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Renewable Resources and Waste Recycling

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NRM – Natural Resources Management

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SUMMARY

In this paper we consider an endogenous growth model in which, among other inputs, we consider a renewable resource and secondary materials. Using this analytical framework we explain the effects of waste recycling on the growth rate of the economy, that we take into account. The effects of secondary materials production on the utility and dynamics of renewable resources are also studied. Furthermore, we consider how the tax and subsidy, levied on natural resource and secondary materials respectively, influence the dynamics of economy during the transitional phase and the stationary growth path. Finally, the validity of Hotelling's rule and the effects of waste recycling on labor productivity are the conclusive topics of our research.

Keywords: Endogenous growth, renewable resources, secondary materials, waste recycling

JEL: O41, Q20

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1 Introduction

In the last decade there has been a widespread opinion that waste management is one of the main problems of environmental economics (Faucheux and O´Connor 1998, Huhtala, 1999). At the beginning the latter issue was studied jointly with behavior of consumers, firms and local public authorities. It was seen like a spatial circumscribed problem of limited relevance, with no consequences for the economy as a whole. The abundance of natural resources for productive aims, and landfill areas for waste disposal purposes, reinforced this wisdom. These considerations can be justified because the first papers regarding this issue consider it from a microeconomic point of view (Hoel, 1978, Keeler *et al.,* 1971, Lusky, 1976, Smith, 1972). More in general we can say that in the seventies there was the general belief that waste management should be considered with a disaggregated approach. Recently, two facts have been observed with regard to the problem that we are handling. Waste production is increasing in the world as a whole. Recycling may influence the macroeconomic figures of the economy. Those arguments could explain why some economic institutions begin to consider this topic in the perspective of the economic system (EPA, 1998, OCDE, 1995, WTO, 1999). The recent interest that economic literature has devoted to the aggregate effects of waste recycling may be justified with several considerations. The increasing needs of the world population raises, at the same time, the demand for natural resources and the quantity of waste produced, suggesting the opportunity to use more renewable inputs and secondary materials, to move towards more sustainable environmental behavior, through the saving of exhaustible resources. On the other hand, the use of waste recycling as a pollution abatement technology allows us to alleviate the pressure on natural resources and, more in general, on the environment. Finally, waste recycling can help us to reduce the damage caused by the harvest and extraction of inputs from the earth's crust, diminishing the quantity of waste discharged into the environment and saving energy (Huhtala, 1999).

The growing economic interest in this topic has prompted more research that considers secondary materials production in a macroeconomic analysis, in static and dynamic frameworks, with regard to the domestic and international aspects of this phenomenon (Beukering, 2001, Beukering, *et al.* 2000, Copeland, 1991, Di Vita, 2001a, 2001b, 1997, Grace *et al.*, 1978, Huhtala, 1999, McKee, 1996, Rich *et al.*, 1999).

In literature there are many articles that study the environment using an endogenous growth framework, but there are just a few that consider natural resource and waste recycling together (Di Vita, 2001a, 2001b). In particular, they consider just the exhaustible resources, but not the replenishable ones.

Huhtala (1999) studies a similar problem, in a dynamic framework, but in her paper there are no implications about the growth path of economy and other macroeconomic figures.

To investigate the long-run links between renewable resources and waste recycling we built an endogenous growth model. The latter consists of three sectors. The first is devoted to producing final output, the second regards the

accumulation of human capital and the last is the waste recycling industry. A standard Cobb-Douglas production function is considered, with constant returns to scale, in which five inputs are taken into account. The law motion of capital depends on the difference between total output and consumption, while the human capital accumulation is similar to that in Lucas (1988). The dynamics of renewable resource is given by a natural reproductive function, less harvest flow. The sector of secondary material production depends on the quantity of labor allotted to this aim, and the amount of flow and stock of waste. The renewable resource and secondary materials are considered as perfect substitutes of each other, but the case in which they are imperfect could also be considered (for a similar problem, regarding exhaustible resources, see Di Vita, 2001b). The fixed labor time, not employed in human capital accumulation, is allocated between total output and secondary materials production. The utility function is additively separable in consumption and waste stock, as in Keeler *et al.* (1971).

Using the welfare function that we want to maximize, under the constraints considered, we obtain our Hamiltonian and thus derive the first order conditions.

Our theoretical framework allows us to consider the effects of waste recycling on the growth rate of economy and the impact of secondary materials production on utility. Under the assumption that renewable resource and secondary materials are perfect substitutes in the production function, we will show what happens if waste recycling or the price of secondary materials changes. The paper continues considering the effects of tax and subsidy on the prices of natural resources and secondary materials respectively, on the utility function, during transitional dynamics and in the stationary growth path. The validity of Hotelling's rule, with regard to the renewable resource and recycled waste, is then examined. Finally, we take a look at the relationship existing between the marginal productivity of labor and secondary material production. We conclude our work with summary remarks.

