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# GENERAL EQUILIBRIUM MODELS OF ENVIRONMENTAL REGULATION AND INTERNATIONAL TRADE

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# General equilibrium models of environmental regulation and international trade

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## Abstract

The literature on the effects of environmental policy on international competitiveness consists mainly of partial equilibrium models. From a methodological point of view a general equilibrium approach is to be preferred. Only very few studies take a general equilibrium point of view but they do not reach clear-cut conclusions and do not to perform sensitivity analyses. In the present paper we make a contribution to the general equilibrium approach and provide some interesting numerical examples, showing that partial equilibrium results do not generally hold in a general equilibrium setting. This has important implications for tax policies in the presence of environmental externalities.

## 1. Introduction

Loosely speaking the expression "ecological dumping" is used to describe the phenomenon that governments, acting strategically, impose too lax environmental taxes in order to enhance the competitiveness of domestic firms on the world market. Seminal work on the theory of ecological dumping and strategic behaviour in the context of international trade has been done by Rauscher (1994). His work is important in several respects. First, it provides a clear definition of the phenomenon of ecological dumping. Second, it constructs a simple but full-fledged general equilibrium model of international trade involving externalities. Third, for several market structures it is shown that, contrary to popular views, ecological dumping might, in the absence of the possibility of reaching a first best optimum due to the unavailability of the desired instruments, not be beneficial from a welfare point of view.

The analysis makes clear that it is difficult to obtain general results and, indeed, particular assumptions with respect to the functions involved have to be made. Sometimes these assumptions do not refer to exogenous parameters but to the values of these functions, or their derivatives, in the presupposed equilibrium or even to the value of determinants composed in a complex way from equilibrium values. This makes it difficult to see from the primitives of an economy (i.e. the parameter values of the model) which conclusions are likely to hold.

In the present paper an attempt is undertaken to provide numerical examples that will reveal the dependence of results on the basic parameters used. We first sketch the approach taken by Rauscher and summarise his results. Subsequently specific functional forms will be introduced to illustrate his findings. In addition the present paper offers a formal general equilibrium model of oligopolistic competition and strategic environmental policy, after a discussion of a partial equilibrium approach along the lines set out by Barrett

(1994). The international trade literature pays increasing attention to strategic behaviour, which make it especially interesting to study oligopolistic markets, where such behaviour is pertinent.

## 2. The model

The models discussed throughout this paper have several characteristics in common that are outlined in the present section. The models are all inspired by the model used by Rauscher (o.c.). A difference is that we shall work with emission taxes instead of standards throughout. In the case of perfect competition taxes allow us to work with the concept of factor price frontier which brings along some advantages.

There are three *consumer commodities*, there is *capital* and there is a *raw material*.

-The first consumer commodity is produced and consumed domestically only. Production takes place according to a technology described by a production function $(F_1)$, with capital $(k_1)$ and raw material $(y_1)$ as inputs. The first consumer commodity serves as the numéraire. Consumption is denoted by $c_1$.

-The second consumer commodity is produced domestically, according to a production function $(F_2)$, having capital $(k_2)$ and raw material $(y_2)$ as arguments. Part of the output is consumed domestically $(c_2)$, part of it is exported $(x)$. Foreign demand depends on the export price $(p_2)$. Hence $x = x(p_2)$. Introduction of a competing commodity will be postponed until section 5, where oligopolistic world markets are introduced.

-The third consumer commodity can not be produced domestically. It is imported. Consumption is denoted by $c_3$. Its world market price is $p_3$. Throughout the paper that price is given to the economy.

-Capital is immobile internationally but mobile between domestic sectors. Empirical as well as theoretical support for the assumption of international immobility of capital can be found in Gordon and Bovenberg (1996). The economy's endowment is given by $\bar{k}$. The domestic rate of return on capital is $r$.

-The raw material is in principle freely available in unlimited amounts. However, processing of the raw material causes pollution, which is deemed damaging. For that reason the government levies taxes $\tau_1$ and $\tau_2$ per unit of raw material used by the firms. These taxes can be differentiated between sectors. The tax revenues are recycled to the consumers in a lump sum fashion.

There is one representative *consumer*. His income consists of the value of the capital endowment $r\bar{k}$, the tax revenues $\tau_1 y_1 + \tau_2 y_2$, and the profits of the firms, which amount to $F_1(k_1, y_1) - rk_1 - \tau_1 y_1$ and $p_2 F_2(k_2, y_2) - rk_2 - \tau_2 y_2$ for the sheltered and the exposed sector respectively, assuming for the moment that the domestic price of the second commodity equals its world market price. Under the assumption of full employment of capital (in a situation where firms maximise profits) total income boils down to (in shorthand) $F_1 + p_2 F_2$. The consumer are maximizes utility, taking prices and income given. Preferences of the consumer refer to two types of commodities. First, they depend on the consumption of the consumer goods. This is represented by a utility function, denoted by $U(c_1, c_2, c_3)$, which is assumed to have all the usually desired properties such as concavity, differentiability and monotonicity. The use of the raw material brings along pollution (in a proportional way). That is the primary reason for the taxation. This part of the preferences is given by the (convex and increasing) damage function $D(y_1 + y_2)$.

An assumption made in the first sections of the paper is that in each sector of the economy there are a large number of price-taking competing firms, identical per sector, which are all profit maximising. Later on, we discuss monopoly and oligopolistic market structures.

