ISSN 0265-8003

R&D COOPERATION AND THE STABILITY OF INTERNATIONAL ENVIRONMENTAL AGREEMENTS

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Discussion Paper No. 1154
April 1995

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CEPR Discussion Paper No. 1154

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ABSTRACT

R&D Cooperation and the Stability of International Environmental Agreements*

International agreements to protect the global environment are typically difficult to reach. In principle they should be profitable for all players involved in the negotiation. Even when they are profitable, however, they are often unstable due to the incentive to free-ride (enjoying the clean environment provided by others' emission reduction without paying the cost). One possible way to overcome this problem is to link the unstable environmental agreement to other agreements which are profitable and stable. This paper presents a model where an environmental negotiation, which is profitable but unstable, is 'stabilized' by linking it to an agreement on R&D cooperation, which is shown to be profitable and stable. The optimality of this linkage is also discussed.

JEL Classification: C7, C72, F02, Q2, O33
Keywords: coalition, environment, negotiations, innovation, global warming

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*This paper is produced as part of a CEPR research programme on *Environmental Policy, International Agreements and International Trade*, supported by grant from the Commission of the European Communities, under its Environment Programme (Contract EV5V–CT92–0184). The authors are grateful to Andrea Moro for his helpful assistance in preparing simulations and figures of the paper. The usual disclaimer applies.

Submitted 28 February 1995

NON-TECHNICAL SUMMARY

International agreements to protect the global environment are typically difficult to reach. In principle they are profitable for all countries involved in the negotiation, but they are also intrinsically unstable due to the incentive to free ride (enjoying the clean environment without paying the cost). We suggest that it is possible to overcome the instability of the global environmental agreements by linking the environmental negotiation to other international agreements which are intrinsically stable. This conclusion, which mirrors some recent developments in actual environmental agreements, is reached by means of a simple model in which we link a global environmental negotiation to an international agreement on technological cooperation.

The global environmental agreement, which is profitable but unstable due to free riding, is 'stabilized' by linking it to an international agreement on technological cooperation which is profitable and stable. This result is proved by using a standard industrial organization model of innovation with spillovers, in which production environmental externalities (emissions) are accounted for, and in which a large number of governments decide whether or not to cooperate on emission reduction and/or on technological cooperation.

The model explicitly considers the interactions between the government and domestic firms in one country, and among governments in different countries. Firms maximize profits and countries maximize their own welfare, which includes profits, consumer surplus and environmental quality.

The environmental agreement and technological cooperation can be analysed as two separate negotiations. The environmental coalition is profitable but unstable; technological cooperation is profitable and stable. The linked negotiation is more profitable than the two separate negotiations, and more stable than the environmental negotiation, as it uses the gains from technological cooperation to offset the environmental free-riding incentives and to reach full cooperation both on technology and on the environment.

The example contained in the paper shows that the benefit of linking two negotiations may be very high, if the linkage is appropriately designed. In particular the environmental benefit, which would otherwise be lost, may be quite relevant. This shows that the present strategy of linking global environmental policy to technological cooperation is a promising one.

R&D COOPERATION AND THE STABILITY OF INTERNATIONAL ENVIRONMENTAL AGREEMENTS

by
Carlo Carraro and Domenico Siniscalco

1. Introduction

The transnational or global dimension of many environmental phenomena, such as global warming, acid rains or the ozone layer depletion, gives rise to international reciprocal externalities. Hence some degree of inefficiency and over–exploitation of natural resorces. In the presence of this interdependence, the optimal use of the environmental resources would require an international institution with the power to issue and enforce regulations to countries. Such an institution, however, does not exist; therefore, the solution of transnational or global environmental problems calls for a coordinated action among sovereign countries, by means of voluntary agreements.

The early literature on environmental agreements represented the environmental interaction as a standard Prisoners dilemma, which inevitably leads to non cooperation and to the over–exploitation of environmental resources. In practice, however, many international environmental agreements exist, and the most recent literature has provided reasons for the emergence of environmental cooperation and explanations of the underlying incentives.

The various contributions in this literature can be divided into two main groups. A first group of papers analyzes the incentive to cooperate in a game where countries interact on emissions only.[1] Games of this class can be one–shot or repeated. The general result of this literature is that, under fairly reasonable assumptions, cooperation among all countries involved in the negotiations can hardly be achieved. Partial cooperation, i.e. the formation of stable coalitions among sub–groups of countries, on the contrary, is more likely to emerge. These

1 See, for example, Hoel (1991), Barrett (1992), Heal (1994).

coalitions, however, tend to be small.[2]

Starting from the results on the existence of small stable coalitions, a second group of papers has explored the possibility to expand coalitions. In this context, the number of signatory countries can be expanded by bribing non signatories through tansfers (Carraro–Siniscalco, 1993a) or by linking environmental agreements to other negotiations where the incentive to free-ride does not exist (Carraro–Siniscalco, 1993b). This means that countries bargain on emissions and other economic variables, thus breaking an artificial separation between the environment and the economy.

In a previous paper (Carraro–Siniscalco, 1993b), we provided a general framework to discuss the profitability, stability and the optimality of linked negotiations.[3] This companion paper presents a simple model in which the environmental agreement is linked to an agreement on R&D cooperation. We show thak linking the negotiation on technological cooperation to the environmental negotiation may solve the instability problem by offsetting the incentive to free-ride on the environmental benefit. This result is proved by using a standard industrial organization model of innovation with partial spillovers, in which production environmental externalities (emissions) are accounted for, and in which a large number of governments decide whether or not to cooperate on emission reduction and/or on technological cooperation.

The structure of the paper is the following: section 2 presents the oligopoly model which will be used in the paper and discusses its main assumptions; section 3 describes the environmental problem and derives the governments' welfare function; sections 4, 5 and 6 solve the three stages of the game: in section 4 the firm's optimal production and R&D levels are determined; in section 5 the optimal government's abatement level are computed; section 6 analyzes the choice between joining and not-joining the coalition: each government non-

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2 Technically, a coalition is a cooperative outcome of a non-cooperative game in which each country's strategy space is "cooperate-not cooperate". The small dimension of stable coalitions was already proved in the oligopoly literature (see D'aspremont et al., 1983; Donsimoni et al., 1986). More recently, similar results have been shown in environmental models (see Barrett, 1992; Carraro-Siniscalco, 1992).

3 Notice that our proposal to link different economic negotiations differs from the one contained in Cesar-De Zeew (1993). We propose the linkage to stabilize coalitions formed by symmetric countries, whereas Cesar-De Zeew propose the linkage to offset payoff differentials when countries are asymmetric.

cooperatively decides whether or not to sign the agreement on technological and environmental cooperation. Section 6 also provides conditions for the linked negotiation to be more profitable and stable than the two separate negotiations. A few concluding remarks are proposed in section 7.

2. Technological Cooperation with Innovation Spillovers

The model that we are going to present explicitly considers the interactions between the government and domestic firms in one country, and among governments in different countries. Firms maximise profit; countries maximise their own welfare, which includes profits, consumer surplus and environmental quality.

