Agricultural trade liberalization and strategic environmental policy: a formal analysis

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Abstract

This paper develops an extended general equilibrium model of international trade in order to analyze the welfare effects of agricultural trade liberalization if a large country influences its terms of trade by means of environmental policy. We derive globally optimal first-best and second-best environmental and trade policy combinations as a benchmark for assessing the trade-distorting character of strategically motivated environmental policies and demonstrate that if second-best rather than first-best policies are chosen as a benchmark the conclusions may differ not only in magnitude but also in direction. We further demonstrate that if a Pigouvian instrument is transformed into a strategic environmental policy, following trade liberalization, the global welfare effect is unambiguously positive. We thereby prove that the distorting effect of an optimal tariff is generally greater than that of a strategically motivated environmental policy.

Introduction

The liberalization of agricultural trade and the increased recognition in policy of the environmental impacts of agriculture are two important trends affecting world agriculture at the turn of the century. Both trends are widely regarded by economists as necessary for social welfare improvements, yet they have given rise to tensions in trade talks. On the one hand, policy makers in Europe and parts of Asia fear that trade liberalization and reduction of agricultural support may adversely affect the positive environmental aspects of agriculture and the achievement of domestic environmental goals. On the other hand, free trade proponents are concerned that some countries might use the positive environmental aspects of agriculture as an excuse to further a protectionist trade agenda or to manipulate the terms of trade in their favor. An important issue for the WTO process will be to decide how the trade-distorting character of environmental policies can be assessed. This paper deals with this question in two ways: first, by analyzing the incentives for a large country to distort its environmental policy and, second, by examining how distorted environmental policies affect global welfare.

The literature on trade and the environment demonstrates that a large country may have strategic incentives to choose an environmental policy that deviates from a Pigouvian (1920) tax or subsidy, since it can take advantage of its monopolistic price leverage in the world market. Several studies have specified strategic environmental policies for large countries trading on international markets. Building upon Bhagwati and Ramaswami's (1963) theory of an optimal tariff, Bhagwati et al. (1969) and Kemp and Nagishi (1969) demonstrate that in the presence of domestic production externalities, the optimal policy response for a large country is a combined production tax and tariff. Vandendorpe (1972) and Markusen (1975) specify the condition for a large country's domestically optimal policy, depending on whether the country is restricted to consumption or production taxes. Krutilla (1991) also demonstrates that the domestically optimal environmental policy partially substitutes for an optimal tariff and thus deviates from the Pigouvian tax or subsidy. While Markusen (1975) and Krutilla (1991) consider competitive supply markets, Kennedy (1994), Conrad (1993), Markusen et al. (1993), Barrett (1994), Rauscher (1994) and Ulph (1994a; 1994b; 1996) analyse domestically optimal environmental policies by assuming a limited number of firms competing in Cournot fashion. Starting from a similar framework of oligopolistic supply markets, Burguet and Sempere (2003) demonstrate how the replacement of optimum tariffs by strategic environmental policy affects social welfare. Burguet and Sempere (2003) assume constant marginal costs of production in order to analyze the welfare effects of symmetrical tariff reductions within a bilateral trade model of two countries and two firms competing in a single good.

This paper extends the literature in a number of ways. First, it analyzes the trade-distorting effects of strategic environmental policies. Second, the modeling approach considers competitive rather than oligopolistic supply markets, since competition is a common feature of agricultural markets. Models of competitive supply markets have also been employed by Markusen (1975) and Krutilla (1991), but without analyzing the impact of strategic environmental policy on global welfare. The welfare effects of trade liberalization and strategic environmental policy have so far, to the best of our knowledge, only been studied by Burguet and Sempere (2003). However, this was within a framework of oligopolistic markets and was based on the restrictive assumption of constant marginal production costs. Third, the analysis is framed in a context of second-best to account for the fact that policy instruments are hardly ever set at their optimal levels. The paper demonstrates that, as long as trade is not *fully* liberalized, the Pigouvian tax or subsidy will not maximize global welfare. We thus argue that Pigouvian policies are an inappropriate benchmark for classifying strategic environmental policies as trade-distorting or otherwise. Finally, we deliver a proof that trade liberalization *generally* enhances global welfare when a large country substitutes a strategic environmental policy for optimal conventional border protection measures.

The structure of the paper is as follows. After presenting the model, we derive domestically optimal policies analytically, i.e. environmental and trade policy combinations that maximize the welfare of an individual country. We then compare these policies with the corresponding policy mix that maximizes global welfare. Next, we analyze domestically and globally optimal policy combinations in a framework of second-best and derive conclusions as to whether a given environmental policy should or should not be classified as trade-distorting. The paper then goes on to prove that a unilateral tariff reduction, when accompanied by a simultaneous strategic change in the environmental policy, will generally enhance global welfare.

The model

We consider a general equilibrium trade model consisting of two large countries trading in goods *a* and *b*. The home country (Country 1) produces quantity S_1^a of good *a* at cost $C_1^a\left(S_1^a\right)$. Analogously, the cost of producing good *b* is $C_1^b\left(S_1^b\right)$. The production of commodity *a* in Country 1 is associated with external environmental effects $E_1^a\left(S_1^a\right)$. We assume that the environmental impact of production is not internalized into the market system and that the externality does not spill over national boundaries. We further assume that production of good *b* has either no impact on the environment or that environmental externalities are efficiently internalized. Both goods are also produced in the rest of the world (Country 2); however, in the interest of simplicity, the environmental impact of production abroad is considered to be neutral.

Country 1 has two policy instruments at its disposal: a tariff (*T*) on good *a*, defined as a specific tax or subsidy on exports or imports, and an environmental tax (*t*) on commodity *a*, modeled as a tax or subsidy on production. We assume that there is no possibility of retaliatory policy measures by Country 2. Hence, tax and tariff instruments are, by assumption, not available to the regulatory authorities abroad and are generally not used for good *b*.

The home country's supply ($S_1^a(P_{S_1^a})$, $S_1^b(P_w^b)$) and demand ($D_1^a(P_{D_1^a})$, $D_1^b(P_w^b)$) are defined as functions of domestic supply and demand prices, respectively, whereas Country 2's supply ($S_2^a(P_w^a)$, $S_2^b(P_w^b)$) and demand ($D_2^a(P_w^a)$, $D_2^b(P_w^b)$) are determined by world market prices.[3] Building upon these relationships, social welfare functions can be derived for the home country and the rest of the world. Country 1's welfare (W_1) is defined as the sum of consumer surplus and 'producer benefit' of both commodities and includes also tax revenues, tariff revenues and the value of the environmental externality:[4]

$$\begin{aligned} W_1(t,T) = & \int_{P_{D_1^a}}^{\infty} D_1^a\left(P_{D_1^a}\right) dP_{D_1^a} + P_{S_1^a} S_1^a\left(P_{S_1^a}\right) - C_1^a\left(S_1^a\left(P_{S_1^a}\right)\right) + t\, S_1^a\left(P_{S_1^a}\right) + T\left[D_1^a\left(P_{D_1^a}\right) - S_1^a\left(P_{S_1^a}\right)\right] \\ & + E_1^a\left(S_1^a\left(P_{S_1^a}\right)\right) + \int_{P_w^b}^{\infty} D_1^b\left(P_w^b\right) dP_w^b + P_w^b S_1^b\left(P_w^b\right) - C_1^b\left(S_1^b\left(P_w^b\right)\right) \end{aligned} \quad . \qquad (1)$$