## 3. The first best optimum; full competition and monopoly

Several steps will be taken in the framework developed above. The first step is to calculate the social optimum subject to equilibrium on the current account: $p_3 c_3 = p_2 x(p_2)$. Mathematically, the problem to be solved by the central planner is to find rates of consumption, inputs in production and exports such that

$$U(c_1, c_2, c_3) - D(y_1 + y_2)$$

is maximised, subject to

(3.1) $c_1 = F_1(k_1, y_1)$

(3.2) $c_2 = F_2(k_2, y_2) - x(p_2)$

(3.3) $p_3 c_3 = p_2 x(p_2)$

(3.4) $k_1 + k_2 = \bar{k}$

The Lagrangian of the problem reads:

$$L = U(c_1, c_2, c_3) - D(y_1 + y_2) + \varphi_1[F_1(k_1, y_1) - c_1] + \varphi_2[F_2(k_2, y_2) - x(p_2) - c_2]$$

$$+ \varphi_3[p_2 x(p_2) - p_3 c_3] + \mu[\bar{k} - k_1 - k_2]$$

Assuming an interior solution and differentiability, in the equilibrium, of the functions involved, we find as necessary conditions

$$U_{c_1} = \varphi_1$$

$$U_{c_2} = \varphi_2$$

$$U_{c_3} = p_3 \varphi_3$$

$$\phi_1 F_{1k} = \mu; \; D_y = \varphi_1 F_{1y}$$

$$\phi_2 F_{2k} = \mu; \; D_y = \varphi_2 F_{2y}$$

$$-\varphi_2 x_p + \varphi_3[x + p_2 x_p] = 0$$

where subscripts refer to (partial) derivatives. In the sequel stars will denote the solution of this problem: $(c_1^*, c_2^*, c_3^*, p_2^*, k_1^*, k_2^*, y_1^*, y_2^*, x^*)$. Also the corresponding multipliers are denoted by stars.

The second step is to show that the first best optimum can be realised in a decentralised setting. To that end emission taxes are set equal to the marginal damage of emissions, domestic prices of the first two commodities should equal world market prices and an import tariff on the third commodity should be imposed. It is assumed that the exporting industry consists of many price-taking firms, but that the economy *as a whole* can influence prices on the world market.

Take

$$p_1 = 1,\ p_2 = p_2^* := \frac{\varphi_2^*}{\varphi_1^*},\ p_3 = \frac{p_3^*}{(1+\frac{1}{\varepsilon^*})},\quad \tau = \frac{D_y(y_1^* + y_2^*)}{\varphi_1^*},\quad r = \frac{\mu^*}{\varphi_1^*}$$

Here $\varepsilon^*$ is the price elasticity of world market demand for the second commodity which, evaluated at the optimum should be smaller than minus unity. Due to the concavity/convexity assumptions the necessary conditions corresponding with the first best social optimum are also sufficient. Hence, the following holds.

-The pair $(k_1^*, y_1^*)$ maximises the profits $F_1(k_1, y_1) - rk_1 - \tau y_1$ of firm 1. This is the case because it maximises

$$F_1(k_1, y_1) - \frac{\mu^*}{\varphi_1^*} k_1 - \frac{D(y_1 + y_2^*)}{\varphi_1^*}$$

-For the same reason $(k_2^*, y_2^*)$ maximises the profits of firm 2, which takes the world market price as given.

-The triple $(c_1^*, c_2^*, c_3^*)$ maximises

$$U(c_1, c_2, c_3)$$

subject to

$$c_1 + p_2 c_2 + p_3 c_3 = F_1 + p_2 F_2 + T$$

where $T$ denotes the recycled import tariff revenues $T = -p_3^* c_3 / (1+\varepsilon^*)$. The triple satisfies the first-best necessary conditions for optimality; the latter are also sufficient in view of the concavity of the utility function. Furthermore, it is affordable because equilibrium on the balance of payments implies that

$$c_1^* + p_2 c_2^* + p_3 c_3^* = F_1 + p_2^*[F_2 - x(p_2^*)] + p_3[\frac{p_2^*}{p_3^*} x(p_2^*)]$$

$$= F_1 + p_2 F_2 + T$$

-Finally, all markets clear at the proposed prices.

This result about implementation is well-known from the general theory of international trade. It implies that in the case of full competition on the world market for the exported commodity ($\varepsilon = -\infty$), it is optimal not to impose an import tariff and to tax emissions according to their marginal damage. Moreover, in the case of a monopoly the first-best optimum can be mimicked in a decentralised economy by setting emissions taxes equal to marginal damage, as in full competition, and by using a tariff on the imported commodity.

## 4. The second best policy in monopoly

This section assumes that, due to international regulations, it is not feasible to use tariffs as an instrument. Then one has to look for a second-best solution. In the case of perfect competition tariffs are not needed to reach the first-best optimum. Therefore our attention will be restricted to monopoly here.

The questions addressed are whether it is optimal to differentiate between domestic sectors with respect to the emission taxes and whether taxes are below the marginal damage or not. Rauscher identifies ecological dumping by taxing below marginal damage (or emission standards corresponding to such taxes) or by the export sector paying a smaller emission fee (or having more lax standards) than the sheltered sector. In section 5 we add a third alternative measure of ecological dumping, taking into account the average taxation in case taxation is not uniform over sectors.

