Optimal Growth with Pollution : How To allocate Pollution Permits ? ¹

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Abstract

We study optimal growth and its decentralization in an overlapping generations model. The decentralization of an optimal path needs some specific taxes in addition to lump-sum transfers if there are externalities. The introduction of market of permits allows to neutralize the external environmental effects. We show that there is a unique management of permits such that the equilibrium coincides with the optimal path: all permits should be auctioned *i.e.* no permits to firms. This conclusion is in contradiction with the usual practice of grandfathering.

JEL Classification: D61,D9,Q28

Key words: Optimal growth, environment, market of permits.

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1 Introduction

Optimal growth problem with pollution is well known and has been analyzed in many contributions. Two main approaches are used when dealing with the effects of pollution on economic growth. The first consists to study the classical Ramsey problem in searching for the existence of a balanced growth of the "golden rule" type accommodating pollution. The second one focuses on the growth path's characteristics in a decentralized economy, where pollution is an externality.

The first approach starts with the seminal paper of Keeler, Spence and Zeckhauser (1971), followed, among others, by Forster (1973) or Gruver (1976). More recents papers discuss some joint problems, introducing natural resources (Forster, 1980; Tahvonen, 1991) or abatement activities (van der Ploeg and Withagen, 1991).

The second approach is illustrated by Smith (1972) or Tahvonen and Kuuluvainen (1991) who study conditions under which the market solution is the optimal solution of the social planner. But an open question is the use of the market of permits to decentralize the optimal path.

Tradeable quota system have also been much studied in the literature. Montgomery (1972) shows that in a competitive market of permits, costeffectiveness is achieved regardless of the initial allocation. Tietenberg (1985) gives the conceptual basis for dynamic permit trading. More recent studies extend his results. In Tietenberg's formulation, a cumulative abatement target is given for the entire time horizon, inter-period trading being implicit in his analysis. Cronshaw and Kruse (1996) and Rubin (1996) analyzes borrowing and banking over the time horizon. They show than inter-temporal trading enables polluting firms to jointly minimize their abatement costs over time. Stevens and Jones (2002) generalize this result by incorporating explicit constraints on permit trading and shows that the decentralized behavior of firms leads to the least-cost solution attainable under joint-cost minimization. It has also been used considering optimization by short-lived governments (Ono, 2002).

In this paper, we use the market of permits for decentralizing the optimal growth path. In the optimal growth problem for the standard overlapping generations model (Diamond, 1984), lump-sum transfers are sufficient for decentralization (this results from the second welfare theorem). In the presence of externalities, proportional taxes should be used in order to neutralize the external effects (see for example Jouvet, Michel, Vidal (2000)).

Does the market of permits allows to neutralize the external effect of environment, given that the total number of permits is chosen by the government? But the allocation of permits is also a policy choice, and we will show that the unique allocation decentralizing the optimal path consists to give no permits to firms, because any permit given to a firm modifies the income of the shareholders and thus the interest rate. We shall show that the market of permits is efficient not only in a static equilibrium, but also in a dynamic one². Our main result is that this use of the market of permits with lump-sum transfers allows to decentralize the optimal growth path.

The paper is set out as follows. Section 2 presents the model. The optimal growth problem is stated in section 3 where we characterized the marginal

 $^{^{2}}$ For the static approach, the allocation conditions are less restrictive (see Jouvet, Michel, Rotillon, (2003)).

optimality conditions. Section 4 define the equilibrium with pollution permits and our main result is proved in section 5. We summarize our results in section 6.

2 The model

2.1 Technologies

Potential output $F(K_t, L_t)$ occurs within a period according to a constant returns to scale production function using capital, K_t , and labor, L_t . The effective output is given by:

$$Y_t = z_t F(K_t, L_t) \tag{1}$$

where z_t is the index of technology used, $0 \le z_t \le 1$ (see Stokey 1998). The ratio of pollution, P_t , on potential output is a continuous differentiable, increasing, convex function $\varphi(z_t)$ satisfying $\varphi(0) = 0$,

$$\frac{P_t}{F(K_t, L_t)} = \varphi(z_t) \tag{2}$$

Note that eliminating z_t between (1) and (2) leads to a standard production function homogeneous of degree on of capital, labor and pollution (Turner, Pearce and Bateman(1994)).

