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An Evolutionary Race to the Top: Trade, Oligopoly and Convex Pollution Damage*

Matthew McGinty

Abstract

A two nation, two sector oligopoly trade model is presented in which one sector creates a negative production externality. Firms switch sectors in response to profit differentials until these are exhausted in the long run evolutionary equilibrium (EE). Under autarky, the optimal EE pollution tax is greater than standard partial equilibrium analysis since the output distortion associated with the tax is mitigated by firms migrating to the non-taxed sector. In a free trade area the pollution haven hypothesis is obtained when nations choose exogenous tax rates that differ. However, with endogenous taxation a prisoners' dilemma is obtained. The Nash equilibrium of the tax game exceeds the social planner's tax, generating a race to the top.

KEYWORDS: environmental policy, evolutionary game theory, free trade agreements, oligopoly

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1 Introduction

The emergence of free trade areas has heightened concern that nations with lax environmental regulations will become havens for polluting industries. Standard Ricardian trade models predict that the nation with the lower pollution tax will produce all, or be completely specialized in, the polluting good (Pethig, 1976, Chichilnisky, 1994). However, Copeland and Taylor (2004) and Jaffe, et al. (1995) make clear that there is little empirical support for the pollution haven hypothesis. Low and Yeats (1992) find evidence in support, but the majority of empirical studies agree with Grossman and Krueger (1993) in rejecting the pollution haven hypothesis. Taylor (2004) and Copeland and Taylor (2004) draw a distinction between the pollution haven hypothesis and the pollution haven effect. The latter recognizes that there is an incentive for dirty industries to locate in nations with lower pollution standards, however pollution havens are not realized since pollution policy may be less important than other determinants, such as factor endowments, in predicting the pattern of trade.

Eaton and Grossman (1986) and Kennedy (1994) among others, have noted that the majority of world trade occurs in markets that are imperfectly competitive. Furthermore, since the vast majority of trade occurs between developed nations that are "large" and relatively similar in factor endowments, perfect competition models based on differences in factor endowments may be less important than the strategic oligopoly model adopted in this paper in explaining observed trade flows.

The strategic trade policy literature has looked at corrective taxes in open economies under imperfect competition. Kennedy (1994) shows that nations have an incentive to reduce pollution taxes to capture rents through improved terms of trade. In a symmetric equilibrium there is no actual improvement in the terms of trade, so the distortions are "purely destructive" (pp. 58). There is also an incentive to increase taxation, shifting pollution to the other nation. The overall effect is to reduce the pollution tax as the rent capture effect dominates the pollution shifting effect. Thus, free trade agreements promote a "race to the bottom" of environmental standards (Bagwell and Staiger, 2001). Krutilla (1991) shows that the optimal domestic tax is less (greater) than the Pigouvian level if the nation imports (exports) the good in the absence of tariffs. This result is obtained by terms of trade effects, where decreasing the price is beneficial for the importing nation. Typically, the optimal tax is less than the Pigouvian level since taxation exacerbates the imperfect market distortion (Markusen, 1975). With convex pollution damage there is an interdependence between the optimal policy and dynamics influencing market structure.

As early as Alchian (1950) Economists have recognized that assumptions such as perfect rationality, foresight and competition need not be the only foundation for theoretical modeling. Alchian (1950) argues that strategies whose actions yield a higher payoff will become relatively more prevalent. Evolutionary game theory builds from this suggestion and assumes "survival of the fittest," with some inertia, in a continuous time framework (Friedman 1991, Weibull 1995). Survival of the fittest is a process of exit and entry where firms that have a lower profit "die" at a higher rate and exit the model. The resources employed by these firms become available to create new firms. New firms are "born" and enter the model as either type.[1] The present paper assumes the net birth rate is zero, thus the total number of firms is held fixed. With a fixed number of firms we may view switching sectors (strategies) and entry/exit driven by "survival of the fittest" as equivalent processes. The important point is the flow of resources across sectors in response to profit advantage, not the existence of any individual firm. Thus, we view the firm as a collection of inputs, which are allocated across sectors to equate profit in the evolutionary equilibrium (EE). We remain agnostic on the details of the process and the speed of adjustment to the EE, and adopt the most general sign-preserving dynamics.