Let us begin by firms. Consider an industry with n firms facing an inverse demand function $D^{-1}(Y)$, where $Y = y_1+y_2+...+y_n$ is the total quantity produced. Each firm has a cost of production $C_i(y_i,x_i,x_{-i})$, which is a function of its own production y_i, of the amount of research x_i that it undertakes, and the amount $x_{-i} = (x_1, x_2, ... x_{i-1}, x_{i+1}, ... x_n)$ that its rivals undertake. For simplicity's sake, both D^{-1} and C are assumed linear, so that:

(1) $$D^{-1}(Y) = a - bY \qquad \text{with } a,b > 0$$

and

(2) $$C_i(y_i,x_i,x_{-i}) = (c - x_i - s_i\Sigma_j x_j)y_i \qquad i=1,2,...,n$$

with $a>c>0$, $1>s_i>0$, and $Y\leq a/b$.

Positive R&D externalities or spillovers s_i imply that some benefit of each firm's R&D flows without payment to other firms. In our specification, the external effect of firm j's R&D is to lower firm i's unit production cost. One interpretation is that successful innovations of rivals can be imitated, and that imitation is cheaper than innovation. The cost of R&D is assumed to be quadratic, reflecting the existence of diminishing returns of R&D expenditures. Firms' strategies consist of a level of R&D and production. These two variables are set simultaneously and non-cooperatively by the n firms.

Each firm is assumed to be located in a different country and subject to a country-specific environmental legislation. The n firms are supposed to sell to a single global market. For

simplicity, neither-transportation, nor other additional costs of selling the good abroad are considered. Each government can use, either cooperatively or non–cooperatively, two strategic variables: the abatement level q_i which is imposed to firms (e.g. an emission standard), and the degree of spillovers occurring in the production of innovations. Countries, in other words, can allow or push greater technological spillovers by means of appropriate instruments (e.g. technological cooperation). In particular, we assume that:

– there are just two degrees of spillovers, s_1 and s_2 (where $s_1 < s_2$).

– technological cooperation affects the level of technological spillovers in the following way: if countries cooperate on technological development and diffusion, the degree of spillovers is s_2; otherwise it is s_1.

Possible explanations are: (i) cooperating countries allow for patents agreement that provide the other countries in the coalition with a larger share of their own innovative technology; (ii) cooperating countries sign agreements on technology transfers and/or joint R&D projects that make the degree of innovation spillovers in the coalition larger than outside the coalition.

As previously stated, countries can also cooperate to protect the environment. Negotiations on environmental policies can take place independently of those on technological cooperation. In this case, technological spillovers are independent of the optimal cooperative abatement level. However, if the two negotiations are linked, we assume the following: if a government chooses to join the coalition, i.e. to sign an international agreement on environmental and technological cooperation, the effect is twofold: the abatement level imposed to domestic firm is higher and its policy towards technology transfers is differentiated. A government joining the coalitions makes it possible larger R&D spillovers towards the other members of the coalitions than towards countries which do not sign the cooperative agreement. Viceversa, if a government does not join the coalition, both the abatement level imposed to the domestic firm and the degree of technological spillovers are lower. More formally, we assume:

Assumption 1: *If negotiations on environmental and technological cooperation are linked, the degree of innovation spillovers is larger among countries which cooperate than among countries which do not cooperate.*

This amounts to saying that the knowledge produced by firm i which spills over a firm j is larger when country i and country j choose cooperatively their environmental and technology policy rather than when they do not cooperate. Following the literature on R&D cooperation[4], we define s_2 as the "information exchange" parameter, and s_1 as the "technological leakage" parameter. For simplicity's sake, we normalize s_1 to zero, and we define $s_2 = \beta > 0$. Hence, β (<1) is the "differential technological leakage" or the "coalition information exchange".

Notice that the above assumptions define the benefit of linking the negotiation on the environment with that on technological cooperation. More cooperation is achieved, i.e. a higher innovation spillover is allowed for, only among those countries which also cooperate to reduce emissions. Trough this linkage, countries belonging to an environmental coalition can induce other countries to cooperate, as technological cooperation, if linked to environmental cooperation, provides an extra-incentive to join the agreement.

3. Technological Cooperation and Environmental Coalitions

Let us define by J the set of countries which sign the environmental agreement, and by J^o the set of countries which do not cooperate. Firm i's profit function can be defined in the following way:

$$\text{(3a)} \quad \pi_i(Y,x_i,x_{-i},q_i) = [(a - bY) - (c - x_i - \beta\Sigma_j x_j)]y_i - \tfrac{1}{2}gx^2_i - \tfrac{1}{2}\Phi q^2_i \qquad \text{if } i,j \in J$$

$$\text{(3b)} \quad \pi_i(Y,x_i,q_i) = [(a - bY) - (c - x_i)]y_i - \tfrac{1}{2}gx^2_i - \tfrac{1}{2}\Phi q^2_i \qquad \text{if } i \in J^o$$

where $\tfrac{1}{2}gx^2_i$ denotes the cost of R&D investments, whereas $\tfrac{1}{2}\Phi q^2_i$ is the cost of abating a level q_i of emissions. The quadratic abatement cost function reflects the existence of diminishing marginal returns in the abatement technology.

The environmental problem arises because the production activity of the n firm produces polluting emissions, which also damage all foreign countries (global externality). Let v_i be the emission–output ratio of the i–th firm, i=1,...,n. The level of emissions in country i is:

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4 Pioniecring works in this field are the ones by Katz (1986), D'Aspremont–Jacquemin (1988). A good survey is Katz–Ordover (1990). Recent developments can be found in Suzumura (1990), Wu–De Bondt (1991) and Motta (1992).

$$c_i = v_i y_i - q_i \geq 0 \qquad i=1, \dots ,n \tag{4}$$

In plain words, emissions are proportional to the output level, but can be reduced by the abatement activity imposed by the government and carried out by the firm. R&D also plays a crucial role in reducing emissions. We asssume that the firm's innovation effort does affect both the economic and environmental features of the production technology. Hence, the firm's R&D can reduce the emission–output ratio v_i. For simplicity, let us write:

$$v_i = v - \alpha(x_i + \beta_e \Sigma_j x_j) \geq 0 \qquad \text{if } i,j \in J \tag{5a}$$

$$v_i = v - \alpha x_i \geq 0 \qquad \text{if } i \in J^o \tag{5b}$$

where $\alpha \geq 0$, $1 \geq \beta_e \geq 0$. Notice that α is a parameter that converts the R&D expenditure into emission units, whereas β_e denotes the "environmental technological leakage". Consistently with Assumption 1, we assume that only those countries which belong to the coalition can profit from such leakage.[5]

As discussed in the Introduction, the environmental problem is global. Hence, the environmental damage depends on the emissions produced by all firms. The damage function can thus be written as:

$$D_i(E) = \delta(e_1 + e_2 \dots + e_n) \qquad i=1,\dots,n \tag{6}$$

where $E = e_1 + e_2 \dots + e_n \geq 0$ are total global emissions. By replacing eq.(4) into (6), we get:

$$D_i(Y,x,q) = \delta(v_1 y_1 - q_1, \dots, v_n y_n - q_n) \geq 0 \tag{7}$$

where $q = (q_1, \dots ,q_n)$, $x = (x_1, \dots ,x_n)$.