2.2 Dynamic

The dynamic of the stock of pollution at time t, S_t , is defined by $S_t = (1-h)S_{t-1} + P_t$ where P_t is the current pollution flow and h the natural level of pollution absorption, $0 \le h \le 1$. The environmental quality, Q_t , is defined by the difference, $Q_t = \overline{Q} - S_t$ where \overline{Q} represents the environmental quality without pollution. Therefore, the environmental quality dynamic is given by

$$Q_t = h\overline{Q} + (1-h)Q_{t-1} - P_t \tag{3}$$

The macroeconomic equilibrium implies that total production is equal to the sum of total consumption, C_t and total investment, I_t :

$$Y_t = C_t + I_t \tag{4}$$

The dynamic of the stock of capital is given by

$$K_{t+1} = (1 - \delta)K_t + I_t \tag{5}$$

where δ is the rate of depreciation for capital, $0 \leq \delta \leq 1$.

2.3 Consumers

Individuals live two periods. Population is constant, N identical agents are born at each period t. Any agent born in period t derives utility from the consumption, c_t , leisure, $1-l_t$ with $0 \le l_t \le 1$, and the quality of environment, Q_t , in her/his first period of life and from the consumption, d_{t+1} , and the quality of environment, Q_{t+1} , in second period of life. The agent's preferences are represented by a general utility function

$$U_t = U(c_t, 1 - l_t, Q_t, d_{t+1}, Q_{t+1})$$
(6)

The function U(.) is strictly concave, increasing, twice continuously differentiable and satisfies the Inada conditions (infinite marginal utility of zero consumption).

3 Optimal growth

3.1 The problem

From relations (1), (4), (5) and with $C_t = Nc_t + Nd_t$ and $L_t = Nl_t$ the resource constraint is

$$z_t F(K_t, Nl_t) = Nc_t + Nd_t + K_{t+1} - (1 - \delta)K_t$$
(7)

and per young this relation is

$$z_t F(k_t, l_t) = c_t + d_t + k_{t+1} - (1 - \delta)k_t$$
(8)

where $k_t = K_t/N$ is the capital per young.

With (2) and (3), the dynamics of environmental quality are

$$Q_t = h\overline{Q} + (1-h)Q_{t-1} - \varphi(z_t)NF(k_t, l_t) , \ \forall t \ge 0$$
(9)

The objective of the central planner is to maximize the welfare of agents,

with a discount factor, γ , $0 < \gamma < 1$,

$$\sum_{t=-1}^{+\infty} \gamma^t U_t \tag{10}$$

The initials values of capital and environment quality are given, respectively k_0 and Q_{-1} . In addition the past variables c_{-1} and l_{-1} are given.³

3.2 Optimality conditions

The central planner chooses the level of consumptions, (c_t, d_t) , the level of labor supply, l_t , and the index of technology used, z_t . The stock variables are capital and environmental quality. Denoting by λ_{t+1} and μ_t respectively the Lagrangiean multiplier of the resources constraint (8) and the environmental quality dynamic (9), the Lagrangiean is defined by

$$\gamma^{-1}U_{-1} + \sum_{t=0}^{+\infty} \gamma^{t} \left\{ \begin{array}{c} U_{t} + \lambda_{t+1} \left[z_{t}F(k_{t}, l_{t}) - c_{t} - d_{t} - k_{t+1} + (1-\delta)k_{t} \right] \\ + \mu_{t} \left[h\overline{Q} + (1-h)Q_{t-1} - \varphi(z_{t})NF(k_{t}, l_{t}) - Q_{t} \right] \end{array} \right\}$$
(11)

One obtains thereby the first order conditions,

- for the first period consumption

$$\frac{\partial U_t}{\partial c_t} = \lambda_{t+1} \tag{12}$$

- for the second period consumption

³Only if the life cycle utility is additively separable, the past consumption of good and leisure do not matter.