Analogously, expression (2) defines Country 2's social welfare (W_2) as the aggregate of consumer surplus and producer benefit for goods *a* and *b*:

$$W_2(t,T) = \int_{P_w^a}^{\infty} D_2^a\left(P_w^a\right) dP_w^a + P_w^a S_2^a\left(P_w^a\right) - C_2^a\left(S_2^a\left(P_w^a\right)\right) + \int_{P_w^b}^{\infty} D_2^b\left(P_w^b\right) dP_w^b + P_w^b S_2^b\left(P_w^b\right) - C_2^b\left(S_2^b\left(P_w^b\right)\right) . \qquad (2)$$

[3] We assume supply and demand functions to be interdependent: $S_1^a(P_{S_1^a}) = s_1^a(P_{S_1^a}, P_w^b(P_{S_1^a}))$; $S_1^b(P_w^b) = s_1^b(P_w^b, P_w^a(P_w^b))$; $D_1^a(P_{D_1^a}) = d_1^a(P_{D_1^a}, P_w^b(P_{D_1^a}))$; $D_1^b(P_w^b) = d_1^b(P_w^b, P_w^a(P_w^b))$; $S_2^a(P_w^a) = s_2^a(P_w^a, P_w^b(P_w^a))$; $S_2^b(P_w^b) = s_2^b(P_w^b, P_w^a(P_w^b))$; $D_2^a(P_w^a) = d_2^a(P_w^a, P_w^b(P_w^a))$; $D_2^b(P_w^b) = d_2^b(P_w^b, P_w^a(P_w^b))$.

[4] We define 'producer benefit' as the difference between total revenues and total costs, which differs from producer surplus, which measures the difference between total revenues and total *variable* costs.

We assume that welfare in the home country and welfare in the rest of the world are not interdependent, hence global welfare can be depicted as the sum of welfare in the two countries: $W = W_1 + W_2$. Furthermore, the model is based on the trade equilibrium requirement of excess supply in Country 1 being equal to excess demand in Country 2 for both goods:

$$S_1^a\left(P_{S_1^a}(t,T)\right) - D_1^a\left(P_{D_1^a}(t,T)\right) = D_2^a\left(P_w^a(t,T)\right) - S_2^a\left(P_w^a(t,T)\right) \tag{3}$$

$$S_1^b\left(P_{S_1^b}(t,T)\right) - D_1^b\left(P_{D_1^b}(t,T)\right) = D_2^b\left(P_w^b(t,T)\right) - S_2^b\left(P_w^b(t,T)\right) . \tag{4}$$

Financial trade accounts in both countries are assumed to be balanced, hence the following constraints apply:

$$\left(S_1^b - D_1^b\right)P_w^b = \left(D_1^a - S_1^a\right)P_w^a \tag{5}$$

$$\left(S_2^b - D_2^b\right)P_w^b = \left(D_2^a - S_2^a\right)P_w^a \ . \tag{6}$$

For simplicity's sake, transaction and transportation costs are neglected. Hence, the margin between the home country's demand price $P_{D_1^a}$ for good *a* and the world price P_w^a is solely determined by the tariff rate, whereas the environmental tax rate exclusively determines the difference between domestic supply price $P_{S_1^a}$ and demand price for good *a*. The model is completed by the supposition that markets operate perfectly, and consequently that supply prices equal marginal production costs both at home and abroad:

$$P_w^a = \frac{\partial C_2^a}{\partial S_2^a} = P_{D_1^a} - T \qquad P_{S_1^a} = \frac{\partial C_1^a}{\partial S_1^a} = P_{D_1^a} - t \tag{7}$$

$$P_w^b = \frac{\partial C_2^b}{\partial S_2^b} \qquad P_w^b = \frac{\partial C_1^b}{\partial S_1^b} \ . \tag{8}$$

Environmental and trade policies in a first-best world

In the absence of international trade agreements, Country 1 is free to set its environmental tax and tariff rates simultaneously in order to maximize national social welfare. The first-order condition for an interior maximum is obtained by taking the partial derivatives of the domestic welfare function W_1 with respect to the tax and tariff rates, setting these as equal to zero and solving simultaneously ($\partial W_1/\partial t = \partial W_1/\partial T = 0$). Taking this rule and applying the constraints in equations (3) – (8) to simplify the result, we obtain:[5]

$$\frac{\partial W_1}{\partial t} = \frac{\partial S_1^a}{\partial P_{S_1^a}} \frac{1}{(\alpha+\beta)} \left(X_1^a (1-\varepsilon) - \left(t + \frac{\partial E_1}{\partial S_1^a} \right) \left(-\frac{\partial D_1^a}{\partial P_{D_1^a}} + \beta \right) + \beta T \right) = 0 \tag{9}$$

and

$$\frac{\partial W_1}{\partial T} = \frac{1}{(\alpha+\beta)} \left(-X_1^a \alpha (1-\varepsilon) + \left(t + \frac{\partial E_1}{\partial S_1^a} \right) \frac{\partial S_1^a}{\partial P_{S_1^a}} \beta - \alpha \beta T \right) = 0 \tag{10}$$

where $X_1^a = S_1^a - D_1^a$; $\alpha = \partial S_1^a / \partial P_{S_1^a} - \partial D_1^a / \partial P_{D_1^a}$; $\beta = \partial S_2^a / \partial P_w^a - \partial D_2^a / \partial P_w^a$; $\varepsilon = \left(\partial P_w^b / \partial P_w^a \right) / \left(P_w^b / P_w^a \right)$.

Simultaneously solving equation (9) and (10) yields:[6]

$$t_1^{**} = -\partial E_1^a / \partial S_1^a \tag{11}$$

and

$$T_1^{**} = -X_1^a (1-\varepsilon) / \beta \ . \tag{12}$$

The results show that the domestically optimal environmental tax t_1^{**} is equal to the Pigouvian tax or subsidy, while the domestically optimal first-best tariff T_1^{**} is identical to Bhagwati and Ramaswami's (1963) optimal tariff of international trade theory. Equations (11) and (12) thus demonstrate that domestic environmental problems are best addressed by environmental regulation, whereas trade-related issues are most efficiently dealt with through tariff instruments.

To assess the trade-distorting character of this domestically optimal policy set one needs to derive as a benchmark the policy set that maximizes *global* welfare. We will refer to the latter as the globally (as opposed to domestically) optimal policy set. It is obtained by setting the partial derivatives of the world welfare function ($W = W_1 + W_2$) equal to zero:[7]

$$\frac{\partial W}{\partial t} = \frac{\partial S_1^a}{\partial P_{S_1^a}} \frac{1}{(\alpha+\beta)} \left(\left(t + \frac{\partial E_1^a}{\partial S_1^a} \right) \left(\frac{\partial D_1^a}{\partial P_{D_1^a}} - \beta \right) + \beta T \right) = 0 \tag{13}$$

$$\frac{\partial W}{\partial T} = \frac{1}{(\alpha+\beta)} \left(\left(t + \frac{\partial E_1}{\partial S_1^a} \right) \frac{\partial S_1^a}{\partial P_{S_1^a}} \beta - \alpha\beta T \right) = 0 \ . \tag{14}$$

Solving equations (13) and (14) for the tax and tariff rates simultaneously, we obtain:[8]

$$t_w^{**} = -\partial E_1^a / \partial S_1^a \tag{16}$$

$$T_w^{**} = 0 \ . \tag{17}$$

The globally optimal first-best policy solution for an open economy is thus free trade ($T_w^{**} = 0$) combined with a Pigouvian tax or subsidy. The intuition behind this finding is that free trade between different nations within an open world economy is identical to free trade between different regions within a closed economy.