More recently, this evolutionary game framework has been applied to issues in international economics. Friedman and Fung (1996) adopt an evolutionary game model of trade between the US and Japan with different modes of production to investigate the internal organization of firms. Using a standard Cournot model they show that each nation will be specialized in a different organizational mode under free trade. Dijkstra and De Vries (2006) adopt an evolutionary framework to address firm and household locations in a model with constant marginal pollution damage. Under a pollution taxation regime they find that firms and households tend to locate in different regions.

Fisher and Kakkar (2004) investigate whether or not specialization according to comparative advantage is obtained in the evolutionary equilibrium when firms are pairwise-matched. The pairwise matching allows payoffs to be represented by simple bimatricies, but at the expense of constrained competition. Firms do not compete against all other firms. They find that the autarky evolutionary equilibrium is a single population Hawk-Dove game in which there

[1] If a new firm is perfectly rational they will enter the sector with the profit advantage. While this will increase the speed of adjustment to the evolutionary equilibrium, perfect rationality is not required to obtain dynamics compatible with profit advantage.

is a stable mix of both goods. Thus, there is a decreasing (increasing) payoff advantage to producing good 1 (2) as the amount of good 1 becomes more prevalent.

An interesting phenomenon occurs in two population Hawk-Dove games with pairwise matching. Since members of the first population are matched only against members of the other population, the interior equilibrium is destabilized. There is a payoff advantage to being the other type, so both populations become "purified" (Friedman, 1996). As Hawks become relatively more prevalent there is an increasing payoff advantage to being a Dove in the other population. In international economics the analogue is that at least one nation is completely specialized. There is an increasing payoff advantage to specialization as nations become more integrated. Fisher and Kakkar (2004) model two different matching procedures. When firms are matched only against a foreign firm they obtain two evolutionary equilibria, both with complete specialization. However, one of these corresponds to comparative disadvantage, a result obtained in Cordella and Gabszewicz (1997) and Chua (2003).[2] Specialization according to comparative advantage is obtained when firms face a random match drawn from both nations. Thus, their results are sensitive to the matching assumption.

The present paper combines elements of Friedman and Fung (1996) and Fisher and Kakkar (2004). The framework includes linear demand, Cournot behavior, and constant marginal cost in the evolutionary setting of Friedman and Fung (1996), but also includes a two sector trade model that does not have a state dependent cost externality. Unlike Fisher and Kakkar (2004), this paper examines the pattern of specialization when firms compete against all rivals, domestic and foreign, rather than a random pairwise match. The paper demonstrates a unique evolutionary equilibrium such that the nation with the lower (exogenous) tax rate specializes in the dirty good. The opposite pattern of specialization is not possible when all firms compete against each other.

The focus of this paper is environmental policy in a free trade area under oligopoly. It shows that the ability of firms to migrate to the non-polluting sector increases the welfare maximizing pollution tax in autarky. This result is obtained since taxation causes a flow of resources to the other sector, partially offsetting the exacerbation of the imperfect competition output distortion. Under free trade, exogenous taxation differences result in the nation with the lower pollution tax becoming a pollution haven. This result occurs since

[2] Cordella and Gabszewicz (1997) augment a standard Ricardian trade model with the assumption that oligopolistic firms behave strategically, recognizing the effect of output decisions on the terms of trade. They find that perverse patterns of trade corresponding to comparative disadvantage may emerge in the non-cooperative outcome.

a pollution tax that is independent of output is equivalent to an exogenous increase in constant marginal cost.