$$\frac{\partial U_{t-1}}{\partial d_t} = \gamma \lambda_{t+1} \tag{13}$$

- for leisure

$$\frac{\partial U_t}{\partial (1-l_t)} = \left[\lambda_{t+1} z_t - \mu_t N \varphi(z_t)\right] F_L(k_t, l_t) \tag{14}$$

- and for the index of technology used,

$$\lambda_{t+1} - \mu_t N \varphi'(z_t) \le 0 \; ; \; = 0 \; if \; z_t < 1$$
 (15)

The dynamics of the shadow prices, λ_{t+1} and μ_t are obtained by differentiating the Lagragiean with respect to k_{t+1} and Q_t , $\forall t \ge 0$

$$\lambda_{t+1} = \gamma \lambda_{t+2} \left[z_{t+1} F_K(k_{t+1}, l_{t+1}) + (1 - \delta) \right] - \gamma \mu_{t+1} N \varphi(z_{t+1}) F_K(k_{t+1}, l_{t+1})$$
(16)
$$\partial U_t = 1 \ \partial U_{t-1}$$

$$\mu_t = \gamma \mu_{t+1} (1-h) + \frac{\partial U_t}{\partial Q_t} + \frac{1}{\gamma} \frac{\partial U_{t-1}}{\partial Q_t}$$
(17)

The transversality condition is (Michel (1990))

$$\lim_{t \to +\infty} \gamma^t \left(\lambda_t k_t + \mu_{t-1} Q_{t-1} \right) = 0 \tag{18}$$

Characterization of the marginal optimality con-3.3ditions

We characterize the first order conditions, in the case where there is under-use of potential output at each period, $z_t < 1, \forall t$. We obtain,

$$N\mu_t = \frac{\lambda_{t+1}}{\varphi'(z_t)} \tag{19}$$

After eliminating the shadow prices for physical capital and for environmental quality and rearranging the terms, we explicit the different trade-offs faced by the central planner.

- Trade-off between generations

$$\frac{\partial U_{t-1}}{\partial d_t} = \gamma \frac{\partial U_t}{\partial c_t} \tag{20}$$

- Trade-off between consumption and leisure

$$\frac{\partial U_t}{\partial (1-l_t)} = \frac{\partial U_t}{\partial c_t} \psi(z_t) F_L(k_t, l_t)$$
(21)

where $\psi(z_t) = z_t - \varphi(z_t)/\varphi'(z_t)$ satisfies $\psi(z_t) > 0.4$ ⁴The strictly convex function φ satisfies for any z > 0:

$$\varphi(z) - \varphi(0) < z\varphi'(z)$$

- Trade-off between consumptions on life cycle (resulting from (16))

$$\frac{\partial U_t}{\partial c_t} = \frac{\partial U_t}{\partial d_{t+1}} \left[\psi(z_{t+1}) F_K(k_{t+1}, l_{t+1}) + (1-\delta) \right]$$
(22)

- Trade-off between "environmental quality and consumptions" (resulting from (17))

$$\frac{N}{\varphi'(z_t)}\frac{\partial U_t}{\partial c_t} = \frac{1-h}{\varphi'(z_{t+1})}\gamma N\frac{\partial U_{t+1}}{\partial c_{t+1}} + \frac{\partial U_t}{\partial Q_t} + \frac{1}{\gamma}\frac{\partial U_{t-1}}{\partial Q_t}$$
(23)

This last trade-off is obtained by substitution of $N\mu_t = \lambda_{t+1}/\varphi'(z_t) = \frac{\partial U_t}{\partial c_t}/\varphi'(z_t)$ in the equation of the environmental quality shadow price (17). In this equation, an increase of one unit of environmental quality at period t, is equal to the sum of direct utility effect at period t, $\frac{\partial U_t}{\partial Q_t} + \frac{1}{\gamma} \frac{\partial U_{t-1}}{\partial Q_t}$ and the welfare effect resulting from the inherited (1 - h) unit of environmental quality of period t + 1 discounted in t, $\gamma(1 - h)\mu_{t+1}$.