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 showing the main results of our study. Conclusive remarks and implications for environmental political economy are the contents of last section.

We confine the mathematical details and some proofs of propositions to the appendix.

2 The model

The final output Y is a function of five inputs: physical capital K, human capital h, total workers L (in our model it is constant), renewable resource E, and flow of recycled waste M ('secondary materials').

The assumptions regarding human capital accumulation are like in Lucas (1988, p. 17). Here we also suppose that L and h have elasticity of substitution equal to unity. v is the labor time not destined to human capital formation.

In the specification of the production function, we assume that renewable resource and secondary materials are perfect substitutes.

[1] $Y = f(K, h, L, E, M) = K^{\alpha_1} (hL\omega_1 v)^{\alpha_2} (E + M)^{\alpha_3}, \quad \sum_{i=1}^{3} \alpha_i = 1.$

where $0 < \omega_1 \leq 1$, is the amount of v devoted to total output production. The investment in physical capital is like in

[2] $\dot{K} = Y - C$, where $K(0) = K_0$ and $K(t) \geq 0$.

We assume that there is no depreciation in physical capital. Aggregate consumption is denoted by $C = xY$, with $0 < x < 1$. Per capita consumption is represented by $c = C/L$. Aggregate saving is $S = sY = \dot{K}$, where $0 \leq s < 1$, and $s = (1 - x)$.

[3] $\dot{h} = B(1 - v)h$, where $B > 0$, $h(0) = h_0$, and $h(t) \geq 0$.

[3] is the law of motion of the per capita human capital stock (it is like equation (13) in Lucas, 1988).

[4] $\dot{R} = f(R) - rR = \sigma \left(1 - \frac{R}{\tau}\right) R - E$, where $R(0) = R_0$, $R(t) \geq 0$.

Equation [4] expresses the dynamics of renewable resource stock. We assume that $f(R)$ is the growth function, with properties $f(R) \geq 0$, for $0 \leq R \leq \tau$, $f'(R) > 0$ for $0 \leq R \leq \bar{R}$, $f'(\bar{R}) = 0$ and $f'(R) < 0$ for $\bar{R} \leq R \leq \tau$, where $\bar{R}$ is the maximum sustainable yield stock level of our renewable resource, and τ is the ecological carrying capacity (Hanley *et al.*, 1997, Li and Löfgren, 2000). We denote with σ the intrinsic growth rate of renewable resource, while E, equal to rR, is the harvest flow of renewable resource, r being the renewable resource rate of use (where $0 \leq r \leq 1$). The assumption with regard to the first derivative of the natural production function $f'(R)$, is justified by the fact that this kind of resource has some maximum 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).

[5] $\dot{J} = \gamma D - M$, $J(0) = J_0$, $J(t) \geq 0$ and $0 \leq \gamma < 1$.

The waste stock J moves during time according to [5]. It depends on the waste flow D, secondary material production and the assimilative capacity of waste of the environment, denoted by $\gamma > 0$. We assume that the waste flow $D = zY$ $(0 < z \leq 1)$, is a constant fraction of total output (see Cassing and Kuhn, 2001, and Conrad, 1999).

[6] $M = n\omega_2 v(D + J)$, and $M \gtreqless D$.

The secondary materials production function is expressed by [6] in which we consider that the amount of M produced depends on $0 < \omega_2 \leq 1$, the fraction of v used in this activity. We suppose that $\omega_1 + \omega_2 = 1$, i.e. the labor time not utilized in human capital formation is allocated between total output and secondary materials production. n is a strictly positive parameter of productivity. The inputs to the waste recycling industry could be the flow

of waste D as well the stock J. This functional form for secondary materials production allows us to reduce the waste stock of economy, if during transitional dynamics it is greater than its optimal value.

The utility depends on the flow of consumption c and the stock of waste J. The utility function is

$$[7] \quad u = u(c, J),$$

it is additively separable, such that $u_{cJ} = 0$, and has continuous first and second partial derivatives, with $u_c > 0$, $u_J < 0$, $u_{cc} < 0$, $u_{JJ} < 0$. It is assumed that for $c \to 0$, $u_c \to +\infty$, and $u_{\bar{J}} = 0$ (Keeler *et al.*, 1971).[2]

The total welfare W associated with any particular time path for c and J comes from summing the discounted flow, at rate $\delta > 0$. The social welfare is

$$[8] \quad W = \int_0^{\infty} u(c, J) L e^{-\delta t} dt,$$

we assume that live agents in our economy consider, in their decisions of consumption and production, the welfare and resources availability of their present or prospective descendants.