Taking the globally optimal policy set (equations 16 and 17) as a benchmark for judging domestically optimal policy combinations (equations 11 and 12), we conclude that a large

[5] Proof in Appendix 1 and 4.
[6] Proof in Appendix 10-12.
[7] The global welfare impact of environmental policies as represented by equation (9) seems to be unaffected by the interaction between the markets of goods *a* and *b*. However, the interaction between the two commodity markets is implicitly accounted for by the way supply and demand functions are specified as being interdependent between markets. Proof in Appendix 1- 6.
[8] Proof for first- and second-order condition for an interior maximum is given in Appendix 7-9.

country has an incentive to distort its trade policy only, while setting its environmental tax rate at the globally optimal level. The rationale for strategic trade policies can be seen from the optimal tariff formula in equation (12). If Country 1 is a net importer ($X_1^a < 0$), its optimum tariff ($T_1^{**} > 0$) will be higher the stronger its influence on the terms of trade. Moreover, equation (12) indicates that the terms of trade effect is stronger the smaller that β is, thus the smaller that the elasticity of foreign demand and supply is. We thus conclude that the larger the size of Country 1 in relation to the rest of the world, the stronger is the terms of trade effect.

The terms of trade effect is also determined by the parameter ε, which is an expression of the responsiveness of world price changes of one commodity to the world price of the other commodity. If commodities *a* and *b* are substitutes, a *real* price rise (reduction) of good *a* will generally lower (raise) the *real* price of good *b*, resulting in a negative value of ε.[9] As a consequence, the terms of trade effect will be greater the stronger the influence of price changes of good *a* on the price of good *b* (the smaller ε). The rationale behind this observation is that financial gains from trade due to price changes of good *a* will be enhanced by terms of trade gains in the market of good *b*.[10]

Environmental policy in a world of second best

We now turn to the case where Country 1 faces tariff reduction requirements as a consequence of an international trade agreement. With the tariff rate now being imposed exogenously, the home country can only vary its environmental tax rate to maximize its

[9] We define *real* prices in a way such that the value of the total world output is constant ($P_w^a(S_1^a + S_2^a) + P_w^b(S_1^b + S_2^b) = \mathrm{k}$). See Appendix 14.

welfare. The analysis is thus framed in the context of a second-best world, which will be denoted by one asterisk in the subsequent exposition. With a given tariff rate, the domestically optimal second-best environmental tax t_1^* can be obtained by resolving equation (9) for t:[11]

$$t_1^* = \frac{X_1^a(1-\varepsilon)}{(-\partial D_1^a / \partial P_{D_1^a} + \beta)} - \frac{\partial E_1}{\partial S_1^a} + T\frac{\beta}{(-\partial D_1^a / \partial P_{D_1^a} + \beta)} \ . \qquad (18)$$

Equation (18) shows that the domestically optimal second-best environmental policy deviates from the globally optimal Pigouvian tax or subsidy. Depending on the size of the trade flow (X_1^a) and the tariff rate T, the environmental tax/subsidy rate may be higher or lower than the Pigouvian rate. However, it is not clear whether in a second-best world the Pigouvian solution is the appropriate criterion for classifying domestic environmental policies as trade-distorting or otherwise. We argue that it is not: if trade is not fully liberalized ($T \neq 0$), a Pigouvian environmental policy instrument may result in a lower level of global welfare than a strategically motivated second-best policy. We argue that if the first-best policy solution is out of reach for political or technical reasons, the globally optimal second-best environmental policy is a more appropriate benchmark for deciding whether domestic environmental policies should be classified as trade-distorting. The globally optimal second-best environmental policy is the one that maximizes global welfare subject to the constraint that the tariff rate is predetermined exogenously. It is obtained by solving equation (13) for the environmental tax rate:[12]

$$t_w^* = -\frac{\partial E_1}{\partial S_1^a} + T\frac{\beta}{(-\partial D_1^a / \partial P_{D_1^a} + \beta)} \ . \qquad (19)$$

[10] Equation (12) further shows that if the two commodities are independent ($\varepsilon = 0$), partial and general equilibrium analysis will lead to the same result with regard to the domestically optimal environmental policy.

The globally optimal second-best environmental policy response (t_w^*) differs from the Pigouvian prescription ($t^{Pigou} = -\partial E_1^a / \partial S_1^a$) for any non-zero tariff rate because the optimal environmental policy would need to correct for an existing trade distortion. In the presence of a positive tariff ($T > 0$), the globally optimal environmental tax will be higher than the Pigouvian tax, given that supply curves are positively and demand curves are negatively sloped. This finding is plausible, since a higher environmental tax curtails domestic production, which was previously raised by the distortive tariff. Based on the reverse reasoning, we can state that the globally optimal environmental tax will generally be lower than the Pigouvian tax if the tariff is negative.

A comparison of equation (18) and equation (19) shows that the domestically optimal second-best environmental policy generally differs from the globally optimal one, this being due to Country 1's influence on its terms of trade, represented by the first term in (18).[13] The strength of the terms of trade effect is negatively correlated with the elasticity of foreign supply and demand. The terms of trade effect is also large when the elasticity of domestic demand is low (indicated by a low absolute value of $\partial D_1^a / \partial P_{D_1^a}$). The latter implies that the domestic supply sector is large relative to the domestic demand sector.

We further conclude that, given normal properties of supply and demand functions, t_1^* will be smaller than t_w^* if Country 1 is an importer. The rationale behind this observation is straightforward: a lower environmental tax rate stimulates domestic production; this causes world prices to fall, improving Country 1's terms of trade. These findings lend support to the

[11] Proof in Appendix 10.
[12] Proof in Appendix 7.
[13] It is assumed that there is trade between Country 1 and the rest of the world ($X_1^a \neq 0$).

suggestion that trade liberalization may lower environmental standards and thereby lead to ecological dumping.