Conversely, the trade-off conditions (20), (21), (22) and (23), imply the first order conditions (12) to (17) with the values of the shadow prices λ_{t+1} and μ_t defined by (12) and (19).

4 Equilibrium with pollution permits

In the economy with a market of tradeable permits of pollution, the government policy consists of issuing a quantity of permits, \overline{P}_t , allocating permits to firms \overline{P}_t^F , and the difference, $\overline{P}_t - \overline{P}_t^F$, is auctioned. It also makes a transfers, τ_t , to the young agent and θ_t to each old agent. Its budget is balanced at each period t. The price on the pollution permits market is denoted q_t .

4.1 Consumers

Consumers take the environmental quality as given. At the first period of life, the young agent supplies, l_t , unit of labor, $0 \le l_t \le 1$, earns $w_t l_t$ where w_t is the wage per unit of labor, and receives a transfer τ_t which may be positive or negative. (S)he consumes, c_t , and saves, s_t . Then, the first period budget constraint is

$$w_t l_t + \tau_t = c_t + s_t \tag{24}$$

When (s)he is old, at the second period of life, (s)he is retired and receives a transfer θ_{t+1} in addition of the return to her/his savings, $R_{t+1}s_t$ with R_{t+1} the growth interest rate. The old agent consumes all her/his income. Then, the second period budget constraint is

$$d_{t+1} = R_{t+1}s_t + \theta_{t+1} \tag{25}$$

The agent maximizes utility (6) by choosing consumptions and leisure subject to the budget constraints (24) and (25). Since prices and environmental qualities, Q_t and Q_{t+1} , are given, the first order conditions are:

$$\frac{\partial U_t}{\partial (1-l_t)} = w_t \frac{\partial U_t}{\partial c_t} \tag{26}$$

and

$$\frac{\partial U_t}{\partial c_t} = R_{t+1} \frac{\partial U_t}{\partial d_{t+1}} \tag{27}$$

The relation (26) corresponds to the trade-off between consumption and leisure and relation (27) corresponds to the trade-off between consumptions on life cycle.

4.2 Firms

Firms are perfectly competitive. We consider a representative firm endowed with a stock of capital K_t and a stock of permits \overline{P}_t^F . The firm takes prices, w_t and q_t as given and maximizes profits with respect to the index of technology used, z_t , labor L_t and the quantity of permits, P_t , as defined by the relation (2), $P_t = \varphi(z_t)F(K_t, L_t)$.

The net revenue⁵ includes the net gains on the permit market *i.e.*

$$Y_t - w_t L_t - q_t (P_t - \overline{P}_t^F)$$
(28)

Hence, using equations (1) and (2), the problem the firm is

$$\max_{0 \le z_t \le 1, L_t \ge 0} \left[z_t - q_t \varphi(z_t) \right] F(K_t, L_t) - w_t L_t + q_t \overline{P}_t^F = \pi_t \tag{29}$$

The profits π_t are the net revenue distributed to shareholder, the owners of the capital stock.

Assuming $1/\varphi'(1) < q_t < 1/\varphi'(0)$, the first order conditions, for an interior solution $(z_t < 1)$ are

$$\varphi'(z_t) = \frac{1}{q_t} \Rightarrow z_t = \varphi'^{-1}(1/q_t) \equiv z(q_t)$$
(30)

and

$$w_t = m(q_t)F_L(K_t, L_t) \tag{31}$$

where $m(q_t) = z(q_t) - q_t \varphi(z(q_t))$, according to the price q_t of permits.

 $^{^5 {\}rm This}$ net revenue is similar to the gross operating surplus defined by Hahn and Solow (1995), p 71.

Therefore, profits per unit of capital are

$$\frac{\pi_t}{K_t} = m(q_t)F_K(K_t, L_t) + q_t\frac{\overline{P}_t^F}{K_t} = R_t - 1 + \delta$$
(32)

By definition the return to savings, R_t , is equal to $\pi_t/K_t + 1 - \delta$. Note that, in general, this return does not satisfy the neo-classical property of equality of factor income with marginal productivity (see Jouvet, Michel and Rotillon (2003)).