Several approaches can be taken to tackle the questions. Rauscher (o.c.) applies an analytical approach, as was done above, looking at total utility, arising from the optimal behaviour of consumers and producers, which all take market prices as given, and letting the government subsequently calculate the optimal emission taxes (in Rauscher's case emission standards), given that it is not feasible to impose an import tariff. Unfortunately, Rauscher finally obtains a mathematical expression whose sign is difficult to determine on the basis of theoretical reasoning (the assumption of strict concavity/convexity of the functions involved still leads to ambiguity). It is assumed that the cross-derivative of the production functions is sufficiently large in equilibrium. Then it follows that ecological dumping not necessarily occurs. However, this cross derivative is not a primitive parameter of the model: its value is endogenous in a general equilibrium. In view of Rauscher's efforts it seems impossible to reach analytical results without further specifying the functions involved. We advocate an approach where specific functional forms are chosen, such that numerical exercises can be conducted. Before doing so we reproduce Rauscher's argument for the model at hand.

Suppose the government has set optimal emission taxes, subject to the constraints that the tax rates do not differ between sectors and such that they equal marginal damage. In a competitive economy the representative consumer maximises utility subject to the budget constraint. This yields

$$U_{c_1} = U_{c_2} / p_2 = U_{c_3} / p_3 .$$

It follows from profit maximisation that

$$F_{1k} = p_2 F_{2k} = r ,\ F_{1y} = \tau_1 = p_2 F_{2y} = \tau_2 = D'/U_{c_1} .$$

Moreover,

$$c_1 = F_1 ,\ c_2 = F_2 - x(p_2),\ c_3 = p_2 x(p_2) / p_3 .$$

Hence the change in welfare $(dW)$ following a change in the tax rate for sector $1$ is:

$$\frac{dW}{d\tau_1} = U_{c_1}[F_{1k}\frac{dk_1}{d\tau_1} + F_{1y}\frac{dy_1}{d\tau_1}] + \frac{U_{c_2}}{p_2}[p_2 F_{2k}\frac{dk_2}{d\tau_1} + p_2 F_{2y}\frac{dy_2}{d\tau_1} - p_2 x_p \frac{dp_2}{d\tau_1}]$$

$$+ \frac{U_{c_3}}{p_3}[x\frac{dp_2}{d\tau_1} + p_2 x_p \frac{dp_2}{d\tau_1}] - D'[\frac{dy_1}{d\tau_1} + \frac{dy_2}{d\tau_1}]$$

Using the properties of the general competitive equilibrium we find:

$$\frac{dW}{d\tau_1} = U_{c_1} x \frac{dp_2}{d\tau_1}$$

In the same way

$$\frac{dW}{d\tau_2} = U_{c_1} x \frac{dp_2}{d\tau_2}$$

Hence the welfare effect of a deviation from equal emission taxes depends only on the impact on the terms of trade (i.e., the price of the exported commodity). So, if a decrease of the emission tax imposed on the sheltered non-exporting sector has a less negative effect on the terms of trade than an equivalent decrease for the exporting sector, then it is beneficial to tax the exporting sector less than the sheltered sector. This is of course in accordance with the findings of Rauscher for the case of emission standards.

Rauscher's subsequent argument, for the case of emission standards, can now be sketched as follows. Suppose the government considers imposing a more lax emission standard on the exporting sector than the one corresponding with marginal damage. The cheaper availability of the raw material for the export sector increases production in that sector and decreases the world market price. Suppose the standard for the sheltered sector is relaxed. Taking prices fixed, the marginal productivity of capital in that sector increases, which in the case of no underemployment causes a flow of capital out of the exporting sector into the sheltered sector, thereby reducing exports of the exporting sector and increasing the export price. Since production in the sheltered sector is enhanced, its price relative to the price of the other produced commodity decreases, and therefore the relative world market price of the exported commodity increases. Hence, relaxing the emission standard in the sheltered sector has two opposing effects on the terms of trade and the aggregate effect is not clear beforehand. We cannot perform a similar analysis with emission taxes because in equilibrium the rate of return on capital and the emission tax should always lie on the factor price frontier of the respective sectors.

We turn to some numerical exercises, which allow us not only to determine in which direction a deviation from a uniform tax rate is optimal but also to calculate the full optimum. We propose the following specifications.

$$(4.1) U(c_1, c_2, c_3) = \ln c_1 + \ln c_2 + \ln c_3$$

$$(4.2) F_1(k_1, y_1) = k_1^{\alpha}\ y_1^{1-\alpha}$$

$$(4.3) F_2(k_2, y_2) = k_2^{\beta} y_2^{1-\beta}$$

$$(4.4) D(y_1 + y_2) = \tfrac{1}{2}[y_1 + y_2]^2$$

$$(4.5) x(p_2) = p_2^{\varepsilon},\ \varepsilon < 0$$

Its simplicity and the fact that these specifications are widely used can defend this choice, at least modestly.