Welfare effects of trade liberalization

We now turn to the question of how trade liberalization affects world welfare if a large country substitutes a strategically motivated environmental policy for a tariff. A global welfare improvement as a result of unilateral trade liberalization requires the marginal welfare change induced by a tariff increase to be negative ($dW\left(t_1^{**},T_1^{**}\right)/dT < 0$), given that the large country is a net importer ($X_1^a < 0$) and operates a positive tariff ($T_1^{**} > 0$). Taking the total differential of the world welfare function, the following expression can be derived:

$$\frac{dW\left(t_1^{**},T_1^{**}\right)}{dT} = \frac{\partial W\left(t_1^{**},T_1^{**}\right)}{\partial T} + \frac{\partial W\left(t_1^{**},T_1^{**}\right)}{\partial t}\frac{dt}{dT} \quad . \tag{20}$$

Since the first-order condition for a domestically optimal environmental policy will be maintained, as Country 1 liberalizes trade, the derivative dt/dT can be derived from the equality condition:

$$\frac{\partial W_1\left(t_1^{**},T_1^{**}\right)}{\partial t} = 0 \quad . \tag{21}$$

Taking the total differential of both sides of equation (21), we obtain:

$$\frac{dt}{dT} = -\frac{\partial^2 W_1\left(t_1^{**},T_1^{**}\right)}{\partial T \partial t} \bigg/ \frac{\partial^2 W_1\left(t_1^{**},T_1^{**}\right)}{\partial t^2} \quad . \tag{22}$$

Substituting (22) into (20) yields:

$$\frac{dW\left(t_1^{**},T_1^{**}\right)}{dT} = \frac{\partial W\left(t_1^{**},T_1^{**}\right)}{\partial T} - \frac{\partial W\left(t_1^{**},T_1^{**}\right)}{\partial t}\frac{\partial^2 W_1\left(t_1^{**},T_1^{**}\right)}{\partial T \partial t} \bigg/ \frac{\partial^2 W_1\left(t_1^{**},T_1^{**}\right)}{\partial t^2} \quad . \tag{23}$$

Making selective use of equations (9)-(14), this can be rearranged as:[14]

$$\frac{dW\left(t_1^{**},T_1^{**}\right)}{dT}=\frac{-\dfrac{\partial D_1^a}{\partial P_{D_1^a}}X_1^a\left(1-\varepsilon\right)}{X_1^a\left(\dfrac{\partial \varepsilon}{\partial t}+\dfrac{\partial \beta}{\partial t}\dfrac{\left(1-\varepsilon\right)}{\beta}\right)+\dfrac{\beta\left(1-\varepsilon\right)}{\left(\alpha+\beta\right)}\dfrac{\partial S_1^a}{\partial P_{S_1^a}}-\dfrac{\partial D_1^a}{\partial P_{D_1^a}}+\beta} \quad . \tag{24}$$

If supply and demand curves are assumed to be well-behaved and convex, then $\partial\beta/\partial t<0$. Hence, if $\partial\varepsilon/\partial t<0$, we can prove that equation (24) assumes a negative value for any $X_1^a<0$. The sign for $\partial\varepsilon/\partial t$ can be determined as follows: given perfectly operating factor and product markets, the price ratio between commodities *a* and *b* must be equal to the slope of the transformation curve:

$$-\frac{P_w^a}{P_w^b}=\frac{\partial S_w^b}{\partial S_w^a} \tag{25}$$

where $S_w^a=S_1^a+S_2^a$ and $S_w^b=S_1^b+S_2^b$.

We define *real* market prices so that the value of total world output is fixed ($P_w^a S_w^a+S_w^b P_w^b=k=\text{constant}$), hence:

$$\varepsilon=\frac{\partial P_w^b}{\partial P_w^a}\frac{P_w^a}{P_w^b}=-\frac{P_w^a S_w^a}{P_w^b S_w^b} \quad . \tag{26}$$

From equations (25) and (26) it can be calculated:[15]

$$\frac{\partial \varepsilon}{\partial t}=-\left(1+\frac{P_w^a}{S_w^a}\frac{\partial S_w^a}{\partial P_w^a}\right)\frac{S_w^a\left(1-\varepsilon\right)}{P_w^b S_w^b}\frac{\partial S_1^a}{\partial P_{S_1^a}}\frac{1}{\left(\alpha+\beta\right)}<0 \quad . \tag{27}$$

Equation (27) proves that $\partial\varepsilon/\partial t<0$, which is the requirement for expression (24) to assume negative values for any $X_1^a<0$. This provides the proof for the supposition that the global

[14] For simplicity's sake, we assume the marginal environmental damage to be constant ($\partial^2 E_1/\partial S_1^{a2}=0$). Proof in Appendix 13.

[15] Proof in Appendix 14.

welfare effect of reducing an optimal tariff is unambiguously positive – even if a country acts strategically in setting its domestic policies following trade liberalization. However, it is important to note that the positive global welfare change represented by equation (24) does not imply that both countries benefit equally from trade liberalization. Although Country 1's optimal adjustment to trade liberalization is a switch towards a strategically motivated environmental policy, its social welfare will fall below the level prior to trade liberalization, because the country moves from a first-best to a second-best policy solution. In contrast, the rest of the world will unambiguously gain from trade liberalization – even if Country 1 acts strategically in implementing its environmental policy. This finding is derived from the observation that global welfare increases following trade liberalization. Hence, the welfare gain for the rest of the world must outweigh the welfare loss for the home country. From this we may conclude that the distorting effect of an optimal tariff is generally greater than the trade distortions caused by strategic environmental policies. This is plausible in as much as social welfare gains for one country, as a result of terms of trade improvements, are generally achieved at the expense of global welfare losses for the rest of the world. Terms of trade improvements are maximized by an optimal tariff; this explains why an optimal tariff policy is more trade-distorting than a strategic environmental policy.

Expression (24) also shows that the size and direction of global welfare change are not dependent on the sign or magnitude of an environmental externality, since $\partial E_1^a / \partial S_1^a$ cancels out as the welfare change is calculated. Hence, if production is not linked to any environmental externalities ($\partial E_1^a / \partial S_1^a = 0$), equation (18) suggests that a large country facing a tariff reduction requirement may still introduce a production tax or subsidy, which it may choose to label an environmental tax/subsidy, even if there are *de facto* no environmental externalities.

Conclusions

This paper develops an extended general equilibrium model of international trade where the production of one commodity is associated with an environmental externality. The model is employed to derive domestically and globally optimal first-best and second-best environmental and trade policy combinations. We prove that free trade combined with a Pigouvian tax or subsidy is the first-best policy combination that is appropriate for maximizing global welfare. This implies that the optimal environmental policy for an open economy is the same as the one for a closed economy, so long as there are no trade restrictions. Conversely, trade liberalization is the globally optimal policy response if all environmental externalities are fully internalized. In both cases, it is assumed that the distortion being dealt with is the only market imperfection and that its removal will lead to the globally optimal first-best policy solution.

It appears logical to choose the first-best policy prescriptions as the benchmark for classifying strategically motivated environmental and trade policies as trade-distorting or otherwise. In practice, however, neither trade nor environmental policies are usually set at their globally optimal levels, implying that the correction of one distortion will not necessarily enhance global welfare. We argue that globally optimal *second-best* environmental policies provide a more appropriate benchmark against which to assess the trade-distorting character of strategic environmental policies. We have derived such second-best policies analytically and demonstrated how they differ from the Pigouvian prescription, because they need to correct for existing market distortions. These policies may thus be classified as 'trade-correcting'. We have demonstrated that if trade-correcting rather than first-best policies are chosen as benchmarks for classifying strategically motivated environmental policies as trade-distorting or otherwise, the conclusions may differ not only in size but also in direction. Recommendations as to how an environmental policy should be adjusted can be contradictory, since the classification of a policy as distorting depends crucially on the choice of the benchmark.