4.3 Equilibrium

The government budget is balanced, *i.e.* satisfied,

$$N\tau_t + N\theta_t = q_t(\overline{P}_t - \overline{P}_t^F) \tag{33}$$

The intertemporal equilibrium is defined, for a given sequence of government decisions, by a sequence of prices, individual variables and aggregate variables satisfying all the equilibrium conditions. The government decisions satisfies its budget constraint. Consumers decisions maximize their utility. Firms decision maximize profit.

The capital stock is equal to savings and the return to savings is defined by profit per unit of capital.

The markets of labor, permits and good clear.

In addition, the dynamic equation of environmental quality holds.

The first old consumption satisfies:

$$d_0 = R_0 s_{-1} + \theta_0 \tag{34}$$

and the initial capital stock $K_0 = Ns_{-1}$ is given.

We explicitly define the equilibrium of the economy as follows:

Definition 1 For a given policy $(\overline{P}_t, \overline{P}_t^F, \tau_t, \theta_t)_{t \ge 0}$, an equilibrium is defined by

- sequence of prices $(q_t, w_t, R_t)_{t \ge 0}$,

- sequence of individuals variables (c_t, l_t, s_t, d_{t+1}) satisfying relations (24)

to (27) and d_0 satisfies (34),

- sequence of aggregate variables (K_t, L_t, Q_t, z_t) satisfying (30), (31). such that the following equilibrium conditions hold:

- the government budget is balanced, (33),

- the capital stock $K_{t+1} = Nk_{t+1}$ is equal to savings Ns_t and satisfies (32),

- the market of labor, permits and good clear:

 $L_t = Nl_t,$ $P_t = \varphi(z_t)F(K_t, L_t) = \overline{P}_t$ $Y_t = z_tF(K_t, Nl_t) = Nc_t + Nd_t + K_{t+1} - (1 - \delta)K_t$

- the dynamic of environmental quality is defined by relation (3).

5 Decentralization of the optimal growth

In the standard overlapping generation model (without environmental constraint) the optimal policy is decentralized with lump-sum transfers (see for example De La Croix and Michel (2003)). In our model, we shall show that the decentralization not only implies a given policy of permits, \overline{P}_t , but zero permits attributed to firms, $\overline{P}_t^F = 0$. The benefice of the government on permits market allows to finance the lump-sum transfers to consumers.

We consider an optimal growth path $c_t^*, l_t^*, d_t^*, k_t^*, z_t^*, Q_t^*$.

Proposition 2 Consider a social optimum satisfying $z_t^* < 1, \forall t$. Any equilibrium which coincides with the social optimum satisfies, $\forall t \ge 0$,

$$z_t = z_t^*$$
$$\overline{P}_{t+1}^F = 0$$

and

$$m(q_t) = \psi(z_t^*).$$

Proof. Let us note

$$TMS(c_t^*, d_{t+1}^*) = \frac{\frac{\partial U_t}{\partial c_t}}{\frac{\partial U_t}{\partial d_{t+1}}} (c_t^*, 1 - l_t^*, d_{t+1}^*)$$

and

$$TMS(1 - l_t^*, c_t^*) = \frac{\frac{\partial U_t}{\partial (1 - l_t)}}{\frac{\partial U_t}{\partial c_t}} (c_t^*, 1 - l_t^*, d_{t+1}^*)$$

Given Q_{-1} and K_0 , by induction the equality of labor $(L_t = L_t^*)$, production $(Y_t = Y_t^*)$ and emissions $(Q_t = Q_t^*)$ implies, $z_t = z_t^*$, $q_t = 1/\varphi'(z_t^*) > 0$ and $K_t = K_t^*$. The equilibrium coinciding with the social optimum satisfies equations (21) and (22). This implies by eliminating $\psi(z_{t+1}^*)$

$$TMS(c_t^*, d_{t+1}^*) = 1 - \delta + TMS(1 - l_{t+1}^*, c_{t+1}^*) \frac{F_K(k_{t+1}^*, l_{t+1}^*)}{F_L(k_{t+1}^*, l_{t+1}^*)}$$