In formal terms we want to maximize [8], subject to [1] - [5]. The current-value Hamiltonian for the problem is

$$[9] \quad \aleph = u(c, J) L + \lambda_1 \left\{ \left[K^{\alpha_1} (hL\omega_1 v)^{\alpha_2} (E + M)^{\alpha_3} \right] - C \right\} + \lambda_2 \left[B(1 - v) h \right] + \lambda_3 \left[\sigma \left(1 - \frac{R}{\tau} \right) R - E \right] + \lambda_4 (\gamma D - M).$$

Where λ_i, $i = 1, 2, 3, 4$, are the current-value Lagrange multipliers.

We report the first order and transversality conditions in appendix A. They are necessary and sufficient for the optimal control problem. The proof that the model describes a stable saddle point equilibrium path is given in appendix B.

3 Model Results

The first order conditions that we derived allow us to highlight a lot of theoretical issues. For example the effects of waste recycling on the growth rate of economy and utility. Moreover, we can study how the dynamics of natural resources change if secondary materials, and the effects of taxation on natural resources, are taken into account. Finally, we show how the labor productivity and Hotelling's rule are influenced by the waste recycling process.

Further, we follow the same order.

The main question is if the growth rate of economy that we depicted in our model is greater in the case in which waste recycling is considered or not. In this case the *a priori* information is the existence of a trade-off if we consider secondary materials production, because in this hypothesis there is a part of

[2] Here $\bar{J}$ is the value that waste stock assumes in the optimal stationary growth path. In this case the first derivative will be zero, because there is no possibility to increase the welfare, by means of a change in J.

labor time that we use in the waste recycling industry and not in the total output sector.

PROPOSITION 1: *Given the values of parameters, assuming* $g_M \neq 0$, *the growth rate of total output is greater in cases in which secondary materials are considered.*

PROOF. See Appendix C.

Therefore, if we have two economies with the same parameters, including labor time devoted to human capital accumulation, then in cases in which waste recycling is taken into account, the growth rate of economy will be greater than in the other.

There are several reasons for this. Essentially, we should consider that there is a positive macroeconomic externality that emerges from the waste recycling process. To understand this, consider that without this activity there is some positive fraction of total labor, not devoted to human capital accumulation of final output production, that we use to collect and discharge waste. If we now imagine that we use the same amount of labor time to get the same result, but besides we also obtain secondary materials, that increase the output availability of our economy, then this result holds (for similar outcomes, in a static environment, see Beukering and Randall, 1998, Di Vita, 1997, Rich *et al.*, 1999).

This positive macroeconomic externality is alone good enough to justify our result, but we can make some further considerations. If we recycle more waste, we diminish the risk of overexploiting the natural resources, bringing the system towards a sustainable path.

In the model we made some assumptions with regard to the effects of waste stock on the utility function, but it is not immediately clear how the marginal disutility of waste stock changes, as a consequence of secondary material production.

PROPOSITION 2: *The marginal disutility of waste stock* u_J *falls as a consequence of secondary materials production.*

PROOF. Using equations $[A8]$ and $[A4]$, and differentiating u_J with respect to M, it follows directly that $\partial u_J/\partial M = -\lambda_1 \alpha_3 Y/\left(E+M\right)^2 L < 0$.■

The intuition behind this outcome is simple. An increase in the quantity of secondary materials produced reduces the stock of waste in the economy that we are considering, such that the marginal disutility of J decreases. The latter is a direct effect, but there is also an indirect one. Whenever we use more secondary materials to produce the goods consumed, this implies a reduction of the negative externality on the environment associated with products that are natural resource intensive, in terms of derivative demand for environmental services, like natural resources and landfill areas to discharge the waste.

Another issue that is worth considering, is the effect of waste recycling on the dynamics of renewable natural resource.

PROPOSITION 3: *An increase of secondary materials production raises the accumulation of renewable resources stock, while a growth in the shadow price of secondary materials reduces the accrue of renewable resources stock.*

PROOF. Putting in evidence E in equation $[A4]$ and substituting in $[4]$, we can calculate the partial derivative of $\dot{R}$ with respect to M and λ_4, to get $\partial\dot{R}/\partial M = 1 > 0$ and $\partial\dot{R}/\partial\lambda_4 = -\lambda_1\alpha_3 Y/\lambda_4^2 < 0$, such that our result holds.■

The first result is intuitive. If we can use more secondary materials, this allows us to reduce the harvest of natural resource. In particular, we can note that $\partial\dot{R}/\partial M = 1$, this means that for an additional unit of secondary materials produced, this allows us to raise the stock of renewable resource by the same amount. It is evident that this result comes only in cases where first and secondary inputs are perfect substitutes for each other, as we assume in our model. On the other hand, a change in the price of secondary materials causes income and substitution effects, that work in the same direction (inferior inputs are not considered here). This way if the price of secondary materials increases, those two effects work to reduce the demand for this input, and vice versa if λ_4 decreases.