Finally, we demonstrated that the introduction of a strategic environmental policy can be classified as trade-distorting because it lowers global welfare – compared with the globally optimal policy mix of a Pigouvian tax or subsidy and a zero tariff. However, if a country acts strategically, this will not necessarily undermine the standard policy proposition that free trade enhances global efficiency. We have proved that if trade liberalization is accompanied by a switch from a Pigouvian tax or subsidy to a strategic environmental policy, the global welfare effects are unambiguously positive for all well-behaved demand and supply functions. This finding is plausible, in as much as a large country will be better off with an optimal tariff rather than a strategic environmental policy, but this is achieved at the expense of even greater welfare losses for the rest of the world. We thus conclude that the distorting effect of an optimal tariff is generally greater than that of a strategic environmental policy if the optimal tariff cannot be implemented.

Appendices

Appendix 1: The partial derivative of Country 1's welfare function with respect to *t*

The partial derivative of W_1 with respect to *t* can be obtained from equation (1):

$$\frac{\partial W_1}{\partial t} = -D_1^a \frac{\partial P_{D_1^a}}{\partial t} + \left(P_{S_1^a} + t\right)\frac{\partial S_1^a}{\partial P_{S_1^a}}\frac{\partial P_{S_1^a}}{\partial t} + \left(\frac{\partial P_{S_1^a}}{\partial t} + 1\right)S_1^a - \frac{\partial C_1^a}{\partial S_1^a}\frac{\partial S_1^a}{\partial P_{S_1^a}}\frac{\partial P_{S_1^a}}{\partial t} + \frac{\partial E_1}{\partial S_1^a}\frac{\partial S_1^a}{\partial P_{S_1^a}}\frac{\partial P_{S_1^a}}{\partial t}$$
$$-T\left(\frac{\partial S_1^a}{\partial P_{S_1^a}}\frac{\partial P_{S_1^a}}{\partial t} - \frac{\partial D_1^a}{\partial P_{D_1^a}}\frac{\partial P_{D_1^a}}{\partial t}\right) + \left(S_1^b - D_1^b\right)\frac{\partial P_w^b}{\partial P_w^a}\frac{\partial P_w^a}{\partial t} + \left(P_w^b - \frac{\partial C_1^b}{\partial S_1^b}\right)\frac{\partial S_1^b}{\partial P_w^b}\frac{\partial P_w^b}{\partial P_w^a}\frac{\partial P_w^a}{\partial t} \quad \text{(a)}$$

Making selective substitution of equations (5), (7) and (8) into (1), we obtain:

$$\frac{\partial W_1}{\partial t} = \left(S_1^a - D_1^a\right)\frac{\partial P_{D_1^a}}{\partial t}\left(1 - \frac{P_w^a}{P_w^b}\frac{\partial P_w^b}{\partial P_w^a}\right) + \left(t + \frac{\partial E_1}{\partial S_1^a}\right)\frac{\partial S_1^a}{\partial P_{S_1^a}}\left(\frac{\partial P_{D_1^a}}{\partial t} - 1\right) - T\left(\alpha\frac{\partial P_{D_1^a}}{\partial t} - \frac{\partial S_1^a}{\partial P_{S_1^a}}\right) \quad \text{(b)}$$

where $\alpha = \partial S_1^a \big/ \partial P_{S_1^a} - \partial D_1^a \big/ \partial P_{D_1^a}$

From equation (3) it can be derived:

$$\frac{\partial S_1^a}{\partial P_{S_1^a}}\frac{\partial P_{S_1^a}}{\partial t} - \frac{\partial D_1^a}{\partial P_{D_1^a}}\frac{\partial P_{D_1^a}}{\partial t} = \frac{\partial D_2^a}{\partial P_w^a}\frac{\partial P_w^a}{\partial t} - \frac{\partial S_2^a}{\partial P_w^a}\frac{\partial P_w^a}{\partial t} \quad \text{(c)}$$

This can be simplified by making use of equation (7):

$$\frac{\partial P_{D_1^a}}{\partial t} = \frac{\partial S_1^a}{\partial P_{S_1^a}}\frac{1}{(\alpha + \beta)} \quad \text{(d)}$$

where $\beta = \partial S_2^a \big/ \partial P_w^a - \partial D_2^a \big/ \partial P_w^a$

Substitution of equation (d) into equation (b) leads to:

$$\frac{\partial W_1}{\partial t} = \frac{\partial S_1^a}{\partial P_{S_1^a}}\frac{1}{(\alpha + \beta)}\left(\left(S_1^a - D_1^a\right)\left(1 - \frac{P_w^a}{P_w^b}\frac{\delta P_w^b}{\delta P_w^a}\right) - \left(t + \frac{\partial E_1}{\partial S_1^a}\right)\left(-\frac{\partial D_1^a}{\partial P_{D_1^a}} + \beta\right) + \beta T\right) \quad \text{(e)}$$

Appendix 2: The partial derivative of Country 2's welfare function with respect to *t*

The partial derivative of W_2 with respect to *t* can be obtained from equation (2):

$$\frac{\partial W_2}{\partial t} = -D_2^a \frac{\partial P_w^a}{\partial t} + P_w^a \frac{\partial S_2^a}{\partial P_w^a}\frac{\partial P_w^a}{\partial t} + \frac{\partial P_w^a}{\partial t} S_2^a - \frac{\partial C_2^a}{\partial S_2^a}\frac{\partial S_2^a}{\partial P_w^a}\frac{\partial P_w^a}{\partial t} - D_2^b \frac{\partial P_w^b}{\partial P_w^a}\frac{\partial P_w^a}{\partial t}$$
$$+ P_w^b \frac{\partial S_2^b}{\partial P_w^b}\frac{\partial P_w^b}{\partial P_w^a}\frac{\partial P_w^a}{\partial t} + \frac{\partial P_w^b}{\partial P_w^a}\frac{\partial P_w^a}{\partial t} S_2^b - \frac{\partial C_2^b}{\partial S_2^b}\frac{\partial S_2^b}{\partial P_w^b}\frac{\partial P_w^b}{\partial P_w^a}\frac{\partial P_w^a}{\partial t} \quad \text{(a)}$$

Making use of equations (6) – (8) and of equation (d), Appendix 1, this becomes:

$$\frac{\partial W_2}{\partial t} = \frac{\partial S_1^a}{\partial P_{S_1^a}} \frac{\left(S_2^a - D_2^a\right)}{\left(\alpha + \beta\right)} \left(1 - \frac{P_w^a}{P_w^b}\frac{\partial P_w^b}{\partial P_w^a}\right) \quad \text{(b)}$$

Appendix 3: The partial derivative of the global welfare function with respect to *t*

Given Appendix 1 and 2, the partial derivative of the global welfare function is:

$$\frac{\partial W}{\partial t} = \frac{\partial S_1^a}{\partial P_{S_1^a}} \frac{1}{\left(\alpha + \beta\right)} \left(\left(S_1^a - D_1^a\right)\left(1 - \frac{P_w^a}{P_w^b}\frac{\partial P_w^b}{\partial P_w^a}\right) - \left(t + \frac{\partial E_1}{\partial S_1^a}\right)\left(-\frac{\partial D_1^a}{\partial P_{D_1^a}} + \beta\right) + \beta T \right)$$
$$+ \frac{\partial S_1^a}{\partial P_{S_1^a}} \frac{\left(S_2^a - D_2^a\right)}{\left(\alpha + \beta\right)} \left(1 - \frac{P_w^a}{P_w^b}\frac{\partial P_w^b}{\partial P_w^a}\right) \quad \text{(a)}$$