At the equilibrium, from relation (32)

$$R_{t+1} = m(q_{t+1})F_K(k_{t+1}^*, l_{t+1}^*) + q_{t+1}\frac{\overline{P}_{t+1}^F}{K_{t+1}} + 1 - \delta$$

Relation (26) and (31) imply

$$\frac{\partial U_{t+1}}{\partial (1-l_{t+1})} = m(q_{t+1})F_L(k_{t+1}^*, l_{t+1}^*)\frac{\partial U_{t+1}}{\partial c_{t+1}}$$

and with (27)

$$R_{t+1} = TMS(c_t^*, d_{t+1}^*)$$

then,

$$q_{t+1} \frac{\overline{P}_{t+1}^F}{K_{t+1}} = R_{t+1} - m(q_{t+1})F_K(k_{t+1}^*, l_{t+1}^*) - (1-\delta)$$

= $TMS(c_t^*, d_{t+1}^*) - TMS(1 - l_{t+1}^*, c_{t+1}^*) \frac{F_K(k_{t+1}^*, l_{t+1}^*)}{F_L(k_{t+1}^*, l_{t+1}^*)} - (1-\delta) = 0$

Thus, since $q_{t+1} > 0$, $\overline{P}_{t+1}^F = 0$.

In addition, we have

$$TMS(c_t^*, d_{t+1}^*) = m(q_{t+1})F_K(k_{t+1}^*, l_{t+1}^*) + (1-\delta) = \psi(z_{t+1}^*)F_K(k_{t+1}^*, l_{t+1}^*) + (1-\delta)$$

then $m(q_{t+1}) = \psi(z_{t+1}^*)$.

At t = 0, we have at the optimum,

$$TMS(1 - l_0^*, c_0^*) = \psi(z_0^*)F_L(k_0, l_0^*)$$

at the equilibrium

$$TMS(1 - l_0^*, c_0^*) = w_0 = m(q_0)F_L(k_0, l_0^*)$$

thus $m(q_0) = \psi(z_0^*)$.

Remark, at t = 0, given the initial capital stock hold by the first old and their past consumption and labor supply, any transfer to the firms (say by permits) can be neutralized by lump-sum tax to old. There is no condition on \overline{P}_0^F .

We can now show that the social optimum, satisfying under-use of potential output at each period, can be decentralized as an intertemporal equilibrium with no free permits to firms and lump-sum transfers.

Proposition 3 The optimal path $(c_t^*, l_t^*, d_t^*, k_t^*, z_t^*, Q_t^*)_{t\geq 0}$ satisfying $z_t^* < 1$, $\forall t \geq 0$, is an equilibrium with

$$\overline{P}_t = \overline{P}_t^* = \varphi(z_t^*) NF(k_t^*, l_t^*), \overline{P}_t^F = 0 \text{ and } q_t = 1/\varphi'(z_t^*)$$

$$\tau_t = c_t^* + k_{t+1}^* - w_t l_t^* \text{ and } w_t = \psi(z_t^*) F_L(k_t^*, l_t^*)$$

$$\theta_t = d_t^* - R_t k_t^* \text{ and } R_t = \psi(z_t^*) F_K(k_t^*, l_t^*) + 1 - \delta$$

Proof. The consumer's optimality conditions (26) and (27) (trade-off between consumption and leisure and decision-making between consumptions on life cycle) are verified with the prices w_t and R_t . The consumer's budget constraints hold by definition of the lump-sum transfers, τ_t and θ_t . With $q_t = 1/\varphi'(z_t^*)$, we have $m(q_t) = \psi(z_t^*)$ and the conditions (30) and (31) and (32) hold with $\pi_t/K_t = m(q_t)F_K(k_t^*, l_t^*)$ since $\overline{P}_t^F = 0$. The constraint of resources, (8) holds at the optimum. It remains to verify the government budget constraint, (33). This constraint results from the constraints of resources, the consumer's budget constraints and the relation, $w_t l_t^* - [R_t - (1 - \delta)]k_t^* = z_t^* F(k_t^*, l_t^*) - q_t \overline{P}_t^*/N$, satisfied by the equilibrium prices. Remark, at the equilibrium with $\overline{P}_t^F = 0$ the return to capital and sav-

Remark, at the equilibrium with $\overline{P}_t^F = 0$ the return to capital and savings is equal to the marginal productivity of capital plus $1 - \delta$ (the capital remanding after depreciation).