We can reproduce the equilibrium path of natural renewable resources and its shadow price in a phase diagram. To this aim we use the equations

$$[4] \quad \dot{R} = \sigma\left(1 - \frac{R}{\tau}\right)R - rR,$$

and

$$[A7] \quad \dot{\lambda}_3 = \delta\lambda_3 - \lambda_3\left[\sigma\left(1 - \frac{2R}{\tau}\right) - r\right].$$

The phase diagram path is drawn below in figure 1, in a (R, λ_3) space.

Figure 1 about here

Letting $\dot{R} = 0$ and $\dot{\lambda}_3 = 0$, we have a system of two equations in two unknown (R, λ_3), that we can solve mathematically. Doing this we get two couples of equilibrium values for natural renewable resource stock and its shadow price, namely $(R^* = \lambda_3^* = 0)$ and $(R^* = \tau - r\tau/\sigma;\ \lambda_3^* = (\delta - 1)\left[\sigma\left(\tau - 2\right) + r\left(1 - \tau\right)\right]/\tau)$. In the first case, if the stock of natural resource that we are considering is zero, its price will be the same. In the other case, for a positive stock of natural resource, $R = \tau - r\tau/\sigma$, the shadow price will be greater than zero, for a social discount rate higher than 1.

We can form the Jacobian matrix to find that the eigenvalues of determinant have opposite signs and the trace of determinant is positive; this implies that we have a locally stable saddle point equilibrium (more analytical details are given in Appendix D).

The phase diagram confirms the analytical findings because we have a saddle path equilibrium. There are two regions in which the system does not converge to its equilibrium (or is unstable). This happens when a low level of resource stock is associated with a shadow price of renewable resource higher than its equilibrium value. In this case too much resource will be harvested such that it will be overexploited, until it is exhausted. Another region in which the system

shows unstable dynamics is that in which the stock of natural resource is higher than its optimal value and the shadow price is lower than its equilibrium. This means that the demand for natural resource is too low and the system does not converge to its stationary growth path.

To analyze how the equilibrium changes as a consequence of waste recycling, we can use equation $[A4]$ and substitute in [4] for E, such that we can write

$$[4'] \qquad \dot{R} = \sigma \left(1 - \frac{R}{\tau}\right) R - \frac{\lambda_1 \alpha_3 Y}{\lambda_4} + M.$$

In this way it is clear that there is a positive correlation between secondary materials production and the change, during time, of natural resource stock; in our diagram we therefore obtain a more concave curve for locus $\dot{R} = 0$, such that the price of natural resources will be lower than without secondary materials production and the optimal stock of natural resource will be higher.

One aspect that has been neglected in previous literature on endogenous growth models with renewable natural resources, is to how the results of the model change if the policy maker levies a tax on virgin ores or subsidizes secondary materials production. We can analyze this kind of problem in two different environments, in transitional dynamics or in the stationary growth path. It is more interesting to consider what happens in the first case, because during transitional dynamics there is no reason why the first and secondary inputs should have the same price. To this aim, we can use the first order conditions reported in appendix A; in particular, considering the equations $[A3]$ and $[A1]$, deriving u_c with respect to the total output, we get

$$[10] \qquad \frac{\partial u_c}{\partial Y} = -\frac{\lambda_3 (E + M)}{\alpha_3 Y^2},$$

such that we can say, in the case of a tax on a renewable natural resource (that increases λ_3), the marginal utility of consumption will be lower than without taxation. If however we consider equations $[A4]$ and $[A1]$ and take the partial derivative of u_c with respect to Y, the result is

$$[11] \qquad \frac{\partial u_c}{\partial Y} = -\frac{\lambda_4 (E + M)}{\alpha_3 Y^2},$$

for which if we are given a subsidy on secondary materials price (such that λ_4 decreases), this implies that the marginal utility of consumption will be higher than without subsidy. These two simple observations allow us to say that, during transitional dynamics, the effects of taxes and subsidy imposed on renewable natural resource and secondary materials respectively, will have asymmetric effects on the marginal utility of consumption. These two measures have the same direct effect to push the firms to use more secondary materials and less natural resources, but the indirect effects are radically different, because in the first case we reduce the marginal utility of consumption and in the second case we raise it.[3]

[3] Huthala (1999) considers the same problem in a different theoretical framework, concluding that the subsidy and taxes have asymmetric effects.