Making use of equation (3), this can be written as:

$$\frac{\partial W}{\partial t} = \frac{\partial S_1^a}{\partial P_{S_1^a}} \frac{1}{\left(\alpha + \beta\right)} \left(\left(t + \frac{\partial E_1}{\partial S_1^a}\right)\left(\frac{\partial D_1^a}{\partial P_{D_1^a}} - \beta\right) + \beta T \right) \quad \text{(b)}$$

Appendix 4: The partial derivative of Country 1's welfare function with respect to *T*

The partial derivative of W_1 with respect to T can be obtained from equation (1):

$$\frac{\partial W_1}{\partial T} = -D_1^a \frac{\partial P_{D_1^a}}{\partial T} + \left(P_{S_1^a} + t\right)\frac{\partial S_1^a}{\partial P_{S_1^a}}\frac{\partial P_{S_1^a}}{\partial T} + S_1^a \frac{\partial P_{S_1^a}}{\partial T} - \frac{\partial C_1^a}{\partial S_1^a}\frac{\partial S_1^a}{\partial P_{S_1^a}}\frac{\partial P_{S_1^a}}{\partial T} + \frac{\partial E_1}{\partial S_1^a}\frac{\partial S_1^a}{\partial P_{S_1^a}}\frac{\partial P_{S_1^a}}{\partial T} - \left(S_1^a - D_1^a\right)$$
$$- T\left(\frac{\partial S_1^a}{\partial P_{S_1^a}}\frac{\partial P_{S_1^a}}{\partial T} - \frac{\partial D_1^a}{\partial P_{D_1^a}}\frac{\partial P_{D_1^a}}{\partial T}\right) + \left(S_1^b - D_1^b\right)\frac{\partial P_w^b}{\partial P_w^a}\frac{\partial P_w^a}{\partial T} + \left(P_w^b - \frac{\partial C_1^b}{\partial S_1^b}\right)\frac{\partial S_1^b}{\partial P_w^b}\frac{\partial P_w^b}{\partial P_w^a}\frac{\partial P_w^a}{\partial T} \quad \text{(a)}$$

Making selective substitution of equations (5), (7) and (8) into (1), we obtain:

$$\frac{\partial W_1}{\partial T} = \left(S_1^a - D_1^a\right)\left(\frac{\partial P_{D_1^a}}{\partial T} - 1\right)\left(1 - \frac{P_w^a}{P_w^b}\frac{\partial P_w^b}{\partial P_w^a}\right) + \left(t + \frac{\partial E_1}{\partial S_1^a}\right)\frac{\partial S_1^a}{\partial P_{S_1^a}}\frac{\partial P_{D_1^a}}{\partial T} - T\alpha\frac{\partial P_{D_1^a}}{\partial T} \quad \text{(b)}$$

From equation (3) there can be derived:

$$\frac{\partial S_1^a}{\partial P_{S_1^a}}\frac{\partial P_{S_1^a}}{\partial T}-\frac{\partial D_1^a}{\partial P_{D_1^a}}\frac{\partial P_{D_1^a}}{\partial T}=\frac{\partial D_2^a}{\partial P_w^a}\frac{\partial P_w^a}{\partial T}-\frac{\partial S_2^a}{\partial P_w^a}\frac{\partial P_w^a}{\partial T} \qquad \text{(c)}$$

This can be simplified by making use of equation (7):

$$\partial P_{D_1^a}/\partial T=\beta/(\alpha+\beta) \qquad \text{(d)}$$

Substitution of equation (d) into equation (b) leads to:

$$\frac{\partial W_1}{\partial T}=\frac{1}{(\alpha+\beta)}\left(-\alpha\left(S_1^a-D_1^a\right)\left(1-\frac{P_w^a}{P_w^b}\frac{\partial P_w^b}{\partial P_w^a}\right)+\left(t+\frac{\partial E_1}{\partial S_1^a}\right)\frac{\partial S_1^a}{\partial P_{S_1^a}}\beta-T\alpha\beta\right) \qquad \text{(e)}$$

Appendix 5: The partial derivative of Country 2's welfare function with respect to *T*

The partial derivative of W_2 with respect to T can be obtained from equation (2):

$$\begin{aligned}\frac{\partial W_2}{\partial T}=&-D_2^a\frac{\partial P_w^a}{\partial T}+P_w^a\frac{\partial S_2^a}{\partial P_w^a}\frac{\partial P_w^a}{\partial T}+\frac{\partial P_w^a}{\partial T}S_2^a-\frac{\partial C_2^a}{\partial S_2^a}\frac{\partial S_2^a}{\partial P_w^a}\frac{\partial P_w^a}{\partial T}-D_2^b\frac{\partial P_w^b}{\partial P_w^a}\frac{\partial P_w^a}{\partial T}\\&+P_w^b\frac{\delta S_2^b}{\delta P_w^b}\frac{\delta P_w^b}{\delta P_w^a}\frac{\delta P_w^a}{\delta T}+\frac{\delta P_w^b}{\delta P_w^a}\frac{\delta P_w^a}{\delta T}S_2^b-\frac{\delta C_2^b}{\delta S_2^b}\frac{\delta S_2^b}{\delta P_w^b}\frac{\delta P_w^b}{\delta P_w^a}\frac{\delta P_w^a}{\delta T}\end{aligned} \qquad \text{(a)}$$

Making use of equations (6) – (8) and of Appendix 1, equation (a) becomes:

$$\frac{\partial W_2}{\partial T}=-\frac{\alpha\left(S_2^a-D_2^a\right)}{(\alpha+\beta)}\left(1-\frac{P_w^a}{P_w^b}\frac{\partial P_w^b}{\partial P_w^a}\right) \qquad \text{(b)}$$

Appendix 6: The partial derivative of the global welfare function with respect to *T*

Given Appendix 4 and 5, the partial derivative of the global welfare function is:

$$\begin{aligned}\frac{\partial W}{\partial T}=&\frac{1}{(\alpha+\beta)}\left(-\left(S_1^a-D_1^a\right)\alpha\left(1-\frac{P_w^a}{P_w^b}\frac{\partial P_w^b}{\partial P_w^a}\right)+\left(t+\frac{\partial E_1}{\partial S_1^a}\right)\frac{\partial S_1^a}{\partial P_{S_1^a}}\beta-\alpha\beta T\right)\\&-\frac{\alpha\left(S_2^a-D_2^a\right)}{(\alpha+\beta)}\left(1-\frac{P_w^a}{P_w^b}\frac{\partial P_w^b}{\partial P_w^a}\right)\end{aligned} \qquad \text{(a)}$$

Making use of equation (3), this can be written as:

$$\frac{\partial W}{\partial T}=\frac{1}{(\alpha+\beta)}\left(\left(t+\frac{\partial E_1}{\partial S_1^a}\right)\frac{\partial S_1^a}{\partial P_{S_1^a}}\beta-\alpha\beta T\right) \qquad \text{(b)}$$

Appendix 7: The globally optimal second-best environmental tax rate

Based on Appendix 3, equation (b), the first order condition for a maximum is:

$$\frac{\partial W}{\partial t} = \frac{\partial S_1^a}{\partial P_{S_1^a}} \frac{1}{(\alpha+\beta)} \left(\left(t_w^* + \frac{\partial E_1}{\partial S_1^a} \right) \left(\frac{\partial D_1^a}{\partial P_{D_1^a}} - \beta \right) + \beta T \right) = 0 \qquad \text{(a)}$$