However, if pollution damage is convex the optimal pollution tax increases in domestic output. In both the Nash equilibrium of the governments' tax game and the planner's tax solution there exists a stable, unique, interior EE in which both nations are incompletely specialized. Thus, there is intra-industry trade and neither nation becomes a pollution haven. At the EE tax rates are identical. Away from the EE the tax rates differ and the nation with the lower tax has an incentive to increase the tax rate until the EE is obtained. In fact, the surprising result emerges that the Nash equilibrium of the government tax game results in a race to the top. The Nash equilibrium tax rate exceeds the socially optimal level as both nations have an incentive to shift production of the polluting good to their trading partner. The tax rates are strategic complements in the neighborhood of the EE, even for a very minor degree of pollution damage convexity. The policy implications are clear. Nations in a free trade agreement have an incentive to coordinate pollution policy, otherwise they are caught in a prisoner's dilemma with tax rates exceeding the social planner's solution.[3]

This result is the opposite of Kennedy (1994), where each government has an incentive to lower the tax to improve the terms of trade. Although the models differ in several respects, the critical difference is that Kennedy's planner does not try to strategically manipulate the terms of trade, as does each government. The planner chooses a tax to maximize welfare of a representative nation (pp. 53). In contrast, the planner in this paper chooses a tax to maximize global welfare. Kennedy (1994) presents a single sector model with transboundary pollution, while the present paper examines a two sector model with no transboundary pollution. In this paper both the Nash and planner's taxes are lower than the Pigouvian level, even though both nations export both goods.

The remainder of the paper is organized as follows. Section 2 solves the autarky short run and evolutionary equilibria, given pollution policy. The free trade evolutionary equilibrium with exogenous pollution policy is determined in Section 3. Section 4 extends the previous results by analyzing endogenous pollution policy, comparing the Nash equilibrium of the governments' tax game with a social planner's tax. Section 5 concludes and discusses future research.

[3]The model does not consider abatement technology as Kennedy (1994) or Copeland and Taylor (2004), mergers as Perry and Porter (1985), or an endogenous number of firms as Krugman (1980).

2 Autarky

In the short run each firm behaves as a Cournot competitor taking the proportion of firms in each sector as given. In the long run the proportion of firms adjusts in response to profit differentials until the evolutionary equilibrium (EE) is obtained. The firm has two roles depending on the time frame. In the short run firms choose quantity and in the long run a sector, clean or dirty. The short run is the typical framework for analyzing a partial equilibrium optimal tax for a polluting oligopolist. In the EE taxation influences the composition of output in both autarky and with trade.

Home demand is assumed to be: $P_i = 1 - Q_i$, where P_i and Q_i are market price and quantity of good i, and $i = c$, d denotes clean and dirty respectively.[4] There are n firms, s proportion of which produce in the clean sector, and $(1-s)$ proportion in the polluting (dirty) sector. It is assumed that all firms have equal access to either the clean or polluting technology and inputs, so that all firms of any given type are of identical size. Market quantities are: $Q_c = snq_c$ and $Q_d = (1-s)nq_d$, where q_i is the quantity produced by a firm in sector i. The firms are assumed to have constant marginal costs normalized to zero, and no fixed costs.[5] The benefit of the simple demand and cost functions is that analytic solutions to the model can be obtained. A pollution tax of t is levied per-unit on dirty output. Pollution damage is assumed to be contained within national borders. Furthermore, it is assumed that firms do not have access to abatement technology. Output is scaled so that one unit of dirty output produces one unit of pollution.

Firms choose quantity to maximize profit, π_i, taking other firms' output as given. Firm profit is $\pi_i = q_i P_i$, $i = c, d$ gross of the pollution tax. At an interior equilibrium $P_c = q_c$ and $P_d = q_d + t$. Thus, $\pi_c = P_c q_c = (q_c)^2$ and $\pi_d = (P_d - t)q_d = (q_d)^2$. The autarky short run Nash equilibrium quantities

[4] Both demand curves are assumed to have the same intercept and slope. Generalizing the model to include differences in demand intercepts, slopes, and marginal costs will not qualitatively effect the results as long as nations are not too different, but greatly reduces the transparency. See Friedman and Fung (1996) for a model with cross-price effects and different marginal costs.