We can also consider the effects of a subsidy on secondary materials, on the natural resource stock, during transitional dynamics, using equations [$A11$] and [$A12$], such that putting in evidence R, and taking the partial derivative with respect to the price of M, we obtain

$$[12] \qquad \frac{\partial R}{\partial \lambda_4} = \frac{u_J L}{\lambda_4^2} \frac{\tau}{2\sigma}.$$

To interpret this result it is worth remembering that $u_J < 0$. In this way it is evident that a subsidy given on secondary materials raises the renewable natural resource stock.

In the stationary growth path we know that, under the hypothesis of perfect substitutability between natural resource and secondary materials, the two shadow prices should converge to an identical value, such that the effects of one measure or another will be the same, because taxes and subsidy levied on renewable resources and secondary materials respectively increase or reduce both prices by the same amount. There is thus no sense in further considering the effects of tax and subsidy in the long-run equilibrium.

There is another interesting issue that we can also investigate, namely the validity of Hotelling's rule for renewable natural resource and secondary materials, along the stationary growth path of economy that we are considering.

PROPOSITION 4: *Along the optimal stationary growth path, the growth rate of shadow prices of renewable resources and secondary materials are both equal to the social discount rate.*

PROOF. Using [$A11$] we can say that $g_{\lambda_3} = \delta$, if and only if $\sigma = r$. Substituting in [$A11$] to R, its possible equilibrium values $(0; \tau - r\tau/\sigma)$ this result holds. From equation [$A12$] it is immediately possible to conclude, if $u_{\bar{J}} = 0$, that $g_{\lambda_4} = \delta$.■

This means that Hotelling's rule is satisfied for both inputs considered here (for a discussion of this issue with regard to renewable resources, see Neher, 1990, p. 178).

The result that $g_{\lambda_3} = \delta$ means that, in the long-run equilibrium, the growth rate of renewable natural resource stock, given by $\sigma(1 - 2R/\tau)$, should be equal to the renewable resource rate of use r. This implies that in the stationary growth path the renewable resource achieves its maximum sustainable level, because the same amount of resources produced will be harvested. The outcome for which $g_{\lambda_4} = \delta$ confirms that in the steady state, the waste stock is at its optimal level, such that it is not possible to increase secondary materials production.

In economic literature there is a considerable line of thought that points out the effects of environmental quality on labor productivity (see, recently, Williams, 2000). From this point of view, it could be interesting to consider how a pollution abatement technology, in the form of secondary materials production, influences labor productivity. To this aim we can use [1], to get

$$[13] \qquad \frac{\partial Y}{\partial \omega_1} = \alpha_2 \frac{Y}{\omega_1}.$$

Using $[A4]$ we can substitute in [13], the equilibrium value of total output, to obtain

$$[14] \qquad \frac{\partial Y}{\partial \omega_1} = \alpha_2 \frac{\lambda_4 (E + M)}{\alpha_3 \lambda_1 \omega_1},$$

thus we can derive [14] with respect to M, getting

$$[15] \qquad \frac{\partial Y}{\partial \omega_1 \partial M} = \alpha_2 \frac{\lambda_4}{\alpha_3 \lambda_1 \omega_1} > 0.$$

This result implies two things: i) that from a production function point of view the two inputs are complementary (Mosak, 1938); ii) that a reduction of waste discharged into the environment, by means of secondary materials production, increases the marginal productivity of labor.

4 Final Remarks

What can we say about waste recycling, from a macroeoconomic point of view? There are a lot of positive effects that this process has on the economy as a whole. In particular, we have shown that the growth rate of total output will be higher in countries that recycle waste than in others. The marginal utility of consumption increases if we produce more secondary materials. The latter production allows us to reduce the harvest of renewable natural resources, driving the economic system towards more sustainable paths. Tax or subsidy, levied on renewable natural resource and secondary materials respectively, will have an asymmetric effect on the marginal utility of consumption, pushing to recycle more waste. Finally, labor productivity increases as a consequence of a more clean environment.

Our findings are not fully known in economic literature. There is just a little stream of economic theory that considers the effects of waste recycling on the growth rate of total output (see, for example, Di Vita, 2001a, 2001b, 1997, Rich *et al.*, 1999), but many problems considered here have been neglected in previous studies. The clear implication for the policy maker is the opportunity to support the waste recycling process, to bring the economic system towards a higher welfare level.

Now the question is: Are the real economies as effective as we have supposed in our model? To answer this question we need more statistical information than is available at the moment. Empirical studies are necessary to verify the ability of our model to give a good representation of the real world and for prediction purposes. We think that this could be an argument for further interesting research.