Solving equation (a) for t_w^*, we can write:

$$t_w^* = -\frac{\partial E_1}{\partial S_1^a} + T\beta \left(-\frac{\partial D_1^a}{\partial P_{D_1^a}} + \beta \right)^{-1} \qquad \text{(b)}$$

Appendix 8: The globally optimal second-best tariff rate

Based on Appendix 6, equation (b), the first order condition for a maximum is:

$$\frac{\partial W}{\partial T} = \frac{1}{(\alpha+\beta)} \left(\left(t + \frac{\partial E_1}{\partial S_1^a} \right) \frac{\partial S_1^a}{\partial P_{S_1^a}} \beta - \alpha\beta T_w^* \right) = 0 \qquad \text{(a)}$$

Solving equation (a) for T_w^*, we can write:

$$T_w^* = \left(t + \frac{\partial E_1}{\partial S_1^a} \right) \frac{\partial S_1^a}{\partial P_{S_1^a}} \frac{1}{\alpha} \qquad \text{(b)}$$

Appendix 9: The globally optimal first-best policy mix

We substitute equation (b) of Appendix 8 into equation (b) of Appendix 7:

$$t_w^{**} = -\frac{\partial E_1}{\partial S_1^a} + \left(-\frac{\partial D_1^a}{\partial P_{D_1^a}} + \beta \right)^{-1} \left(t_w^{**} + \frac{\partial E_1}{\partial S_1^a} \right) \frac{\partial S_1^a}{\partial P_{S_1^a}} \frac{\beta}{\alpha} \qquad \text{(a)}$$

Solving equation (a) for the first-best tax t_w^{**} yields:

$$t_w^{**} = -\partial E_1 / \partial S_1^a \qquad \text{(b)}$$

By substituting equation (b) into equation (b) of Appendix (8), the first-best tariff becomes:

$$T_w^{**} = 0 \qquad \text{(c)}$$

From Appendix 7, we can obtain:

$$\frac{\partial^2 W\left(t_w^{**}, T_w^{**}\right)}{\partial t^2} = -\frac{\partial S_1^a}{\partial P_{S_1^a}} \frac{1}{(\alpha+\beta)}\left(-\frac{\partial D_1^a}{\partial P_{D_1^a}} + \beta\right) < 0 \tag{d}$$

From Appendix 8, we can also derive:

$$\frac{\partial^2 W\left(t_w^{**}, T_w^{**}\right)}{\partial T^2} = -\frac{\alpha\beta}{(\alpha+\beta)} < 0 \tag{e}$$

Appendix 10: The domestically optimal second-best environmental tax rate

Based on Appendix 1, equation (e), the first-order condition for an interior maximum is:

$$\frac{\partial W_1}{\partial t} = \frac{\partial S_1^a}{\partial P_{S_1^a}} \frac{1}{(\alpha+\beta)}\left(\left(S_1^a - D_1^a\right)\left(1 - \frac{P_w^a}{P_w^b}\frac{\partial P_w^b}{\partial P_w^a}\right) - \left(t_1^* + \frac{\partial E_1}{\partial S_1^a}\right)\left(-\frac{\partial D_1^a}{\partial P_{D_1^a}} + \beta\right) + \beta T\right) = 0 \tag{a}$$

Solving equation (a) for t_1^*, we can write:

$$t_1^* = -\frac{\partial E_1}{\partial S_1^a} + \left(-\frac{\partial D_1^a}{\partial P_{D_1^a}} + \beta\right)^{-1}\left(\left(S_1^a - D_1^a\right)\left(1 - \frac{P_w^a}{P_w^b}\frac{\partial P_w^b}{\partial P_w^a}\right) + \beta T\right) \tag{b}$$

Appendix 11: The domestically optimal second-best tariff rate

Based on Appendix 4, equation (e), the first order condition for a maximum is:

$$\frac{\partial W_1}{\partial T} = \frac{1}{(\alpha+\beta)}\left(-\alpha\left(S_1^a - D_1^a\right)\left(1 - \frac{P_w^a}{P_w^b}\frac{\partial P_w^b}{\partial P_w^a}\right) + \left(t + \frac{\partial E_1}{\partial S_1^a}\right)\frac{\partial S_1^a}{\partial P_{S_1^a}}\beta - T_1^* \alpha\beta\right) = 0 \tag{a}$$

Solving equation (a) for T_1^*, we can write:

$$T_1^* = \left(t + \frac{\partial E_1}{\partial S_1^a}\right)\frac{\partial S_1^a}{\partial P_{S_1^a}}\frac{1}{\alpha} - \left(S_1^a - D_1^a\right)\frac{1}{\beta}\left(1 - \frac{P_w^a}{P_w^b}\frac{\partial P_w^b}{\partial P_w^a}\right) \tag{b}$$

Appendix 12: The domestically optimal first-best policy mix

We substitute equation (b) of Appendix 10 into equation (b) of Appendix 11:

$$t_1^{**} = -\frac{\partial E_1}{\partial S_1^a} + \left(-\frac{\partial D_1^a}{\partial P_{D_1^a}} + \beta\right)^{-1}\left(\left(S_1^a - D_1^a\right)(1-\varepsilon) + \beta\left(\left(t_1^{**} + \frac{\partial E_1}{\partial S_1^a}\right)\frac{\partial S_1^a}{\partial P_{S_1^a}}\frac{1}{\alpha} - \frac{\left(S_1^a - D_1^a\right)(1-\varepsilon)}{\beta}\right)\right) \tag{a}$$

where $\varepsilon = \left(\partial P_w^b / P_w^b\right) / \left(\partial P_w^a / P_w^a\right)$.

Solving equation (a) for the first-best tax t_1^{**} yields:

$$t_1^{**} = -\frac{\partial E_1}{\partial S_1^a} + \left(t_1^{**} + \frac{\partial E_1}{\partial S_1^a}\right)\frac{\partial S_1^a}{\partial P_{S_1^a}}\frac{\beta}{\alpha}\left(-\frac{\partial D_1^a}{\partial P_{D_1^a}} + \beta\right)^{-1} = -\frac{\partial E_1}{\partial S_1^a} \tag{b}$$

By substituting equation (b) into equation (b) of Appendix (11), T_1^{**} becomes:

$$T_1^{**} = -\left(S_1^a - D_1^a\right)(1-\varepsilon)/\beta \tag{c}$$

Appendix 13: Welfare effects of trade liberalization

From equation (10), we can derive:

$$\begin{aligned}\frac{\partial^2 W_1}{\partial T \partial t} &= \left[\frac{1}{(\alpha+\beta)}\right]'\left(-\alpha X_1^a(1-\varepsilon) + \left(t + \frac{\partial E_1}{\partial S_1^a}\right)\frac{\partial S_1^a}{\partial P_{S_1^a}}\beta - \alpha\beta T\right) \\ &\quad + \frac{1}{(\alpha+\beta)}\left[\left(-\alpha X_1^a(1-\varepsilon) + \left(t + \frac{\partial E_1}{\partial S_1^a}\right)\frac{\partial S_1^a}{\partial P_{S_1^a}}\beta - \alpha\beta T\right)\right]'\end{aligned} \tag{a}$$