In each country the government, or a regulatory agency, takes two decisions. The first one is whether or not to join the coalition. The government joining the coalition knows that it will

5 The "environmental technological leakage" for those countries which do not join the coalition is normalised to zero.

obtain benefits both from environmental and technological cooperation, as the two issues are linked. The decision about cooperation is taken by anticipating that all countries which do not cooperate cannot profit from the coalition innovation leakage. The second decision concerns the environmental standard, i.e. the abatement level to be imposed to the firms.

Both decisions are taken by maximizing a social welfare function defined as the sum of the domestic firm's profits, the domestic consumers' surplus, minus the environmental damage born by the country:

(8) $$P_i(Y,E,q) = \pi_i(Y,x,q_i) + CS_i(Y) - D_i(Y,x,q) \qquad i=1,\dots,n$$

Given the linearity of the inverse demand function, it is easy to show that:

(9) $$CS_i(Y) = \tfrac{1}{2}by^2_i$$

The firm's decisions are taken by maximising the profit function (3a) or (3b). The sequence of decisions is the following: first the government decides whether or not to cooperate; then, given this decision, it sets the optimal environmental standard (abatement level); finally, all firms decide simultaneously and non–cooperatively R&D expenditure and production.

4. The Last Stage of the Game: Production and R&D

Solving the game backward, suppose that j countries have decided to cooperate, and that the abatement levels are equal to q_i if $i \in J$, and to q^o_i if $i \in J^o$. The firm's first order conditions are:

(10a) $$a - c - b(n-j)y^o_h - b(j+1)y_i + (x_i + \beta(j-1)x_j) = 0 \qquad i,j \in J,\ h \in J^o$$

(10b) $$y_i - gx_i = 0 \qquad i \in J$$

(11a) $$a - c - bjy_j - b(n-j+1)y^o_i + x^o_i = 0 \qquad i \in J^o,\ j \in J$$

(11b) $$y^o_i - gx^o_i = 0 \qquad i \in J^o$$

where y^o_i and x^o_i denote the production and R&D level of non–cooperating countries, respectively. The two groups of countries' Nash–Cournot best–reply functions are:

$$\text{(12a)}\quad y_i = \frac{a-c-b(n-j)y^o_h}{b(j+1)-k(1+\beta(j-1))} \qquad i\in J,\ h\in J^o$$

and

$$\text{(12b)}\quad y^o_h = \frac{a-c-bjy_i}{b(n-j+1)-k} \qquad i\in J,\ h\in J^o$$

where we used the relation $x_i = ky_i$ if $i\in J$, and $x^o_i = kx^o_i$ if $i\in J^o$, $k=1/g$.

Both functions are negatively sloped if $b > k$. Hence, whenever a group of cooperating countries expand their own production, the remaining countries reduce their output. The reason is the following: firms belonging to cooperating countries have a lower marginal cost (through the differential technological leakage): hence, they increase their market share (see Figure 1a). This effect is crucial for the results that we will obtain in the sequel. We therefore assume:

Assumption 2: *The reaction functions of the two groups of countries are negatively sloped, i.e. $b > k$.*

The solution of the system defined by (12a) and (12b) determines the equilibrium production level for the two groups of firms:

$$\text{(13a)}\qquad y_i(j) = h(b-k)/\theta_o \qquad i\in J$$

$$\text{(13b)}\qquad y^o_h(j) = h[b - k(1+\beta(j-1))]/\theta_o \qquad h\in J^o$$

where $\theta_o = b^2(n+1)+bk[j^2\beta-j\beta(n+2)+n(\beta-1)+\beta-2]+k^2(1+\beta(j-1)) > 0$ for $2\le j\le n$, $\beta<1$. Both production levels are positive if $b \geq k(1+\beta(j-1))$ for all $2 \leq j \leq n$. Moreover, it is $y_i \geq y^o_h$ for $n \geq j \geq 2$, as shown in Figure 1.a. Notice that both output levels depend on the number of countries joining the coalition.

In order to obtain meaningful results we need to impose the following restriction: the marginal cost of firms belonging to cooperating countries must be non–negative[6]. In other words, the coalition information exchange must not reduce the firms' production cost more than c. This is equivalent to say that $c_i(j) \geq 0$, $i \in J$, for all $2 \leq j \leq n$, which is guaranteed by the following normalization:

$$c = ak(1+\beta(n-1))/(b(n+1)) \tag{14}$$

Morcovevr, we assume:

Assumption 3: *No firm find it profitable to exit the market, whatever the size of the environmental coalition.*

The reason is that we want to guarantee that the environmental game is played by n governments (i.e. n firms): hence no firm exits the market. This implies that each firm's equilibrium profit must be positive for all $2 \leq j \leq n$. As previously said, production is positive if $b \geq k(1+\beta(j-1))$ for all $2 \leq j \leq n$. However, firms' profit depends on R&D and abatement costs. Using the first order conditons (3), it is possible to write:

$$\pi_i(j) = (2b-k)\tfrac{1}{2}y^2_i(j) - \tfrac{1}{2}\Phi q^2_i \geq 0 \qquad i \in J \tag{15a}$$
$$\pi^o_h(j) = (2b-k)\tfrac{1}{2}y^{o2}_h(j) - \tfrac{1}{2}\Phi q^{o2}_h \geq 0 \qquad h \in J^o \tag{15b}$$

where $y_i(j)$ and $y^o_i(j)$ are defined by eqs. (13). Figure 1.b shows the relationship between $\pi_i(j)$ and the number of cooperating countries for a given q_i. Notice that profits first increase and then decrease, as j increase. The reason is the following: when the coalition gets larger, firms belonging to countries in the coalition increase their profits both because their marginal cost is lower, and because they increase their market share. This latter effect disappears as j

6 This is sufficient to guarantee that also the marginal cost of firms belonging to non–cooperating countries is non–negative.

approximates n. When j=n, all firms are identical, and profits are higher than in the cooperative case only because marginal costs are lower (through the R&D effect).

The restrictions $\pi_i(j)\geq 0$, $i\in J$, and $\pi^o_h(j)\geq 0$, $h\in J^o$ imply that there must exist an upper bound on the governments' environment policy, i.e. if the abatement policy is excessively stringent, firms prefer to exit the market[7]. The abatement strategy q_i must therefore belong to the strategy space $[0,q_{max}]$ if $i\in J$, and to the strategy space $[0,q^o_{max}]$ if $j\in J^o$. These upper bounds are implicitly defined by $\pi_i(j) \geq 0$, and $\pi^o_h(j) \geq 0$. They will be determined in the next section.