Appendix

A. First Order and Transversality Conditions

The first order conditions are

$$[A1] \quad \frac{\partial \aleph}{\partial c} = u_c L - \lambda_1 L = 0, \text{ or } \lambda_1 = u_c,$$

$$[A2] \quad \frac{\partial \aleph}{\partial v} = \lambda_1 \alpha_2 \frac{Y}{v} - \lambda_2 Bh = 0, \text{ or } \lambda_2 = \frac{\lambda_1 \alpha_2 Y}{vBh},$$

$$[A3] \quad \frac{\partial \aleph}{\partial E} = \lambda_1 \alpha_3 \frac{Y}{E+M} - \lambda_3 = 0, \; \lambda_3 = \lambda_1 \alpha_3 \frac{Y}{E+M},$$

$$[A4] \quad \frac{\partial \aleph}{\partial M} = \lambda_1 \alpha_4 \frac{Y}{E+M} - \lambda_4 = 0, \; \lambda_4 = \lambda_1 \alpha_3 \frac{Y}{E+M},$$

$$[A5] \quad \dot{\lambda}_1 = \delta \lambda_1 - \frac{\partial \aleph}{\partial K} = \delta \lambda_1 - \lambda_1 \alpha_1 \frac{Y}{K},$$

$$[A6] \quad \dot{\lambda}_2 = \delta \lambda_2 - \frac{\partial \aleph}{\partial h} = \delta \lambda_2 - \lambda_1 \alpha_2 \frac{Y}{h} - \lambda_2 \left[B \left(1 - v \right) \right],$$

$$[A7] \quad \dot{\lambda}_3 = \delta \lambda_3 - \frac{\partial \aleph}{\partial R} = \delta \lambda_3 - \lambda_3 \left[\sigma \left(1 - \frac{2R}{\tau} \right) - r \right],$$

$$[A8] \quad \dot{\lambda}_4 = \delta \lambda_4 - \frac{\partial \aleph}{\partial J} = \delta \lambda_4 - u_J L.$$

The growth rates of dynamic multiplier are

$$[A9] \quad g_{\lambda_1} = \frac{\dot{\lambda}_1}{\lambda_1} = \delta - \alpha_1 \frac{Y}{K},$$

$$[A10] \quad g_{\lambda_2} = \frac{\dot{\lambda}_2}{\lambda_2} = \delta - \alpha_2 \frac{\lambda_1 Y}{\lambda_2 h} - B \left(1 - v \right),$$

$$[A11] \quad g_{\lambda_3} = \frac{\dot{\lambda}_3}{\lambda_3} = \delta - \left[\sigma \left(1 - \frac{2R}{\tau} \right) - r \right],$$

$$[A12] \quad g_{\lambda_4} = \frac{\dot{\lambda}_4}{\lambda_4} = \delta - \frac{u_J L}{\lambda_4}.$$

Differentiating the equations $[A1] - [A4]$ logarithmically, the result will be

$$[A13] \quad g_{\lambda_1} = g_{u_c},$$

$$[A14] \quad g_{\lambda_2} = g_{\lambda_1} + g_Y - g_h,$$

$$[A15] \quad g_{\lambda_3} = g_{\lambda_1} + g_Y - g_{E+M},$$

$$[A16] \quad g_{\lambda_4} = g_{\lambda_1} + g_Y - g_{E+M}.$$

The transversality conditions are

$$[A17] \quad \lim_{t\to\infty} e^{-\delta t}\aleph(t) = 0,$$

$$[A18] \quad \lim_{t\to\infty} \left[e^{-\delta t}\lambda_1(t) K(t)\right] = 0,$$

$$[A19] \quad \lim_{t\to\infty} \left[e^{-\delta t}\lambda_2(t) h(t)\right] = 0,$$

$$[A20] \quad \lim_{t\to\infty} \left[e^{-\delta t}\lambda_3(t) R(t)\right] = 0,$$

$$[A21] \quad \lim_{t\to\infty} \left[e^{-\delta t}\lambda_4(t) J(t)\right] = 0.$$

B. Proof that the Optimal Growth Path is Locally a Stable Saddle Point

We define the endogenous stationary growth path equilibrium that in which the growth rates of $Y/K = \beta$, and $C/K = \beta\chi$, will be equal. This implies that the growth rates of total output, capital and consumption will be the same in the optimum (Barbier, 1996, Schou, 2000, Stiglitz, 1974).