6 Conclusion

We have shown that it is possible to decentralize optimal growth path only with lump-sum transfers and a market of permits. But a necessary condition to realize such a decentralization is to allocate no permits to firms, at the difference with the practices like grandfathering. The reason of this property of optimal decentralization is that the equilibrium market of permits gives the optimal rate of interest.

A consequence of this property is that at the decentralized equilibrium the interest rate is equal to the marginal productivity of capital.

Note that if at the equilibrium the income of the government auctioning the permits allows to make positive transfers to all consumers, these transfers could be made in the form of direct distribution of permits to the consumers.

In our study, we have not consider public expenditure for pollution abatement. The optimal growth would then include an optimal pollution abatement policy. Given this policy, the way of decentralization would be unchanged.

References

- Asako K. (1980): "Economic Growth and Environmental Pollution under the Max-Min Principle"; Journal of Environmental Economic and Management 7, 157-183.
- [2] Cronshaw M.B., Kruse J.B. (1996): "Regulated Firms in Pollution Permit Markets with Banking", Journal of Regulatory Economics, 9, 179-189.
- [3] Diamond Peter A. (1984): Search-Equilibrium Approach to the Micro Foundations of Macroeconomics, Cambridge, Mass : MIT Press.
- [4] Forster B. (1980): "Optimal Energy Use in a Polluted Environment", Journal of Environmental Economic and Management 7, 321-333.
- [5] Gruver G. (1976): "Optimal Investment and Pollution Control in a Neoclassical Growth Context", Journal of Environmental Economic and Management 5, 165-177.
- [6] Jouvet P.-A., Michel P., Rotillon G. (2003): "International Markets for Pollution Permits and Factor Income", WP. THEMA.

- [7] Jouvet P-A., Ph. Michel et J.P. Vidal (2000), "Intergenerational Altruism and the Environment", *Scandinavian Journal of Economics*, 102.
- [8] Keeler E, Spence M., Zeckhauser R. (1971): "The Optimal Control of Pollution", Journal of Economic Theory 4, 19-34.
- [9] Montgomery D.W. (1972): "Markets in Licenses and Efficient Pollution Control Programs", Journal of Economic Theory, 5, 395-418.
- [10] Ono T. (2002): "Effects of Emission Permits on Growth and the Environment", *Environmental and Resource Economics* 21, 75-87.
- [11] Rubin J.D. (1996): "A Model of Intertemporal Emission Trading, Banking, and Borrowing", Journal of Environmental Economic and Management 31, 269-286.
- [12] Smith V. (1972): "Dynamics of Waste Accumulation : Disposal Versus Recycling", Quaterly Journal of Economics 86, 600-616.
- [13] Stevens B., Rose A. (2002): "A Dynamic Analysis of the Marketable Permits Approach to Global Warming Policy: A Comparison of Spatial and Temporal Flexibility", *Journal of Environmental Economic and*

Management 44, 45-69.

- [14] Stokey, N. L. (1998): "Are there limits to growth ?", International Economic Review, 39, 1-31.
- [15] Tahvonen O., Kuuluvainen J. (1991): "Optimal Growth with Renewable Resources and Pollution", *European Economic Review* 35, 650-661.
- [16] Tahvonen O. (1991): "On the Dynamics of Renewable Resource Harvesting and Pollution Control", *Environmental and Resource Economics* 1, 97-117.
- [17] Tietenberg T., (1985): "Emission Trading and Exercise in Reforming Pollution Policy", Resources for the Future, Washington DC.
- [18] Turner K. R., Pearce D., (1994): Environmental Economics: an Elementary Introduction, Harvester Wheatsheaf, New York.
- [19] Van der Ploeg F., Withagen C. (1991) : "Pollution Control and the Ramsey Problem", Environmental and Resource Economics 1, 215-230.