It follows from utility maximisation subject to the budget constraint that

$$c_1 = p_2c_2 = p_3c_3 = \tfrac{1}{3}[F_1 + p_2F_2].$$

Together with the conditions for market equilibrium $((F_1 = c_1,\ F_2 = c_2 + x(p_2))$ this yields:

$$c_1 = p_2x(p_2),\ c_2 = x(p_2), c_3 = p_2x(p_2)/p_3$$

It follows from profit maximisation that equilibrium prices are on the factor price frontiers, corresponding with zero profits, defined by:

$$(4.6)\quad 1 = \left(\frac{r}{\alpha}\right)^{\alpha}\left(\frac{\tau_1}{1-\alpha}\right)^{1-\alpha} = g_1(r,\tau_1)$$

$$(4.7)\quad p_2 = \left(\frac{r}{\beta}\right)^{\beta}\left(\frac{\tau_2}{1-\beta}\right)^{1-\beta} = g_2(r,\tau_2)$$

Factor demands are:

$$(4.8)\quad k_1(r,\tau_1,F_1) = \left(\frac{r}{\alpha}\right)^{\alpha-1}\left(\frac{\tau_1}{1-\alpha}\right)^{1-\alpha} F_1$$

$$(4.9)\quad y_1(r,\tau_1,F_1) = \left(\frac{r}{\alpha}\right)^{\alpha}\left(\frac{\tau_1}{1-\alpha}\right)^{-\alpha} F_1$$

$$(4.10)\quad k_2(r,\tau_2,F_2) = \left(\frac{r}{\beta}\right)^{\beta-1}\left(\frac{\tau_2}{1-\beta}\right)^{1-\beta} F_2$$

$$(4.11)\quad y_2(r,\tau_2,F_2) = \left(\frac{r}{\beta}\right)^{\beta}\left(\frac{\tau_2}{1-\beta}\right)^{-\beta} F_2$$

Welfare optimisation on the part of the government should take the constraints outlined above into account. After some straightforward substitutions the Lagrangian can be written as

$$\ln p_2 x(p_2) + \ln x(p_2) + \ln p_2 x(p_2) / p_3 - \tfrac{1}{2}[y_1(r, \tau_1, p_2 x(p_2)) + y_2(r, \tau_2, x(p_2))]^2$$

$$+ \lambda[k_1(r, \tau_1, p_2 x(p_2)) + k_2(r, \tau_2, x(p_2)) - \bar{k}] + \mu_1[1 - g_1(r, \tau_1)] + \mu_2[p_2 - g_2(r, \tau_2)]$$

This poses a well-defined mathematical programming problem that can in principle be solved. However, even the simple functional forms we selected do not allow for much analytical work. Something can be said though. Denoting a percentage change of a variable $z$ by $\gamma_z$ we find that $\gamma_{c_1} = (1+\varepsilon)\omega$, $\gamma_{c_2} = \varepsilon\omega$, $\gamma_{c_3} = (1+\varepsilon)\omega$, where $\omega$ is defined by

$$\omega / \beta = -\frac{1-\alpha}{\alpha}\gamma_{\tau_1} + \frac{1-\beta}{\beta}\gamma_{\tau_2}.$$

Therefore, if the price elasticity of world demand is not too negative and the emission tax on the exported commodity is increased, whereas the emission tax on the sheltered sector is decreased, utility from consumption will increase. If, moreover, the weight attached to pollution is small, such a policy will have a positive total welfare effect.

We perform several numerical experiments. All the calculations were done in *Mathematica* (see Wolfram (1996) and Culioli (1996)). We use the following parameter values: $\alpha = \beta, \bar{k} = 10, p_3 = 1$. This presents a case where the exertion of monopoly power in international trade does not necessarily imply "ecological dumping", i.e., lower emission taxes in the exporting sector than in the sheltered sector.

We solve the model numerically as follows. Fix $\tau_1$. Then $r$ is determined by equation (4.6). If, in addition, $\tau_2$ is fixed, equation (4.7) determines $p_2$. From this we can derive foreign demand and subsequently the rates of consumption. Hence also production is determined and therefore the capital and raw materials inputs. However, we loose one degree of freedom because of the clearing of the capital market: $k_1 + k_2 = 10$. This enables us to determine $\tau_2$. We conclude that equilibrium in the product and capital markets leaves the government with one degree of freedom ($\tau_1$) to maximise the social welfare function.

Figure 4.1 depicts the results for the case where the price elasticity of world demand $(\varepsilon)$ equals $-1/2$[1]. The optimal tax rate ratio $\tau_2 / \tau_1$ is drawn as a function of the production elasticity of capital, which is assumed equal in both production sectors $(\alpha = \beta)$. These elasticities range from 0.1 to 0.8.

Insert figure 4.1 about here

It is seen that in this case the exporting sector should be taxed higher than the sheltered sector to maximise (second best) social welfare. The more so when the production elasticity gets larger and the production elasticity of the raw material (pollution) gets smaller. The intuition is that with inelastic world demand the terms of trade can be improved considerably by taxing the exporting sector, especially when the production elasticity of pollution as input is relatively small.

This intuition is to some extent confirmed in figure 4.2 where the same exercise is performed for a price elasticity of world demand equal to –0.95.

Insert figure 4.2 about here

Here we see that the exporting sector should be taxed more heavily for small values of the production elasticity of capital, and less severely when the production elasticity of capital becomes higher. The tax rates in this case are equal when the production elasticity of capital is about 0.52. Notice however that the optimal domestic ratio is decreasing now instead of increasing as in the previous case. This is due to the high price elasticity of world demand.