To demonstrate that we have a locally stable saddle path, we define the variables that will be constant in the long run equilibrium.

$$[B1] \quad \beta = \frac{Y}{K},$$

$$[B2] \quad \beta\chi = \frac{C}{K},$$

$$[B3] \quad \theta = \frac{E}{R},$$

$$[B4] \quad \varphi = \frac{M}{J}.$$

Then

$$[B5] \quad g_K = \beta - \beta\varkappa,$$

$$[B6] \quad g_\beta = g_Y - \beta + \beta\varkappa,$$

$$[B7] \quad g_{\beta\varkappa} = g_C - \beta + \beta\varkappa,$$

$$[B8] \quad g_\theta = g_E - \theta,$$

$$[B9] \quad g_\varphi = g_M - g_J.$$

Using the first order conditions, and after a little algebra, we can define the dynamic system $(\beta, \beta\varkappa, \theta, \varphi)$ in terms of the following equations.

$$[B10] \quad g_\beta = B(1-v) - \left(1 + \frac{\alpha_1\alpha_3}{\alpha_2}\right)\beta + \beta\varkappa,$$

$$[B11] \qquad g_{\beta\varkappa} = B\left(1-v\right) - \left(1+\frac{\alpha_1\alpha_3}{\alpha_2}\right)\beta + \beta\varkappa,$$

$$[B12] \qquad g_\theta = -\theta,$$

$$[B13] \qquad g_\varphi = B\left(1-v\right) - \left[1+\frac{\alpha_3}{\alpha_2}\right]\alpha_1\beta + \varphi\left(1-\frac{\gamma}{n\omega_2 v}\right) + \gamma.$$

In the stationary growth path we assume that $g_\beta = g_{\beta\varkappa} = g_\theta = g_\varphi = 0$, such that $\beta = \bar{\beta}$ (where the bar denotes the optimal value of variable), etc. Thus we can write the Jacobian that we evaluate at the steady state.

$$Jac = \begin{bmatrix} \frac{\partial\dot{\beta}}{\partial\beta} & \frac{\partial\dot{\beta}}{\partial\beta\varkappa} & \frac{\partial\dot{\beta}}{\partial\theta} & \frac{\partial\dot{\beta}}{\partial\varphi} \\ \frac{\partial\dot{\beta\varkappa}}{\partial\beta} & \frac{\partial\dot{\beta\varkappa}}{\partial\beta\varkappa} & \frac{\partial\dot{\beta\varkappa}}{\partial\theta} & \frac{\partial\dot{\beta\varkappa}}{\partial\varphi} \\ \frac{\partial\dot{\theta}}{\partial\beta} & \frac{\partial\dot{\theta}}{\partial\beta\varkappa} & \frac{\partial\dot{\theta}}{\partial\theta} & \frac{\partial\dot{\theta}}{\partial\varphi} \\ \frac{\partial\dot{\varphi}}{\partial\beta} & \frac{\partial\dot{\varphi}}{\partial\beta\varkappa} & \frac{\partial\dot{\varphi}}{\partial\theta} & \frac{\partial\dot{\varphi}}{\partial\varphi} \end{bmatrix} =$$

$$\begin{bmatrix} -\pi - \bar{\beta}\varkappa & \frac{\bar{\beta}\varkappa+\pi}{\eta} & 0 & 0 \\ -\eta^2\left[\bar{\beta} - \frac{\pi}{\eta}\right] & \eta\bar{\beta} - \pi & 0 & 0 \\ 0 & 0 & 0 & 0 \\ \mu\alpha_1\left(\frac{\pi}{\left(\frac{\gamma}{n\omega_2 v}-1\right)} - \frac{\mu\alpha_1}{\left(\frac{\gamma}{n\omega_2 v}-1\right)}\bar{\beta} - \gamma\right) & 0 & 0 & \mu\alpha_1\bar{\beta} - \pi + \gamma \end{bmatrix}.$$

To simplify the symbology of the above Jacobian we put: $B\left(1-v\right) = \pi$, $\left(1+\frac{\alpha_1\alpha_3}{\alpha_2}\right) = \eta$ and $\left(1+\frac{\alpha_3}{\alpha_2}\right) = \mu$. After some little algebra, we may check that the determinant of the Jacobian Matrix is negative, and that

$$[B14] \qquad TrJac = -\pi - \bar{\beta\varkappa} + \eta\bar{\beta} - \pi + \mu\alpha_1\bar{\beta} - \pi + \gamma > 0,$$

this implies that we have a locally stable saddle point equilibrium.[4]

C. Proof of Proposition 1

To check the result shown in Proposition 1, we use the assumptions made in Appendix B. If v is held constant, it immediately follows that its growth rate will be equal to zero (see Schou (2000) among others for the same assumption).