[5] Fixed costs are normalized to zero for each type since they do not effect output decisions at the margin. If fixed costs are positive and equal then there is no impact on the EE proportion of clean and dirty firms. The EE will be shifted towards the lower fixed cost type where they to differ, but otherwise the model would be unchanged.

and profits are functions of (s, n, t).

$$\begin{aligned} q_c &= \frac{1}{sn+1} \\ q_d &= \frac{1-t}{(1-s)n+1} \end{aligned} \tag{1}$$

In the long run, the composition of firms responds to the profit advantage. Evolutionary dynamics may arise from firms switching sectors in response to the profit differential (Friedman and Fung 1996, Friedman, 1998) or from a process of firms exiting (dying) and entering (being born) the model (Weibull, 1995). When a firm exits the model resources are made available for the creation of a new firm. Firms with a payoff advantage have a higher net birth rate. For the population as a whole the net birth rate is zero, thus firms switching type and entry/exit are equivalent processes. We are holding n fixed, but allowing the population to evolve.

The function $\Pi_D \equiv \frac{\pi_c}{\pi_d} = \left(\frac{q_c}{q_d}\right)^2$ is the relative profit advantage of a clean firm, where π_i satisfies the short run Cournot-Nash equilibrium for type i.[6] At the short run Nash equilibrium Π_D is:

$$\Pi_D = \left[\frac{(1-s)n+1}{(sn+1)(1-t)}\right]^2 \tag{2}$$

The adjustment dynamics to the long run equilibrium are only required to be compatible (Friedman, 1991). Thus, the proportion of clean firms increases when clean has a profit advantage, $\dot{s} = A(s)\Pi_D(s)$, where $A(s) > 0$ for $\Pi_D(s) > 1$ and $A(s) < 0$ for $\Pi_D(s) < 1$, and the dot denotes the time derivative. Sign-preserving dynamics are more general than Replicator dynamics, in which strategies that have a relatively higher payoff advantage increase at a faster rate.[7] The EE is the value of s where $\Pi_D = 1$. Proposition 1 characterizes the autarky EE.

Proposition 1: In autarky there is a unique, stable, interior evolutionary equilibrium at $s^{ee} = \frac{n+t}{n(2-t)}$ *for all* $t < \bar{t} \equiv \left(\frac{n}{n+1}\right)$. *For* $t \geq \bar{t}$ *the evolutionary equilibrium is* $s = 1$.

[6] I am grateful to an anonymous referee for suggesting this form for Π_D, which was initially defined as a difference, and for the interpretation following Proposition 1.

[7] Replicator dynamics for this model are $\dot{s} = \left[\pi_c(s) - \frac{s\pi_c(s)+(1-s)\pi_d(s)}{2}\right] s$. The growth rate of the population share of clean firms is increasing in their profit advantage relative to the population average. Replicator dynamics are a special case of sign-preserving dynamics. See Friedman (1998) for a discussion of adjustment dynamics in evolutionary games.

Proof: The solution to $\Pi_D = 1$ is $s = \frac{n+t}{n(2-t)}$. There is an irrelevant root $s = \frac{(n+2)-t}{tn} > 1$ for $t < \left(\frac{n+2}{n+1}\right)$, and the dirty good market ceases to exist if $t \geq \bar{t}$. Stability is determined by: $\frac{\partial \Pi_D}{\partial s} = \frac{-2n(n+2)[(1-s)n+1]}{(sn+1)^3(1-t)^2} < 0$, where Π_D is a smooth, continuous, decreasing function of s. $\Pi_D > (<)1$ for $s < (>)\frac{n+t}{n(2-t)}$.■

Denoting the number of clean and dirty firms as $n_c \equiv sn$ and $n_d \equiv (1-s)n$ and evaluating Π_D at the EE implies $\frac{(n_d+1)/n}{(n_c+1)/n} = (1-t)$. As the tax approaches 1 (0) the proportion of dirty firms approaches 0 (1/2). The fixed point of $\Pi_D = 1$ is stable and unique, implying that both types of firms will exist in the long run under autarky. For $t = 0$ the EE is $s = 0.5$ and s^{ee} is increasing in t.[8] The EE satisfies both the short run quantity decision that maximizes profits, and the additional requirement that firms have no incentive to switch type in the long run.