5. The Second Stage of the Game: Optimal Abatement Levels

Let us assume that j countries join the coalition. The decision about abatement levels of the j cooperating countries and of the n-j non-cooperating countries is taken by anticipating the firms' reactions to environmental policy. Using eqs. (5),(7),(9) and (15), we can re-write country i's social welfare function (8) in the following way:

$$(16a)\quad P_i(j) = (3b-k)\tfrac{1}{2}y^2_i(j) - \tfrac{1}{2}\Phi q^2_i + \delta(jq_i + (n-j)q^o_h) + \delta\alpha k[j(1+\beta_c(j-1))y^2_i(j) + (n-j)y^{o2}_h(j)] - \delta v(jy_i(j) + (n-j)y^o_h(j)) \qquad i\in J,\ h\in J^o$$

$$(16b)\quad Q_h(j) = (3b-k)\tfrac{1}{2}y^{o2}_h(j) - \tfrac{1}{2}\Phi q^{o2}_h + \delta(jq_i + (n-j)q^o_h) + \delta\alpha k[j(1+\beta_c(j-1))y^2_i(j) + (n-j)y^{o2}_h(j)] - \delta v(jy_i(j) + (n-j)y^o_h(j)) \qquad i\in J,\ h\in J^o$$

where $P_i(j)$ denotes the payoff of the i-th cooperating country when the coalition is formed by j governments, whereas $Q_h(j)$ denotes the payoff of the h-th non-cooperating country. Given the symmetry of the game, we will not use the subscipts i and h in the sequel.

Notice that P(j) and Q(j) are defined by three components:

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7 In this paper, we assume that re-location costs are sufficiently high to prevent firms from moving their plants to a country with a weaker environmental policy.

(i) *The production effect*: $H(j) = (3b-k)\frac{1}{2}y^2_i(j) \geq 0$, and $H^o(j) = (3b-k)\frac{1}{2}y^{o2}_h(j) \geq 0$, as $b > k$ by Assumption 1. This component captures the effect of the coalition on the domestic firms' profits and consumers' surplus. As the coalition reduces unit production costs, through the information exchange parameter β, it increases production, thus increasing the firms' profit and the consumers' surplus. However, as j approximates n, the market-share effect tends to zero; hence, the shape of H(j) looks like the shape of $\pi_i(j)$ as depicted in Figure 1.b.

(ii) *The abatement effect*: $A(j) = \delta(jq_i+(n-j)q^o_h) - \frac{1}{2}\Phi q^2_h$ and $A^o(j) = \delta(jq_i+(n-j)q^o_h) - \frac{1}{2}\Phi q^{o2}_h$. This is the part of the welfare function which is commonly used in the environmental literature (e.g. Hoel,1991; Barrett,1992; Carraro-Siniscalco,1992). It is composed by two effects. The positive effect of abatement levels on emission control (a cleaner environment), and the negative effect of the abatement costs.

(iii) *The emission/output technological effect*: $T(j) = \delta\alpha k[j(1+\beta_e(j-1))y^2_i(j) + (n-j)y^{o2}_h(j)] - \delta v(jy_i(j) + (n-j)y^o_h(j)) = T^o(j) \leq 0$. This additional component of the welfare function derives from the negative effect of production on emissions. This negative effect can be reduced by firms' R&D, which changes the environmental features of the production technology, and therefore the emission/output ratio v_i, i=1,..n.

We can therefore write:

(17a) $$P(j) = H(j) + A(j) + T(j)$$

(17b) $$Q(j) = H^o(j) + A^o(j) + T^o(j)$$

The above three components are very important to understand how the coalition is formed, and which forces defines its profitability and stability.

Before tackling such issue, let us first determine the optimal abatement levels. By maximising eqs. (16a) and (16b), we get:

(18a) $$q_i = \delta j/\Phi \qquad i \in J$$

(18b) $$q^o_h = \delta/\Phi \qquad h \in J^o$$

As usual (see Barrett, 1992, Carraro–Siniscalco, 1992), the cooperative abatement level increases with the number of countries which join the coalition, whereas the non–cooperative one is constant. This case correspond to a situation in which the governments' reaction functions are orthogonal. In words, this amounts to saying that non–cooperating countries profit from the cleaner environment produced by the abatement effort of the coalition, but do not expand their emissions whenever the cooperating countries reduce their own emissions. As argued in Carraro–Siniscalco (1993a), this situation is the most likely when the environmental problem is global (e.g. global warming). Moreover, as shown in Barrett (1992), Carraro–Siniscalco (1992), orthogonal reaction functions provide the most favourable conditions for stable environmental (partial) coalitions to emerge.

By replacing the equilibrium abatement levels into the second component of the welfare functions we get:

(19a) $$A(j) = \delta^2(j^2-2j+2n)/2\Phi \geq 0$$

(19b) $$A^o(j) = \delta^2(2j^2-2j+2n-1)/2\Phi \geq 0$$

which are strictly positive for all $2 \leq j \leq n$. Hence, the function P(j) has two positive components, H(j) and A(j), and one negative component, T(j).

We need to show that the equilibrium abatement levels defined by eqs. (18) do not induce firms to exit the market (notice that this would also produce a drop in the country welfare which would become negative). As far as cooperating countries are concerned, the maximum abatement cost and the minimum profit is achieved when $2<j=n$. Hence, a sufficient condition for $\pi_i(j) \geq 0$, $i \in J$, is $\pi_i(n) \geq 0$, i.e. $k \leq b[2-(n^2\delta^2(n+1)^2b)/(a^2\Phi)]$, which implies $k<2b$, and is implied by Assumption 2 if $a^2 \geq (n^2\delta^2(n+1)^2b)/\Phi$. By solving this inequality with respect to Φ, we obtain the level of q_{max} previously defined:

$$q_{max} = a^2/[\delta bn(n+1)^2]$$

Notice that the above restrictions require either that the unit marginal cost of R&D should not be too high or that the level of market demand should be sufficiently high not to induce firms belonging to J to exit the market.