Differentiating equation [1] logarithmically we obtain

$$[C1] \qquad g_Y = \alpha_1 g_K + \alpha_2 g_h + \alpha_3 g_{E+M}.$$

Where $g_{E+M} = g_E + g_M$, such that we can rewrite the equation $[C1]$ as

$$[C2] \qquad g_Y = \alpha_1 g_Y + \alpha_2 g_h + \alpha_3 g_E + \alpha_3 g_M.$$

(remember that in the optimal stationary equilibrium path $g_Y = g_K = g_C$). From [4] we know that $g_E = \sigma(1 - R/\tau) - r$, substituting in this equation the optimal values of renewable natural resources stock $(0; \tau - r\tau/\sigma)$, we will find

[4] For a similar explanation of saddle point existence see Schou, 2000.

that in the optimal stationary growth path $g_E = 0$. From [3], it follows that $g_h = B(1-v)$, such that

$$[C3] \qquad g_Y = \frac{\alpha_2 [B(1-v)] + \alpha_3 g_M}{1-\alpha_1}.$$

Equation $[C3]$ represents the growth rate of the economy in cases where the waste recycling process is considered.

To derive the growth rate of total output in cases where we do not take into account waste recycling, we just set up the relative production function, that will be

$$[C4] \quad Y = f(K,h,L,v,E) = K^{\alpha_1} (hL\omega_1 v)^{\alpha_2} E^{\alpha_3}, \quad \sum_{i=1}^{3} \alpha_i = 1.$$

Differentiating [4] logarithmically the result is

$$[C5] \qquad g_Y = \alpha_1 g_K + \alpha_2 g_h + \alpha_3 g_E.$$

After some little algebra we obtain that

$$[C6] \qquad g_{Y_P} = \frac{\alpha_2 [B(1-v)]}{1-\alpha_1},$$

such that for the same values of parameters and of v, with $g_M \neq 0$, the result in Proposition 1 claims.

D. Proof that we have a locally stable saddle point equilibrium in an R, λ_3 space

Using equations [4] and $[A7]$ and setting $\dot{R} = 0$ and $\dot{\lambda}_3 = 0$, we obtain these two equations

$$[D1] \quad \sigma \left(1 - \frac{R}{\tau}\right) R - rR = 0,$$

and

$$[D2] \quad \delta\lambda_3 - \lambda_3 \left[\sigma \left(1 - \frac{2R}{\tau}\right) - r\right] = 0.$$

Such that we can form the Jacobian matrix

$$Jac = \begin{bmatrix} \frac{\partial \dot{R}}{\partial R} & \frac{\partial \dot{R}}{\partial \lambda_3} \\ \frac{\partial \dot{\lambda}_3}{\partial R} & \frac{\partial \dot{\lambda}_3}{\partial \lambda_3} \end{bmatrix} = \begin{bmatrix} \sigma \left(1 - \frac{2R}{\tau}\right) - r & 0 \\ \frac{2\sigma\lambda_3}{\tau} & \delta - \left[\sigma \left(1 - \frac{2R}{\tau}\right) - r\right] \end{bmatrix}.$$

The determinant of the Jacobian matrix is

$$det = \sigma \left(1 - \frac{2R}{\tau}\right) \delta - \left[\sigma \left(1 - \frac{2R}{\tau}\right)\right]^2 - r\delta - r^2,$$

such that our second order equation is

$$-\left[\sigma\left(1-\frac{2R}{\tau}\right)+r\right]^2-\delta\left[\sigma\left(1-\frac{2R}{\tau}\right)\delta+r\right]=0.$$

The two rows $(\delta/2;-\delta^3/2)$ have opposite signs, this implies that we have a saddle path equilibrium.

We can also calculate the trace of determinants

$$\text{TrJac}=\sigma\left(1-\frac{2R}{\tau}\right)-r+\delta-\sigma\left(1-\frac{2R}{\tau}\right)+r=\delta>0.$$

These results mean that we have a locally stable saddle point equilibrium.

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(xlvi) This paper was presented at the Sixth Meeting of the Coalition Theory Network organised by the Fondazione Eni Enrico Mattei and the CORE, Université Catholique de Louvain, Louvain-la-Neuve, Belgium, January 26-27, 2001
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(li) This paper was presented at the Fourth Toulouse Conference on Environment and Resource Economics on "Property Rights, Institutions and Management of Environmental and Natural Resources", organised by Fondazione Eni Enrico Mattei, IDEI and INRA and sponsored by MATE, Toulouse, May 3-4, 2001
(lii) This paper was presented at the International Conference on "Economic Valuation of Environmental Goods", organised by Fondazione Eni Enrico Mattei in cooperation with CORILA, Venice, May 11, 2001
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