Any initial proportion of clean firms, $s \in [0, 1]$, will converge to the EE, and the EE is robust to perturbations. This stable, unique, interior equilibrium is the analogue of a single population, non-linear, Hawk-Dove game in the evolutionary game literature. At $s = 0$ the profit advantage is: $\Pi_D = \left[\frac{n+1}{1-t}\right]^2 > 1$, and at $s = 1$ the profit advantage is: $\Pi_D = \left[\frac{1}{(n+1)(1-t)}\right]^2 < 1$. As a type becomes more prevalent, its payoff advantage decreases (Weibull 1995). By contrast, Friedman and Fung (1996) model a coordination game since there is a positive cost externality among firms. Their model generates two pure EE's ($s = 0$, $s = 1$) whose basins of attraction are separated by the mixed strategy Nash equilibrium.

At the autarky EE output and profit are functions of (n, t).

$$\begin{aligned} q_c^{ee} &= q_d^{ee} = \frac{2-t}{n+2} \\ Q_c^{ee} &= \frac{n+t}{n+2} \\ Q_d^{ee} &= \frac{n-t(n+1)}{n+2} \\ \pi_c^{ee} &= \pi_d^{ee} = \left(\frac{2-t}{n+2}\right)^2 \end{aligned} \tag{3}$$

At the EE the tax increases clean market output, decreases market output in the taxed sector and reduces aggregate output. In the EE firm output and

[8] The profit advantage and s^{ee} are increasing in the tax: $\frac{\partial \Pi_D}{\partial t} = \frac{2[(1-s)n+1]^2}{(1+sn)^2(1-t)^3} > 0$ and $\frac{\partial s^{ee}}{\partial t} = \frac{n+2}{n(2-t)^2} > 0$.

profit are equalized across sectors, thus clean firms are also harmed by the pollution tax.

2.1 Autarky pollution policy

The government chooses a pollution tax to maximize welfare, defined as the sum of consumer surplus (CS) and profit (Π) in each sector, pollution damage ($E(Q_d)$), and tax revenue (TR). Environmental damage E is a negative externality that does not effect the production functions and is contained within the nation's borders. The tax revenue is lump-sum redistributed to either producers, consumers or both, but does not impact decisions at the margin.

$$W = CS_c + CS_d + \Pi_c + \Pi_d + TR - E(Q_d) \tag{4}$$

A comparison of the Nash and evolutionary welfare maximizing tax rates follows. At the EE (3) the tax increases output in the clean market, an effect that is absent in the short run (1). A government choosing the pollution tax to maximize welfare holding s constant does not recognize these effects. In the EE the tax results in a negative profit spillover to the clean industry, so the tax that maximizes welfare given (1) differs from the EE welfare maximizing tax.

Short run welfare can be simplified by market,

$$W = \frac{sn(sn+2)}{2(sn+1)^2} + \frac{(1-s)n\left[(1-s)n(1-t^2)+2(1-t)\right]}{2\left[(1-s)n+1\right]^2} - E(Q_d) \tag{5}$$

where the first term is consumer surplus and profit generated by the clean market, and the second term is consumer surplus, profit and tax revenue from the dirty market. The tax does not effect the clean market welfare components in the short run. The short run tax balances the reduction in welfare from the dirty market $\frac{\partial[CS_d+\Pi_d+TR]}{\partial t} = \frac{-n_d(tn_d+1)}{(n_d+1)^2} < 0$ with the increase in welfare from pollution reduction $-\frac{\partial E(Q_d)}{\partial t} = -\frac{E'(Q_d)\partial Q_d}{\partial t} = \frac{n_d E'(Q_d)}{n_d+1}$, where E' is the marginal damage of a unit of dirty output. The short run welfare maximizing tax is:

$$t = \frac{(n_d+1)\,E'(Q_d)-1}{n_d} \tag{6}$$

The tax is for a given value of s, and this tax drives the system to an EE. However, neither this tax nor the EE value of s that it generates maximize welfare. The EE is:

$$s^{ee} = \frac{n-1+E'(Q_d)}{n\,(2-E'(Q_d))} \tag{7}$$

Using (7) to eliminate s in (6) is non-trivial as the marginal damage is a function of dirty output, which in turn is a function of both t and s. Thus, the short run tax (6) changes along the adjustment path to the EE. The short run tax evaluated at the EE is:

$$t_{|s=s^{ee}} = \frac{(n+2)E'\left(Q_d\right) - 2}{n+1} \tag{8}$$

The tax is positive for all $E'\left(Q_d\right) > \frac{2}{n+2}$. The upper bound on the tax consistent with an interior equilibrium is $\bar{t}$. This implicitly defines a marginal damage upper bound that is less than the demand intercept ($t_{|s=s^{ee}} < \bar{t}$ implies $E'\left(Q_d\right) < 1$). The short run welfare maximizing tax is positive for all $E'\left(Q_d\right) > \frac{1}{(n_d+1)}$. Using $\bar{t}$ as above we find $E'\left(Q_d\right) < \frac{n(n_d+1)+1}{(n+1)(n_d+1)} < 1$. So, $t \in (0, \frac{n}{n+1})\forall \frac{1}{(n_d+1)} < E'\left(Q_d\right) < \frac{n(n_d+1)+1}{(n+1)(n_d+1)}$. For marginal damage greater than one the optimal tax is such that the dirty market ceases to exist.[9]

A more sophisticated policy recognizes the tax spillover to the clean industry in the EE and chooses the welfare maximizing tax accordingly. Using equation (3) welfare at the evolutionary equilibrium simplifies to:

$$W^{ee} = \frac{2n(n+4) - t^2(n^2+2n+2) - 4tn}{2\left(n+2\right)^2} - E\left(Q_d^{ee}\right) \tag{9}$$

The EE welfare maximizing tax balances the reduction in profit and consumer surplus in both sectors caused by the tax $\frac{\partial[CS_c+CS_d+\Pi_c+\Pi_d+TR]}{\partial t} = -\frac{t(n^2+2n+2)+2n}{(n+2)^2} < 0$ with the reduction in pollution damage $-\frac{\partial E(Q_d^{ee})}{\partial t} = -\frac{E'\left(Q_d^{ee}\right)\partial Q_d^{ee}}{\partial t} = \frac{(n+1)E'\left(Q_d^{ee}\right)}{n+2}$. The EE welfare maximizing tax is:

$$t^{ee} = \frac{\left(n^2+3n+2\right)E'\left(Q_d^{ee}\right) - 2n}{n^2+2n+2} \tag{10}$$

The EE welfare maximizing tax is positive for all $E'\left(Q_d^{ee}\right) > \frac{2n}{n^2+3n+2}$.

Introducing evolutionary dynamics changes the optimal tax. In the short run s is held fixed and the standard partial equilibrium optimal tax is obtained. Since there is an output distortion due to imperfect competition, the tax is less than marginal damage. In the long run resources flee the taxed sector and s increases (Proposition 1 shows that $\frac{\partial s^{ee}}{\partial t} > 0$). The evolutionary equilibrium tax rate recognizes this effect. The EE tax rate is greater than the short run tax since there is a smaller reduction in consumer surplus. Output increases as

[9]For $t \geq \bar{t}$, the dirty market ceases to exist ($s^{ee} = 1$) and welfare at the EE becomes: $W^* = \frac{n(n+2)}{2(n+1)^2}$.

resources flow to the non-taxed sector. For a given tax rate, the EE reduction in total output is less than the short run reduction. Proposition 2 compares the short run and EE welfare maximizing taxes.

Proposition 2: The autarky evolutionary equilibrium welfare maximizing tax is greater than the short run welfare maximizing tax evaluated at the evolutionary equilibrium.