Let us consider non–cooperating countries. The minimum profit is achieved by the firm in the non–cooperating country when n–1 countries cooperate because, in such case, the competitors technological advantage is maximum. Hence, a sufficient condition for $\pi^o_h(j)\geq 0$, $h\in J^o$, is $\pi^o_h(n)\geq 0$. Without loss of generality, we normalize $\pi^o_h(n)=0$, thus obtaining:

(20) $$\beta = [b-k]/[k(n-1)] - [\delta^2 b(n+1)(b-k)]/[ak\Phi(2b-k)(n-1)]$$

which is lower than one for b>k and a>0. By solving this equation with respect to Φ, we obtain:

$$q^o_{max} = [a(2b-k)(b-k(1+\beta(n-1))]/[b\delta(n+1)(b-k)]$$

By replacing eqs. (14) and (20) into the equilibrium values of production (eqs. 13), we get:

(21a) $$y_i(j) = [a(n-1)(an\Phi(2b-k)+\delta^2(b-k)(n+1))]/\theta$$

(21b) $$y^o_i(j) = [a\Phi(2b-k)(n-j)+b\delta^2(j-1)(n+1)][a\Phi(2b-k)n+\delta^2(b-k)(n+1)]/[\Phi(2b-k)\theta]$$

where $$\theta = (n+1)[bn^2(a\Phi(2b-k)+b\delta^2(j-1))-(b(j-1)+k)(an\Phi(2b-k)+b\delta^2(j-1)) + (b(j-2)+k)(a\Phi j(2b-k)-bn\delta^2(j-1))]$$

Finally, the governments' welfare function is defined either by eq. (16a) or (16b), were $y_i(j)$ and $y^o_i(j)$ are given by eqs. (21), whereas q_i and q^o_i are given by eqs. (18).

6. The First Stage of the Game: Stable Coalitions

It is now possible to determine the size of the profitable and stable coalitions. Using the definitions proposed in Carraro–Siniscalco (1993a), the Largest coalition satisfying both the Profitability and the Stability condition (henceforth LPS coalition) is defined by j^* such that:

(22a) $$P(j^*) \geq 0$$
(22b) $$L(j^*) = 0$$

where $L(j) = P(j) - Q(j-1)$ is the stability function (see Carraro–Siniscalco, 1993a).[8]

The previous literature on stable environmental coalitions only considers the second component, i.e. A(j), of the welfare functions (17). In such case, the profitability of any coalition is easily proved, because $A(j) > 0$ for all $2 \leq j \leq n$. Hence, the LPS coalition is defined by the j^* such that $A(j) - A^o(j-1) = \delta^2(4j-j^2-3)/2\Phi = 0$. The stability function component $A(j)-A^o(j-1)$ is shown in Figure 1.c. It is easy to check that $j^* = 3$, whatever n. This result was first proposed in the cartel stability literature (D'Aspremont et al., 1983), and can be found in Hoel (1991), Carraro–Siniscalco (1992,1993a), and Barrett (1992). As stated in the Introduction, the result is quite strong. Profitable and stable coalitions exists, but they tend to be small, whatever the number of countries. Hence, their contribution to environmental protection is generally small.[9]

However, the above conclusions neglect the role of R&D and of R&D cooperation, both on production (profits and consumers' surplus) and on the emission/output ratio. Let us consider first the production effect. Given Assumption 3, $H(j) \geq 0$ for all $2 \leq j \leq n$ if and only if $3b>k$, which is implied by Assumption 2. The stability function of the production effect is:

$$(23) \qquad \begin{aligned} &H(j) - H^o(j-1) = \\ &= (1/\theta_{II})an^2(j-1)(3b-k)[bn^2-n(bj+k)+bj^2-(3b-k)(j-1)] \\ &\quad [2bn^3-n^2(3b(j-1)+2k)+n(3j-1)(k+b(j-2))-(j-1)(bj^2-(3b-k)(j+1))] \end{aligned}$$

where $\theta_{II} = 2(n+1)^2[bn^2-n(k+b(j-1))+j(k+b(j-2))]^2[bn^2-n(k+b(j-2))+(j-1)(k+b(j-3))]^2$

The difficulty of studying this function with respect to the value of j is self-evident. We therefore present some numerical simulations of the function (23), which is plotted, for two different sets of the parameters, in Figure 2 (in particular, we assume n=100)[10]. Figure 2 shows

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8 In Carraro–Siniscalco (1994b) this definition of stability is compared with other proposals: the coalition–proof equilibrium proposed by Bernheim–Peleg–Whinston (1987), and the non–myopic stability concept proposed by Rotschild (1992) (see also Bauer, 1993). It is shown that the latter implies non–zero conjectural variations which are not consistent with the Nash equilibrium concept.

9 Of course, this conclusion depends on the assumption of symmetric countries. Were countries different, the coalition of the largest ones could produce significative effects on emissions.

10All pictures are drawn by taking into account the restrictions imposed on the parameter of the model. In particular, $b > k$, $\pi_i(j) \geq 0$, $\pi^o_i(j) \leq 0$ which imply $0 \leq q_i \leq q_{max}$, $0 \leq q^o_i \leq q^o_{max}$ and $c_i(j) \geq 0$, $2 \leq j \leq n$, i=1,2,...n.

that the production effect is much more stable than the abatement effect. The stability function (23) may never cross the x–axis for $j \leq n$.

The reason is the following: the production effect, which derives from the differential innovation leakage on the production cost, is appropriable, i.e. the coalition can exclude non cooperating countries from such benefit. By contrast, the abatement effect, i.e. the benefit from a cleaner environement, is not excludable, i.e. all countries profit from the coalition higher abatement levels.

Notice that the production effect could completely offset the instability of the abatement effect.[11] This is shown in Figure 3, which presents situations in which the LPS coalition determined by considering both the production and the abatement effects is equal to $j^{*}=n=100$. Moreover, the two effects add on in terms of profitability. As previously stated, both A(j) and H(j) are positive for $2 \leq j \leq n$. Hence, the linkage of negotiations on technological cooperation with negotiations on environmental protection increases both the profitability and the stability of the emerging coalition.

The humped shape of the stability function component $H(j) - H^{o}(j-1)$ can be understood be re–calling that entering the coalition has two positive effects for the firm: on the one side, production costs decrease; on the other side, market share increases. However, this latter effect becomes smaller and smaller as the coalition size increases. Hence, the loss from leaving the coalition decreases when j is above a given intermediate value. This obviously reduces the coalition stability.

Let us finally consider the last effect, which accounts for the impact on emissions of positive production levels, and on the emission/output ratio of the firms' R&D. This effect is negative, because T(j) measures the welfare effect of positive emission levels. As positive production levels imply positive emissions, the effect on the welfare function is negative. Figure 4 shows two possible graphs of T(j). Notice that T(j) is increasing for most values of j. The

11 A general theoretical framework from which conditions for the linkage of two negotiations to stabilize a coalition are derived, is contained in Carraro–Siniscalco (1993b).

reason is the following: when more countries cooperate, the environmental innovation leakage increases, thus reducing the emission/output ratio and emissions. This effect is partly offset by the increased production of cooperating countries. The positive slope of T(j) for most $j<n$ is important because it explains why a larger coalition can become more stable through the effect on the emission–output ratio induced by the environmental innovation leakage.

The stability function component T(j)–T(j–1) cannot be studied analytically. Its behaviour is represented in Figure 5 for two sets of parameters (which correspond to the ones used in Figure 4). It is clear that this component of the stability function L(j) adds stability to the coalition because it is positive unless j becomes very large. The reason, as previously suggested, is related to the role of the environmental innovation leakage. Whenever a country exits the coalition, its firms cannot share the environmental benefits of the coalition information exchange (i.e. a lower emission–output ratio). Hence, there exists an incentive not to leave the coalition, partly offset by the fact each firm's production keeps increasing as j goes to n.