The phenomenon described here is even more pronounced in figure 4.3, where we have used a highly elastic world demand $(\varepsilon = -2)$.

Insert figure 4.3 about here.

As a third approach to investigating the occurrence of ecological dumping one could compare the marginal damage of emissions to social welfare with the sectors' emissions tax rates as well as the average emission rate $(\bar{\tau})$. The marginal damage of emissions is $D'(y_1 + y_2)$ in terms of social welfare. The monetary equivalent is found by dividing

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[1] Note that demand is assumed inelastic here. In the presence of our particular monopolistic structure this poses no problem, because the government creates a monopolistic price for price-taking firms.

$D'(y)$ by the marginal welfare of income, $U_{c_1}$. The following table shows the various rates for selected values of $\alpha$ when $\varepsilon = -2$.

| $\alpha$ | $\tau_1$ | $\tau_2$ | $\bar{\tau}$ | $D'$ |
|---|---|---|---|---|
| 0.4 | 1.37457 | 1.46807 | 1.43552 | 1.15869 |
| 0.45 | 1.46327 | 1.44211 | 1.4491 | 1.15703 |
| 0.5 | 1.57536 | 1.40747 | 1.45931 | 1.1505 |
| 0.55 | 1.72303 | 1.36297 | 1.46502 | 1.13793 |
| 0.6 | 1.92818 | 1.30747 | 1.46464 | 1.11796 |
| 0.65 | 2.23357 | 1.23999 | 1.45587 | 1.08887 |
| 0.7 | 2.73293 | 1.15991 | 1.43528 | 1.04864 |

As one can see the tax rates are much higher than marginal social damage would indicate. Foreign consumers can be effectively taxed to finance a domestic policy of 'anti-pollution'.

As a conclusion from these exercises we can state that there are indeed examples where it pays to tax the exporting sector more heavily than the sheltered sector. Also, there is a strong sensitivity of this result with respect to the production elasticities and the price elasticity of world demand, which would be worthwhile to study in more detail. However this was not the intention of the present section.

## 5. Oligopoly; partial equilibrium

In this section we consider the case where the country under investigation is an oligopolist on the world market. It is common in the literature to study the oligopoly case in a partial equilibrium framework. Rauscher is an exception, but he does not provide a formal analysis. In the next section we shall work within the general equilibrium framework, developed above. But first we summarise the work by Barrett (1994).

We cast Barrett's basic model in the format used above. It is quite common in the literature to restrict attention to the case where the exported commodity is not consumed domestically. We adhere to that assumption. In Barrett's model domestic and foreign firms compete on the world market. The symbol $x^f$ denotes the total supply by the foreign firms. Let there be $n(\geq 1)$ domestic producers, indexed by $i$, of the exported commodity. Note that this index does not indicate the sector, as in the previous sections, but firms within the exporting sector. For simplicity it is assumed that the unit cost functions of all firms are identical: $c_i(r,\tau) = c(r,\tau)$. Total domestic production is $x = \sum x_i$. In the Barrett model the firm's costs consist of production costs, depending only on production, and abatement costs, depending on production as well as on the emission standard set by the government. Since we want to stay as close as possible to the general equilibrium model set out above, and since this still serves to illustrate the main idea behind Barrett's work, our model does not incorporate abatement nor emission standards. Instead we use emission taxes.

In the partial equilibrium approach the government takes as given all that occurs in the domestic sheltered sector. Neither is the government is interested in total social welfare per se: pollution by the aggregate domestic sectors is not taken into account. Hence the government seeks to maximise export revenues minus social costs, the latter consisting of capital costs and the external damage costs caused by emissions of the exporting sector. In the sequel a distinction is made between Cournot and Bertrand competition.

*a. Cournot competition*

In Barrett's benchmark scenario the government takes output of domestic and foreign firms as given. In such circumstances, given the output of the domestic firms, the optimal standard arises from the equality of marginal abatement costs and marginal damage. Implementation of this rule requires information about the abatement cost function. In our model an analogous approach would be to assume that the government knows the production function, from which demand for the raw material (and hence emissions) can be derived. Taking Shephard's lemma and constant returns to scale into account, this implies $y_i = \frac{\partial c}{\partial \tau} x_i$. Subsequently the government sets the uniform tax rate equal to marginal damage. Hence, $\tau = D'(\sum \frac{\partial c}{\partial \tau} x_i) = D'(\frac{\partial c}{\partial \tau} x)$, from which $\tau$ can be solved as a function of the outputs. This is an increasing function because of the concavity of the unit cost function and the convexity of the damage function.

Each firm maximises its profits taking other firms' supply and input prices as given. It follows that

$$p'(x + x^f)x_i + p(x + x^f) = c(r, \tau)$$

where $p$ denotes the inverse world demand function. So supply by domestic firms is downward sloping as a function of the emission fee. Together with the tax rate schedule derived above this establishes the firm's reaction function. It is assumed to be downward sloping, as is the case if the demand function is linear.