Proof: Suppose the converse is true. Comparing (8) and (10) $t_{|s=s^{ee}} > t^{ee}$ implies $E'(Q_d) > \frac{(n^2+2n+1)E'(Q_d^{ee})+2}{n^2+2n+2}$, or $E'(Q_d) > E'(Q_d^{ee}) + \frac{2-E'(Q_d^{ee})}{n^2+2n+2}$. Then $E'(Q_d) > E'(Q_d^{ee})$ since $E'(Q_d^{ee}) < 2$. However, $E(Q_d)$ is assumed to be a smooth, continuous, convex function, thus E' is strictly increasing in Q_d. Furthermore, equations (1) and (3) show Q_d and Q_d^{ee} are both monotonically decreasing in t, $\frac{\partial Q_d}{\partial t} = \frac{-n_d}{n_d+1} < 0$, and $\frac{\partial Q_d^{ee}}{\partial t} = \frac{-(n+1)}{n+2} < 0$. Therefore, if $t_{|s=s^{ee}} > t^{ee}$, then $Q_{d|s=s^{ee}} < Q_d^{ee}$ and $E'(Q_d) < E'(Q_d^{ee})$, a contradiction.$\blacksquare$

Proposition 2 is a somewhat surprising result. The partial equilibrium welfare maximizing tax is too low. Allowing firms to switch sectors increases the tax rate. This is because firms' ability to flee the taxed sector increases the incentive for a welfare maximizing government to tax pollution. As firms flee the taxed sector they increase output in the other sector, and firms that remain in the taxed sector increase their output. The overall impact is a smaller reduction in output than would be obtained with standard partial equilibrium analysis. The EE pollution tax balances the reduction in profit and consumer surplus that accompanies the tax, mitigated by the lump-sum redistribution of the tax revenue, with the reduction in pollution damage. One might imagine that allowing firms to flee the taxed sector would decrease the incentive of a welfare maximizing government to tax pollution, however, it is exactly the opposite. The reason is that the exacerbation of the output distortion by taxation is mitigated by firms fleeing the taxed sector. Evolutionary dynamics imply that firms exploit all profitable deviations, thus the evolutionary value of s results in the highest combined profit across the two sectors. Proposition 3 compares the short run and EE taxes with a Pigouvian tax, which is the marginal damage of the last unit of pollution.

Proposition 3: Both the autarky short run and evolutionary equilibrium welfare maximizing tax rates are lower than the Pigouvian level.

Proof: The Pigouvian tax is equal to marginal damage: $E'(Q_d)$. (i) $t = \frac{(n_d+1)E'(Q_d)-1}{n_d} = E'(Q_d) - \frac{(1-E'(Q_d))}{n_d}$. Therefore, $t < E'(Q_d)$ since $E'(Q_d) < 1$.

(ii) $t^{ee} = \frac{\left(n^2+3n+2\right)E'\left(Q_d^{ee}\right)-2n}{n^2+2n+2} = E'\left(Q_d^{ee}\right) - \frac{n\left(2-E'\left(Q_d^{ee}\right)\right)}{n^2+2n+2}$. Thus, $t^{ee} < E'\left(Q_d^{ee}\right)$ since $E'\left(Q_d^{ee}\right) < 1$.■

2.2 Foreign market

The demand and cost conditions are assumed identical across nations. The foreign market autarky equilibrium is given by equations (1) to (3) with s^*, n^*, and t^* replacing s , n, and t. The equilibrium value of s^* will be different than s if tax policy differs. The foreign market autarky Nash equilibrium quantities are $q_c^* = \frac{1}{s^*n+1}$ and $q_d^* = \frac{1-t^*}{(1-s^*)n+1}$. The short run profits are $\pi_c^* = (q_c^*)^2$ and $\pi_d^* = (q_d^*)^2$. The dynamics are given by: $\dot{s}^* = B(s)\Pi_D^*(s)$, where $B(s^*) > 0$ for $\Pi_D^*(s^*) > 1$ and $B(s^*) < 0$ for $\Pi_D^*(s^*) < 1$.

There is a stable mix of both types of firms in both nations in autarky. This is the evolutionary game analogue to two separate single population Hawk-Dove games. In this situation, when one strategy type becomes too prevalent there is a payoff advantage to being the other type.[10] The populations are separated under autarky, but interact with both their own and the other population with trade.

3 Trade

The central issue is harmonization of environmental standards in a free trade area. The home and foreign markets are separated, yet firms from each nation sell in both markets. The functions are assumed to be identical across countries so that the implications of the model are driven by environmental policy, rather than differences in preferences, market size, or cost.