Making selective use of equations (11) and (12), we obtain:

$$\frac{\partial^2 W_1\left(t_1^{**}, T_1^{**}\right)}{\partial T \partial t} = \frac{1}{(\alpha+\beta)}\begin{pmatrix} -\frac{\partial(\alpha(1-\varepsilon))}{\partial t}X_1^a - \alpha(1-\varepsilon)\frac{\partial X_1^a}{\partial t} \\ +\frac{\partial S_1^a}{\partial P_{S_1^a}}\beta + \frac{\partial \alpha}{\partial t}(1-\varepsilon)X_1^a + \frac{\partial \beta}{\partial t}\frac{\alpha(1-\varepsilon)X_1^a}{\beta}\end{pmatrix} \tag{b}$$

From Appendix 1, equation (c) we can derive:

$$\frac{\partial X_1^a}{\partial t} = -\frac{\beta}{(\alpha+\beta)}\frac{\partial S_1^a}{\partial P_{S_1^a}} \tag{c}$$

Inserting equation (c) into equation (b) yields:

$$\frac{\partial^2 W_1\left(t_1^{**}, T_1^{**}\right)}{\partial T \partial t} = \frac{1}{(\alpha+\beta)}\left(\alpha X_1^a\left(\frac{\partial \varepsilon}{\partial t} + \frac{\partial \beta}{\partial t}\frac{(1-\varepsilon)}{\beta}\right) + \frac{\alpha\beta(1-\varepsilon)}{(\alpha+\beta)}\frac{\partial S_1^a}{\partial P_{S_1^a}} + \frac{\partial S_1^a}{\partial P_{S_1^a}}\beta\right) \tag{d}$$

From equation (9), we can derive:

$$\begin{aligned}\frac{\partial^2 W_1}{\partial t^2} &= \frac{1}{(\alpha+\beta)}\left(\left[\frac{\partial S_1^a}{\partial P_{S_1^a}}\right]' - \frac{\partial S_1^a}{\partial P_{S_1^a}}\frac{\left(\alpha' + \beta'\right)}{(\alpha+\beta)}\right)\left(X_1^a(1-\varepsilon) - \left(t + \frac{\partial E_1}{\partial S_1^a}\right)\left(-\frac{\partial D_1^a}{\partial P_{D_1^a}} + \beta\right) + \beta T\right) \\ &\quad + \frac{\partial S_1^a}{\partial P_{S_1^a}}\frac{1}{(\alpha+\beta)}\left(\left[X_1^a(1-\varepsilon)\right]' - \left[\left(t + \frac{\partial E_1}{\partial S_1^a}\right)\left(-\frac{\partial D_1^a}{\partial P_{D_1^a}} + \beta\right)\right]' + [\beta T]'\right)\end{aligned} \tag{e}$$

Making selective use of equations (11) and (12), we obtain:

$$\frac{\partial W_1\left(t_1^{**},T_1^{**}\right)}{\partial t^2}=\frac{\partial S_1^a}{\partial P_{S_1^a}}\frac{1}{(\alpha+\beta)}\left(\frac{\beta(1-\varepsilon)}{(\alpha+\beta)}\frac{\partial S_1^a}{\partial P_{S_1^a}}+X_1^a\left(\frac{\partial\varepsilon}{\partial t}+\frac{\partial\beta}{\partial t}\frac{(1-\varepsilon)}{\beta}\right)+\left(-\frac{\partial D_1^a}{\partial P_{D_1^a}}+\beta\right)\right) \tag{f}$$

From equations (11)-(14), we obtain:

$$\frac{\partial W\left(t_1^{**},T_1^{**}\right)}{\partial t}=-\frac{\partial S_1^a}{\partial P_{S_1^a}}\frac{X_1^a(1-\varepsilon)}{(\alpha+\beta)} \tag{g}$$

and

$$\frac{\partial W\left(t_1^{**},T_1^{**}\right)}{\partial T}=\frac{\alpha X_1^a(1-\varepsilon)}{(\alpha+\beta)} \tag{h}$$

Making use of equations (d), (f), (g), (h) and (23), we derive:

$$\frac{dW\left(t_1^{**},T_1^{**}\right)}{dT}=\frac{-\frac{\partial D_1^a}{\partial P_{D_1^a}}X_1^a(1-\varepsilon)}{X_1^a\left(\frac{\partial\varepsilon}{\partial t}+\frac{\partial\beta}{\partial t}\frac{(1-\varepsilon)}{\beta}\right)+\frac{\beta(1-\varepsilon)}{(\alpha+\beta)}\frac{\partial S_1^a}{\partial P_{S_1^a}}-\frac{\partial D_1^a}{\partial P_{D_1^a}}+\beta} \tag{i}$$

Appendix 14: Calculation of $\partial\varepsilon/\partial t$

Solving the maximization problem $\max_{S_w^a}\left(S_w^aP_w^a+P_w^bS_w^b\left(S_w^a\right)\right)$ yields:

$$\partial S_w^b/\partial S_w^a=-P_w^a/P_w^b \tag{a}$$

Based on a fixed world output ($P_w^aS_w^a+S_w^bP_w^b=k=\text{constant}$), we can write:

$$P_w^b=\frac{k}{S_w^b}-P_w^a\frac{S_w^a}{S_w^b} \tag{b}$$

Hence:

$$\frac{\partial P_w^b}{\partial P_w^a}=-\frac{k}{\left(S_w^b\right)^2}\frac{\partial S_w^b}{\partial P_w^a}-P_w^a\left(\frac{1}{S_w^b}\frac{\partial S_w^a}{\partial P_w^a}-\frac{S_w^a}{\left(S_w^b\right)^2}\frac{\partial S_w^b}{\partial P_w^a}\right)-\frac{S_w^a}{S_w^b} \tag{c}$$

Making use of equation (a), this can be written as:

$$\partial P_w^b/\partial P_w^a=-S_w^a/S_w^b \tag{d}$$

Hence:

$$\varepsilon = \frac{\partial P_w^b}{\partial P_w^a}\frac{P_w^a}{P_w^b} = -\frac{P_w^a S_w^a}{P_w^b S_w^b} \tag{e}$$

From equation (e), we can derive:

$$\frac{\partial \varepsilon}{\partial t} = -\left(\frac{S_w^a}{P_w^b S_w^b} + \frac{P_w^a}{P_w^b S_w^b}\frac{\partial S_w^a}{\partial P_w^a} - \frac{P_w^a S_w^a}{P_w^b \left(S_w^b\right)^2}\frac{\partial S_w^b}{\partial P_w^a} - \frac{P_w^a S_w^a}{\left(P_w^b\right)^2 S_w^b}\frac{\partial P_w^b}{\partial P_w^a}\right)\frac{\partial P_w^a}{\partial t} \tag{f}$$

Making use of equation (e) and Appendix 1, equation (d), this can be written as:

$$\frac{\partial \varepsilon}{\partial t} = -\left(1 + \frac{P_w^a}{S_w^a}\frac{\partial S_w^a}{\partial P_w^a}\right)\frac{S_w^a(1-\varepsilon)}{P_w^b S_w^b}\frac{\partial S_1^a}{\partial P_{S_1^a}}\frac{1}{(\alpha + \beta)} \tag{g}$$

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