda_5 = 0, \text{ or } \lambda_3 = \lambda_1 \alpha_3 \frac{y}{e+r} - \lambda_5,$$

[A3] $$\frac{\partial \aleph}{\partial r} = \lambda_1 \alpha_3 \frac{y}{e+r} - \lambda_4 - \lambda_5 = 0, \text{ or } \lambda_4 = \lambda_1 \alpha_3 \frac{y}{e+r} - \lambda_5,$$

[A4] $$\frac{\partial \aleph}{\partial l_1} = \alpha_2 \lambda_1 \frac{y}{l_1} - \lambda_6 = 0, \text{ or } \lambda_6 = \alpha_2 \lambda_1 \frac{y}{l_1},$$

[A5] $$\frac{\partial \aleph}{\partial l_2} = \lambda_2 \xi A - \lambda_6 = 0, \text{ or } \lambda_6 = \lambda_2 \xi A,$$

[A6] $$\dot{\lambda}_1 = \delta \lambda_1 - \frac{\partial \aleph}{\partial K} = \delta \lambda_1 - \lambda_1 \alpha_1 \frac{y}{K},$$

[A7] $$\dot{\lambda}_2 = \delta \lambda_2 - \frac{\partial \aleph}{\partial A} = \delta \lambda_2 - \lambda_1 \alpha_2 \frac{y}{A} - \lambda_2 \xi l_2,$$

[A8] $$\dot{\lambda}_3 = \delta \lambda_3 - \frac{\partial \aleph}{\partial E} = \delta \lambda_3,$$

[A9] $$\dot{\lambda}_4 = \delta \lambda_4 - \frac{\partial \aleph}{\partial R} = \delta \lambda_4 + \lambda_4 \left(\frac{2\sigma R}{\pi} - \sigma + \rho \right),$$

[A10] $\dot{\lambda}_5 = \delta\lambda_5 - \frac{\partial\aleph}{\partial J} = \delta\lambda_5 + J^{\omega} - \gamma\lambda_5.$

The growth rates of the dynamic multiplier are

[A11] $g_{\lambda_1} = \frac{\dot{\lambda}_1}{\lambda_1} = \delta - \alpha_1 \frac{y}{K},$

[A12] $g_{\lambda_2} = \frac{\dot{\lambda}_2}{\lambda_2} = \delta - \lambda_1 \alpha_2 \frac{y}{\lambda_2 A} - \xi l_2,$

[A13] $g_{\lambda_3} = \frac{\dot{\lambda}_3}{\lambda_3} = \delta,$

[A14] $g_{\lambda_4} = \frac{\dot{\lambda}_4}{\lambda_4} = \delta + \frac{\sigma 2R}{\pi} - \sigma + \rho,$

[A15] $g_{\lambda_5} = \frac{\dot{\lambda}_5}{\lambda_5} = \delta + \frac{\gamma J^{\omega}}{\lambda_5} - \gamma.$

Differentiating equations [$A1$], [$A4$] and [$A5$] logarithmically, the results will be

[A16] $g_{\lambda_1} = g_{u_c},$

[A17] $g_{\lambda_6} = g_{\lambda_1} + g_y,$

[A18] $g_{\lambda_6} = g_{\lambda_2} + g_A.$

Using [$A2$] and [$A3$], deriving logarithmically, we may also write

[A19] $g_{\lambda_3} = g_{\lambda_4}.$

The transversality conditions are

[A20] $\lim_{t\to\infty} e^{-\delta t} \aleph(t) = 0,$

[A21] $\lim_{t\to\infty} \left[e^{-\delta t} \lambda_1(t) K(t)\right] = 0,$

[A22] $\lim_{t\to\infty} \left[e^{-\delta t} \lambda_2(t) h(t)\right] = 0,$

[A23] $\lim_{t\to\infty} \left[e^{-\delta t} \lambda_3(t) E(t)\right] = 0,$

[A24] $\lim_{t\to\infty} \left[e^{-\delta t} \lambda_4(t) R(t)\right] = 0,$

[A25] $\lim_{t\to\infty} \left[e^{-\delta t} \lambda_5(t) J(t)\right] = 0.$

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(lix) This paper was presented at the ENGIME Workshop on “Mapping Diversity”, Leuven, May 16-17, 2002

(lx) This paper was presented at the EuroConference on “Auctions and Market Design: Theory, Evidence and Applications”, organised by the Fondazione Eni Enrico Mattei, Milan, September 26-28, 2002

(lxi) This paper was presented at the Eighth Meeting of the Coalition Theory Network organised by the GREQAM, Aix-en-Provence, France, January 24-25, 2003

(lxii) This paper was presented at the ENGIME Workshop on “Communication across Cultures in Multicultural Cities”, The Hague, November 7-8, 2002

(lxiii) This paper was presented at the ENGIME Workshop on “Social dynamics and conflicts in multicultural cities”, Milan, March 20-21, 2003

(lxiv) This paper was presented at the International Conference on “Theoretical Topics in Ecological Economics”, organised by the Abdus Salam International Centre for Theoretical Physics - ICTP, the Beijer International Institute of Ecological Economics, and Fondazione Eni Enrico Mattei – FEEM Trieste, February 10-21, 2003

(lxv) This paper was presented at the EuroConference on “Auctions and Market Design: Theory, Evidence and Applications” organised by Fondazione Eni Enrico Mattei and sponsored by the EU, Milan, September 25-27, 2003

(lxvi) This paper has been presented at the 4th BioEcon Workshop on “Economic Analysis of Policies for Biodiversity Conservation” organised on behalf of the BIOECON Network by Fondazione Eni Enrico Mattei, Venice International University (VIU) and University College London (UCL) , Venice, August 28-29, 2003

(lxvii) This paper has been presented at the international conference on “Tourism and Sustainable Economic Development – Macro and Micro Economic Issues” jointly organised by CRENoS (Università di Cagliari e Sassari, Italy) and Fondazione Eni Enrico Mattei, and supported by the World Bank, Sardinia, September 19-20, 2003

(lxviii) This paper was presented at the ENGIME Workshop on “Governance and Policies in Multicultural Cities”, Rome, June 5-6, 2003

(lxix) This paper was presented at the Fourth EEP Plenary Workshop and EEP Conference “The Future of Climate Policy”, Cagliari, Italy, 27-28 March 2003

(lxx) This paper was presented at the 9th Coalition Theory Workshop on "Collective Decisions and Institutional Design" organised by the Universitat Autònoma de Barcelona and held in Barcelona, Spain, January 30-31, 2004

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