We finally add the three components of the welfare function. From Figure 6 and 7, which describe the profitability and stability of the linked negotiation, we observe the behaviour of the functions P(j) and L(j). It can be seen that there exist parameter configurations such that the LPS coalition is equal to $j^*=100$. This is the case when the environmental damage coefficient δ and/or the emission/output ratio v_i are sufficiently low, so that the production boost induced by R&D cooperation among signatories can increase profits without excessively increasing pollution. We can therefore conclude that, in our numerical example, all countries may find it profitable to join the coalition, and to cooperatively reduce emissions, even in the absence of a supra–national authority and of any form of commitment.

The optimality of linking the negotiations about R&D and environmental cooperation can easily be proved if $j^* = 100$. In such case, signatories achieve both the benefits of the R&D coalitions (which could be achieved anyway, because stable for all $2\leq j\leq n$) and the benefits of the environmental coalition (which is unstable, but it is stabilized by linking the two negotiations).[12]

12 General conditions for the Pareto optimality of linking two negotiations are provided in Carraro–Siniscalco (1993b).

7. Concluding Remarks

This paper has provided theoretical support to a claim contained in Carraro–Sinscalco (1993b, 1994a) where it is argued that the linkage of negotiations on environmental protection with negotiations on other economic issues may increase the number of countries which decide to adopt measures to protect the environment. In the model proposed in this paper, the environmental negotiation is linked to the negotiation on technological cooperation. The reason is that the latter has the characteristics indicated in Carraro–Siniscalco (1993b) for the coalition emerging from the linked negotiation to be profitable and more stable than the one resulting from negotiating on the environment only.

As proved in the paper, the environmental agreement and technological cooperation can be analyzed as two separate negotiations. The environmental coalition is profitable but unstable; technological cooperation is profitable and stable. The linked negotiation is more profitable than the two separate negotiations, and more stable than the environmental negotiation, as it uses the gains from technological cooperation to offset the environmental free–riding incentives and to reach full cooperation both on technology and on the environment.

The profitability and the stability of the coalition emerging from linking negotiations on technological and environmental cooperation are the result of four different effects on welfare. Three effects are unambiguously positive, both with respect to profitability and stability. First, the benefits from technological cooperation are partly excludable and mostly confined to the countries which sign the environmental agreement. Technological cooperation decreses marginal costs of the firms belonging to the cooperating countries, increasing their profits and welfare thereafter. Second, by reducing costs it increases output (a Cournot oligopoly is assumed), and raises the consumer surplus in the cooperating countries. Third, the incentive to cooperate on technology (linked to environmental cooperation) overcomes the incentive to free–ride on the environment. Since environmental cooperation is profitable, the expansion of the environmental coalition through the link between negotiations increases welfare. Finally, there is a negative environmental effect: the increase in output generates additional emissions. In the numerical example provided, the net effect on welfare is positive and the link of the two negotiations is optimal, as it increases the ex-post welfare of all cooperating countries.

The assumptions adopted in the paper are the most favourable to a succesful linkage of negotiations on technological and environmental cooperation. In particular, we assumed that countries which do not join the coalition can be completely excluded from the benefits arising from technological cooperation. Moreover, we assumed that technological innovation reduces both the average production cost and the emission/output ratio. Both these assumptions can be relaxed without modifying the main conclusions of the paper. It simply becomes more difficult to achieve full cooperation if innovation partly spills over countries outside the coalition and/or technological innovation only concerns the emissio/output ratio. More importantly, we have neglected negotiation costs that can increase when negotiations take place over two economic issues instead of focusing on one issue only. These "transaction costs" can be large, and can explain why negotiation linkages are hardly observed in reality. However, as shown in the paper, the benefit of linking two negotiations may be very high, if the linkage is appropriately designed. In particular, the environmental benefit which would otherwise be lost may be quite relevant. Hence, policymakers are recommended to explore the possibility of linking environmental negotiations to negotiations on other issues (e.g technological cooperation), and to carefully evaluate benefits and costs of such linkage.

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FIGURE 1

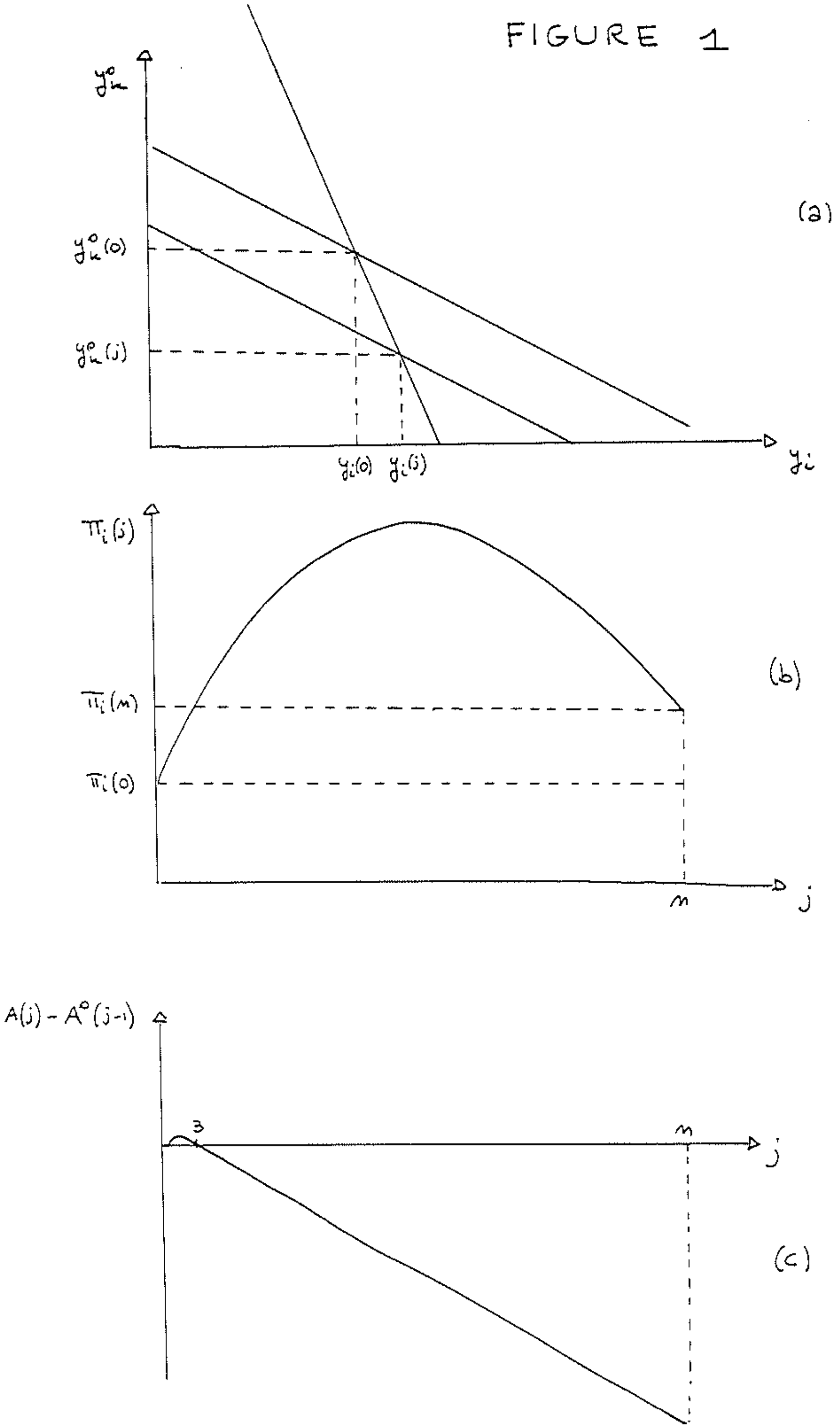
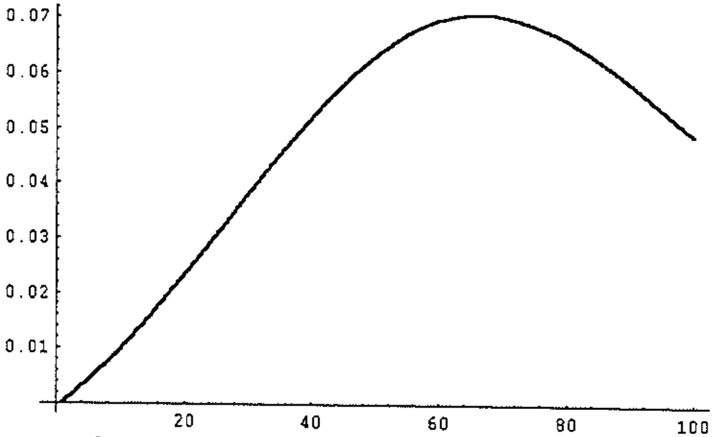