Social welfare is given by

$$W = p(x + x^f)x - r\sum k_i - D(\sum y_i)$$

where it is to be understood that damage is expressed in monetary values. The effect of a change in the emission tax rate, evaluated at the marginal damage, is given by:

$$\frac{dW}{d\tau} = p'(x + x^f)x[\frac{dx}{d\tau} + \frac{dx^f}{d\tau}] + p(x + x^f)\frac{dx}{d\tau} - r\sum\frac{dk_i}{d\tau} - D'(\sum y_i)\sum\frac{dy_i}{d\tau}$$

Taking into account that $k_i = \frac{\partial c(r,\tau)}{\partial r}x_i$, $y_i = \frac{\partial c(r,\tau)}{\partial \tau}x_i$, $\tau = D'$, we find (in shorthand notation):

$$\frac{dW}{d\tau} = [p'x + p]\frac{dx}{d\tau} - c(r,\tau)\frac{dx}{d\tau} + p'x\frac{dx^f}{d\tau}$$

$$= p'x\frac{n-1}{n}\frac{dx}{d\tau} + p'x\frac{dx^f}{dx}\frac{dx}{d\tau}$$

Clearly the sign of the effect of lowering the emission tax rate is not unambiguous in general. However, if there is one domestic producer the first term on the right hand side vanishes. The second term on the right hand side is negative, because $p' < 0$, $\frac{dx^f}{dx} < 0$, $\frac{dx}{d\tau} < 0$. Hence, if there is one domestic producer, it is optimal to set emission taxes lower than marginal damage. If there are multiple domestic producers it might be optimal to have higher emission taxes. Two types of impacts can be distinguished due to a decrease in the emission tax rate. On the one hand, the government has an incentive to relax the tax rate below marginal damage because in doing so production will be increased, thereby enhancing profits from exports on the world market, at least as long as the reaction curves are downward sloping. On the other hand, the domestic firms are also competing amongst each other and consequently producing more than in the case of a domestic monopoly. The total effect is therefore not unambiguous. This is also found by Barrett (o.c.) and by Ulph (1997), who employ a somewhat different model, but to which the same type of argument applies.

To illustrate the results obtained for the general case we return to the example of a Cobb-Douglas technology, a quadratic damage function of section 4, with a single domestic producer. For computational simplicity we employ a linear world demand function: $p(x + x^f) = 1 - a[x + x^f]$. Demand for the raw material is

$$y = \left(\frac{r}{\beta}\right)^{\beta}\left(\frac{\tau}{1-\beta}\right)^{-\beta} x$$

Without strategic behaviour on the part of the government the emission tax rate equals marginal damage: $\tau = D'(y) = y$. Combining the two equations we get a relationship between the emission tax and output.

$$(5.1) \quad \tau = \left(\frac{r}{\beta}\right)^{\frac{\beta}{1+\beta}}\left(\frac{1}{1-\beta}\right)^{\frac{-\beta}{1+\beta}} x^{\frac{1}{1+\beta}}$$

Paraphrasing Barrett this schedule can be called the *environmentally optimal emission tax*. Next we consider the possibility of strategic behaviour on the part of the government. Given the tax rate the exporting firm maximises its profits

$$[1 - a[x + x^f]]x - c(r, \tau)x$$

After some straightforward manipulations this yields:

$$(5.2) \; 1 - 2ax - ax^f = \left(\frac{\tau}{1-\beta}\right)^{1-\beta}\left(\frac{r}{\beta}\right)^{\beta}$$

Note that the reaction curve is indeed downward sloping for all tax rates. The next question is what happens when the emission tax is lowered, below the "environmentally optimal" one. Clearly, given the foreign country's output, the domestic firm's reaction curve shifts outward and the new equilibrium has higher domestic production and less foreign production. What is the implication for social welfare? Social welfare is

$$W = [1 - a[x + x^f]]x - rk - \tfrac{1}{2} y^2$$

Hence

$$\frac{dW}{d\tau} = [1 - 2ax - ax^f]\frac{dx}{d\tau} - ax\frac{dx^f}{dx}\frac{dx}{d\tau} - [r\frac{dk}{dx} + y\frac{dy}{dx}]\frac{dx}{d\tau}$$

This expression has to be evaluated at the environmentally optimal emission fee. Hence $\tau = y$. In an optimum for the firm we have $1 - 2ax - ax^f = c(r, \tau)$. Hence

$$\frac{dW}{d\tau} = -ax\frac{dx^f}{dx}\frac{dx}{d\tau}$$

Taking into account that

$$\frac{dx}{d\tau} < 0 \text{ and } \frac{dx^f}{dx} < 0,$$

we can conclude that it is indeed optimal for the government to set an emission tax lower than the environmentally optimal one. This is not only true under the assumption that the foreign government does not react strategically, but the conclusion holds as well if the foreign government does react strategically.

### *b. Bertrand competition*

Here the case of competition by means of prices is considered. Barrett's results are reversed now: the countries impose more stringent standards than the "environmentally optimal" ones. We go into the partial equilibrium analysis for our particular model below. We employ a linear demand curve again:

$$x = 1 - ap_2 + bp^f$$

where $a$ and $b$ are positive constants and $p^f$ denotes the price set by the foreign country. Again the government takes in first instance the prices (and therefore output) as given. This yields the environmentally optimal emission tax, which is equal to the one derived above, with production replaced by the demand function.

The firm maximises its profits. As before this leads to:

$$1 - 2ap_2 + bp^f = a\left(\frac{\tau}{1-\beta}\right)^{1-\beta}\left(\frac{r}{\beta}\right)^{\beta}$$

Social welfare equals revenues minus capital costs minus environmental damage. In the case at hand the reaction curve is increasing and the sign of the change in welfare due to a change in the tax rate equals:

$$\text{Sign} \quad bp_2 \frac{dp^f}{dp_2}\frac{dp_2}{d\tau}$$

which is clearly positive, since an increase in the tax rate shifts the reaction curve upward, causing the foreign price to increase. This holds in the absence of governmental policy by the foreign country. But, clearly, in a Nash equilibrium both governments will set their taxes higher than environmentally optimal.

### *c. Domestic consumption*

A more realistic case is one where domestic consumption of the exported commodity is allowed for. It received only minor attention in the literature. According to Ulph (1997), if there is domestic consumption and the domestic market is oligopolistic, there is an incentive for the government to impose less stringent taxation in the case of Cournot competition because imperfect competition will in general lead to too low output levels from the point of view of social welfare. Hence production for the domestic market should be stimulated.

## 6. Oligopoly; general equilibrium

In this section a general equilibrium model is constructed with one domestic producer who is an oligopolist on the world market. For the time being we abstract from domestic consumption of the commodity, as in the previous section.

The motivation for analysing oligopoly in a general equilibrium setting was originally given by Rauscher, who argues that the strategy of increasing domestic production (in his case by relaxing the standards) has an effect also on the allocation of capital in the economy through the rate of return. This effect is neglected in a partial equilibrium setting, but still it might be important.

We employ a slightly modified version of the model of section 4. Attention will be restricted to *Cournot* competition with one domestic producer. National income equals $F_1 + p_2F_2$. In view of the utility functions and in the absence of domestic consumption of the exported commodity, it follows from utility maximisation on the part of the consumers that:

$$c_1 = \tfrac{1}{2}[F_1 + p_2F_2], \quad c_3 = \tfrac{1}{2}[F_1 + p_2F_2] / p_3$$

Equilibrium on the current account implies that $p_3c_3 = p_2F_2 = p_2x$. Hence $c_1 = p_2F_2 = p_2x$. Profit maximisation in the sheltered sector requires that the equilibrium prices lie on the factor price frontier given by: $1 = g_1(r, \tau_1)$. See equation (4.6). When the linear world demand function of the previous section is maintained, profit maximisation on the part of the exporting sector implies

$$p_2'(x + x^f)x + p_2(x + x^f) = 1 - 2\alpha x - \alpha x^f = \left(\frac{r}{\beta}\right)^{\beta}\left(\frac{\tau_2}{1-\beta}\right)^{1-\beta} = g_2(r, \tau_2)$$

See equation (4.7). The capital and raw material inputs are given by (4.8)-(4.11).

The mathematical problem faced by the government can now be stated as:

$$\text{Max } \ln p_2(x + x^f)x + \ln p_2(x + x^f)x / p_3 - \tfrac{1}{2}[y_1 + y_2]^2$$

subject to

$$(6.1)\quad k_1 = k_1(r, \tau_1, p_2(x + x^f)x)$$

$$(6.2)\quad y_1 = y_1(r, \tau_1, p_2(x + x^f)x)$$

$$(6.3)\quad k_2 = k_2(r, \tau_2, x)$$

$$(6.4)\quad y_2 = y_2(r, \tau_2, x)$$

$$(6.5)\quad g_1(r, \tau_1) = 1$$

$$(6.6)\quad p_2'(x + x^f)x + p_2(x + x^f) = g_2(r, \tau_2)$$

$$(6.7)\quad k_1 + k_2 = \bar{k}$$

This problem can not be solved in such a way that the sensitivity with respect to the parameters can be determined analytically, as one would wish to do in order to find out how to set optimal taxes in different circumstances. Therefore a number of numerical optimisations will be executed. In these exercises the following parameter values are used throughout: $\bar{k} = 10$, $p_3 = 1$. The results are summarised in the figures displayed below.

In figure 6.1 we assume that the home country takes supply by the foreign country as given. In particular $x^f = 1$. It is also assumed that world demand is linear with $a = 0.05$, $b = 1$ and that $\beta = 1 - \alpha$. Depicted is $\tau_2 / \tau_1$ as a function of $\alpha$.

Insert figure 6.1 about here

It follows that, depending on the production elasticity of capital, there are again several qualitatively different tax constellations in equilibrium. It might indeed be optimal to tax the exporting sector more heavily, but the other way around is a possibility as well.

In the next figure we derive the overall equilibrium, where it is assumed that there is perfect symmetry between the countries. So we now have a general equilibrium in both countries as well as between them. In this run it is assumed that $\alpha = \beta$ as in the monopoly model.

Insert figure 6.2 about here.