Figure 2: $\Delta H(j)$

Parameter values: a = 20, b = 1, n = 100, k = 0.5, phi = 2, delta = 0.001



Parameter values: a = 20, b = 1, n = 100, k = 0.9, phi = 2, delta = 0.001

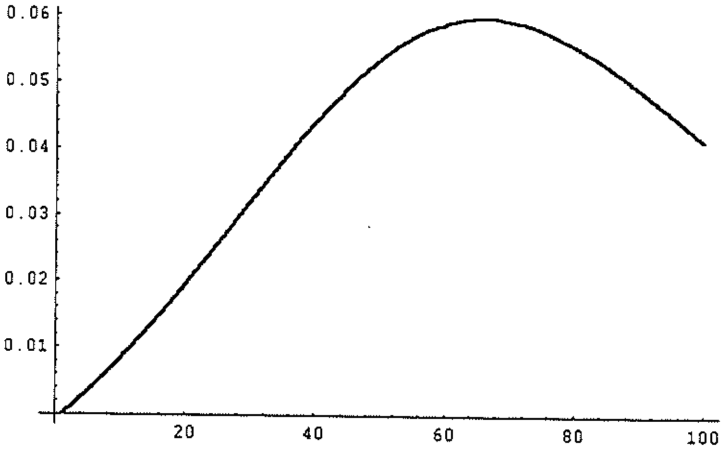
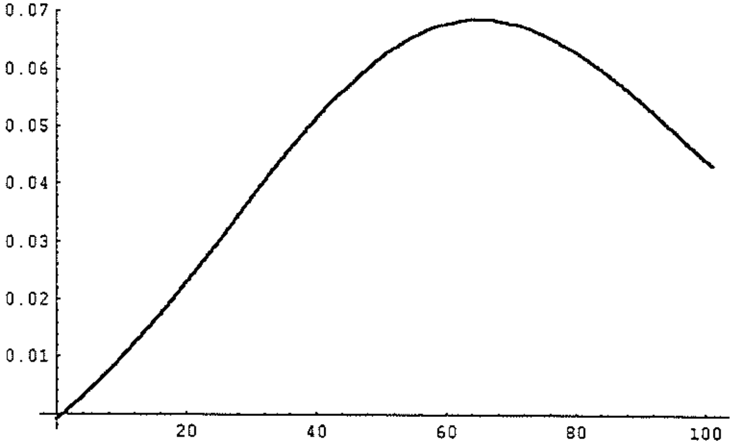


Figure 3: ΔA(j)+ΔH(j)

Parameter values: a = 20, b = 1, n = 100, k = 0.5, phi = 2, delta = 0.001



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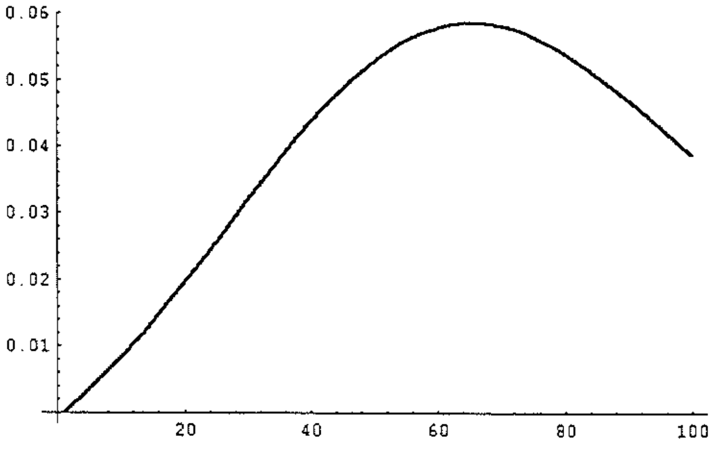
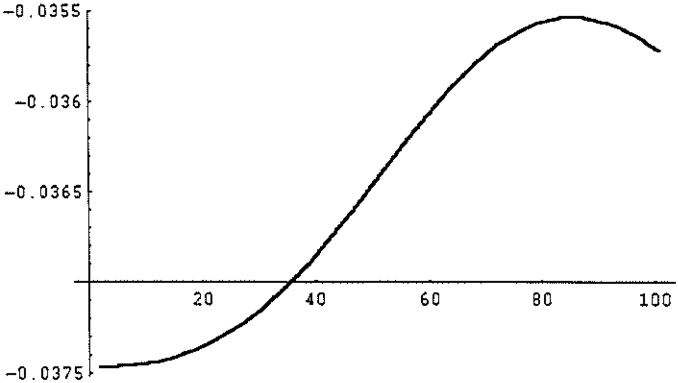


Figure 4: T(j)

Parameter values: a=20, b=1, n=100, k=0.5, phi=2, delta=1/1000, β_0=0.01, $\alpha = 1, v = 2$



Parameter values: a=20, b=1, n=100, k=0.9, phi=2, delta=1/1000, β_0=0.01, $\alpha = 1, v = 2$