In figure 6.2 we display the reaction curves of both countries, which are increasing, after eliminating the Nash-equiibrium tax rates. If the production elasticities equal 0.5 the equilibrium is found at $x = x^f = 1.6759...$ The equilibrium tax rates are $\tau_1 = 1.887$, $\tau_2 = 1.058$. The table below compares the emission tax rates to marginal social damage. Clearly for this particular model the emission tax rates are often *below* marginal damage. It is not true, however, that taxes $\tau_2$ in the export sector are always below the socially optimal rate. Note that in the neighbourhood of $\alpha = 1/2$ the average rate is higher than the socially optimal rate, although taxes in the export sector are below this value.

| $\alpha$ | $\tau_1$ | $\tau_2$ | $\bar{\tau}$ | $D'$ |
|---|---|---|---|---|
| 0.2 | 0.889927 | 85.2619 | 1.08903 | 1.79578 |
| 0.3 | 0.974876 | 5.68604 | 1.26717 | 1.69743 |
| 0.4 | 1.21272 | 1.91588 | 1.40642 | 1.49565 |
| 0.5 | 1.8311 | 1.12756 | 1.41248 | 1.3857 |
| 0.6 | 3.89418 | 0.856093 | 1.27744 | 1.37999 |
| 0.7 | 17.0492 | 0.750334 | 1.07864 | 1.41035 |

## 7. Conclusion

The present paper has addressed the issue of ecological dumping. We have developed a model in the spirit of Rauscher, with emission taxes, that could be used to analyse several market structures: full competition, monopoly and oligopoly. We were able to ascertain some conjectures raised by Rauscher. It is indeed possible that in a second-best world where import tariffs are not allowed, it is optimal in a situation of monopoly on the world market to tax the exposed export sector more heavily than the sheltered sector. This conclusion holds also in the case of an oligopoly on a third market. Hence the result obtained by Barrett, that emission fees on the exporting sector are too low in the case of oligopoly does not hold true anymore in a general equilibrium setting. We have also discussed an alternative measure of ecological dumping where the average actual emission fees are compared with the socially optimal emission tax. For further study we recommend more numerical exercises in order to perform a sensitivity analysis to find out where switch points from one regime to another can be found. This can be helpful in designing economic and environmental policy in practice.

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Figure 4.1

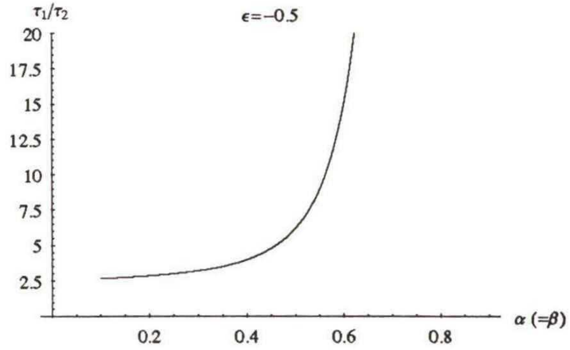


Figure 4.2

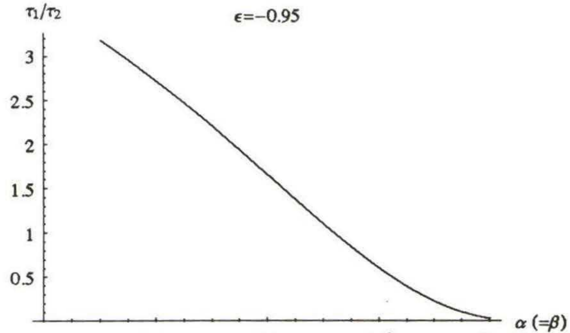


Figure 4.3

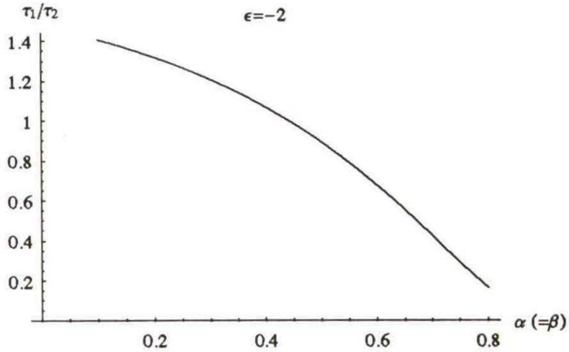


Figure 6.1

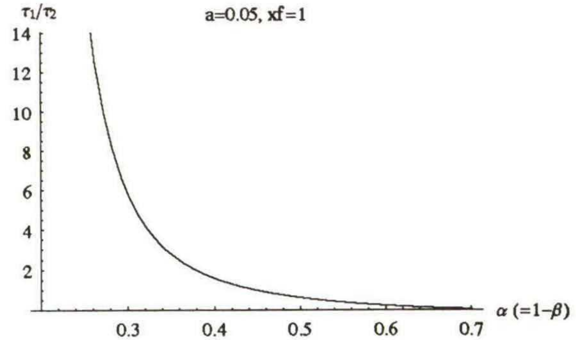
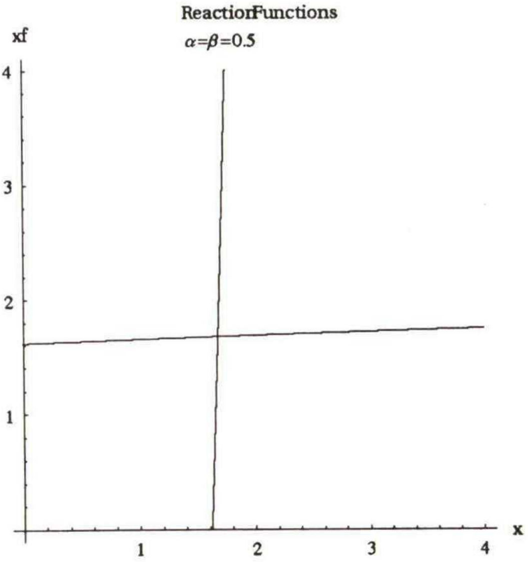


Figure 6.2



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