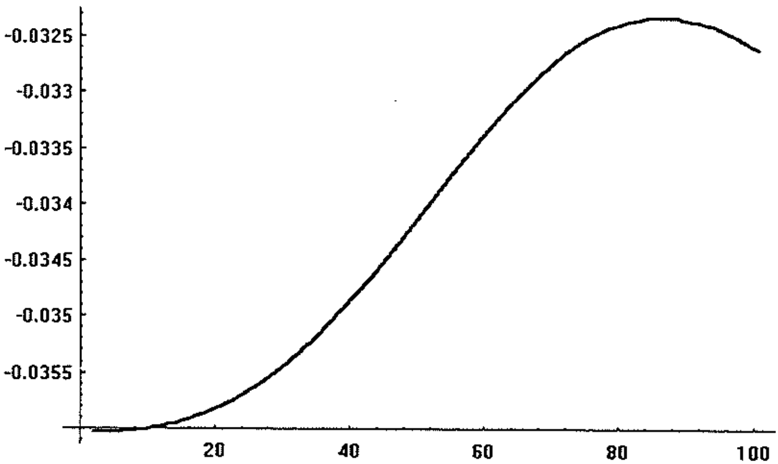
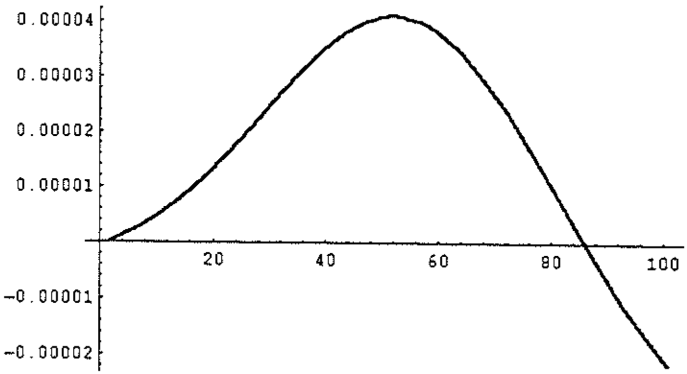


Figure 5: T(j) – T(j–1)

Parameter values: a=20, b=1, n=100, k=0.5, phi=2, delta=1/1000, β_o=0.01, $\alpha = 1, v = 2$



Parameter values: a=20, b=1, n=100, k=0.9, phi=2, delta=1/1000, β_o=0.01, $\alpha = 1, v = 2$

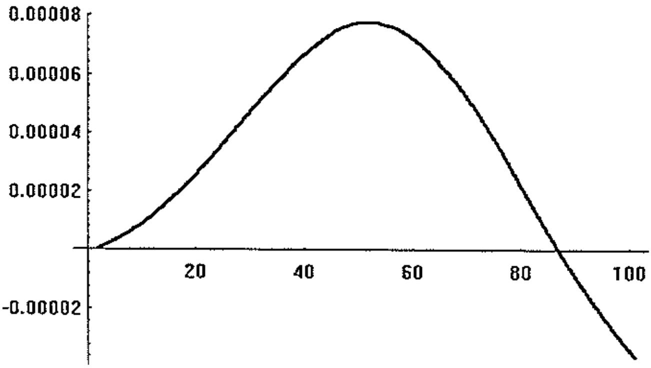
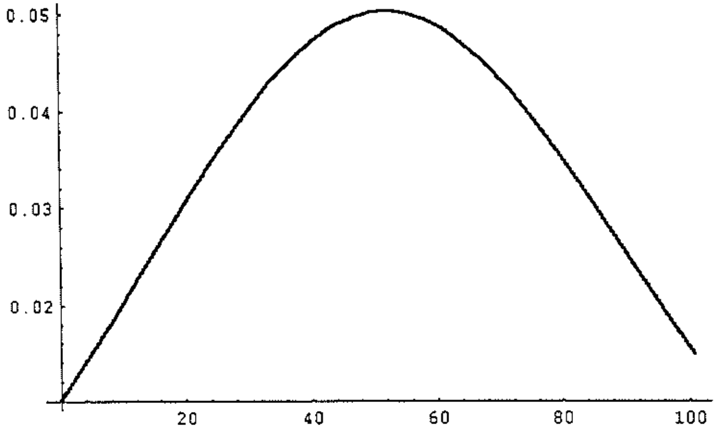


Figure 6: P(j)

Parameter values: n = 100, a = 20, b = 1 k = 0.5, $\varphi = 2$; δ =1/1000, β_o =0.01, δ = 0.001, α = 1, v = 2



Parameter values: n = 100, a = 20, b = 1 k = 0.9, $\varphi = 2$; δ =1/1000, β_o =0.01, δ = 0.001, α = 1, v = 2

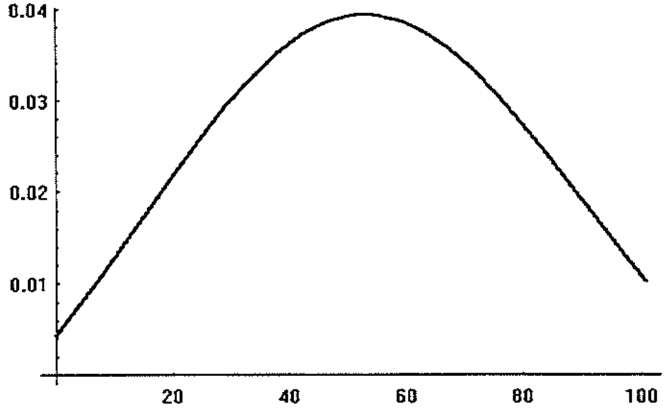
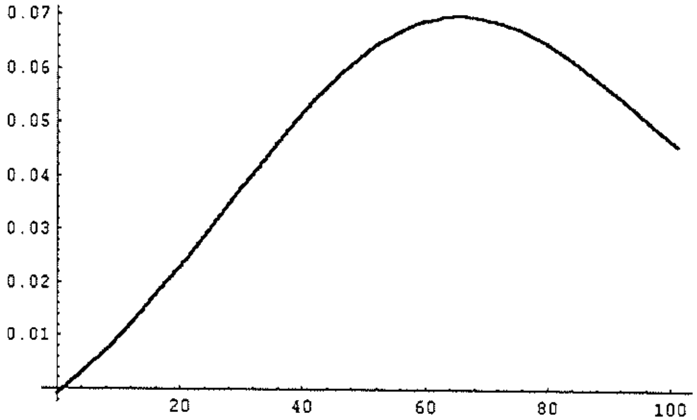


Figure 7: L(j)

Parameter values: n = 100, a = 20, b = 1 k = 0.5, $\varphi = 2$; $\delta = 1/1000$, $\beta_o = 0.01$, $\delta = 0.001$, $\alpha = 1$, v = 2



Parameter values: n = 100, a = 20, b = 1 k = 0.9, $\varphi = 2$; $\delta = 1/1000$, $\beta_o = 0.01$, $\delta = 0.001$, $\alpha = 1$, v = 2