The home and foreign autarky evolutionary equilibria serve as the initial condition when the model is opened up to trade, which is relevant if there is more than one basin of attraction. In the short run each firm maximizes profits by simultaneously choosing quantities for sale in both the home and foreign markets. Products are assumed to be differentiated only by type and not by the nation of origin. The Nash equilibrium now consists of four quantities in each market.

[10] In general a Hawk-Dove game is linear in its payoff differentials and there is a random match of players from the two populations. Since the firms' payoffs are non-linear in the state space s or s^* and firms compete against all other firms the game can not easily be reduced to a bimatrix. Fisher and Kakkar (2004) get around this problem by assuming that a firm is randomly matched against one other firm.

As with autarky, in the short run firms simultaneously choose quantities taking their type, the output of other firms, and s and s^*as given. The short run profit function for a home clean firm is $\pi_c = (q_c^h)^2 + (q_c^f)^2$, and the short run profit function for a foreign clean firm is $\pi_c^* = (q_c^{*h})^2 + (q_c^{*f})^2$, where the superscript denotes sales in the home (h) and foreign (f) markets, and $*$ denotes foreign. A home firm will sell the same amount of output in both nations since there are no barriers to trade, goods of either type are identical regardless of national origin, and demand is identical in both nations. Thus, $q_c^h = q_c^f$, and both are denoted q_c. The Nash equilibrium output and profits are:

$$\begin{aligned}
q_c &= \frac{1}{sn + s^*n + 1} = q_c^* \qquad (11)\\
q_d &= \frac{1 - t + (1 - s^*)n(t^* - t)}{(1 - s)n + (1 - s^*)n + 1}\\
q_d^* &= \frac{1 - t^* + (1 - s)n(t - t^*)}{(1 - s)n + (1 - s^*)n + 1}\\
\pi_c &= 2\left(q_c\right)^2 = \pi_c^*\\
\pi_d &= 2\left(q_d\right)^2\\
\pi_d^* &= 2\left(q_d^*\right)^2
\end{aligned}$$

Home and foreign clean firms produce the same quantity, however the dirty firms that are taxed less have greater output. Now there is an international dimension to the tax spillover. A tax in one nation impacts the amount sold of all types in the EE, but only the dirty types in the short run.[11]

The evolution of the state variables s and s^* is mutually dependent since firms are selling in both markets. Again, the dynamics are driven by the profit advantage of clean firms.[12] The two clean profit advantages are $\Pi_D = \left(\frac{q_c}{q_d}\right)^2$ and $\Pi_D^* = \left(\frac{q_c^*}{q_d^*}\right)^2$. As with autarky the dynamics are only assumed to be sign preserving, $\dot{\Pi}_D = F(s, s^*)\Pi_D$ and $\dot{\Pi}_D^* = G(s, s^*)\Pi_D^*$. The functions F and G are such that $F(s, s^*) \gtreqless 0$ for $\Pi_D \gtreqless 1$ and $G(s, s^*) \gtreqless 0$ for $\Pi_D^* \gtreqless 1$. Along the equal profit loci there is no incentive for firms to switch type. Proposition 4 characterizes the EE with exogenous taxation.

[11] At the short-run Nash equilibrium, the own tax effect on dirty output is greater in magnitude and opposite in sign than the cross tax effect on output. $\frac{\partial q_d}{\partial t} = \frac{-[(1-s^*)n+1]}{[(1-s^*)+(1-s)]n+1} \in [-1, 0] \in \forall s, s^* \in [0, 1]$ $\frac{\partial q_d}{\partial t^*} = \frac{(1-s^*)n}{[(1-s^*)+(1-s)]n+1} \in [0, 1) \in \forall s, s^* \in [0, 1]$.

[12] It is assumed that factors of production are not mobile across borders. That is, firms can not locate in a different country to take advantage of a lower tax. Thus, we are taking the number of firms in each country to be exogenous.

Proposition 4: If home and foreign have equal pollution tax rates that are independent of s, s^* *then both home and foreign loci have slope -1. Any pattern of specialization such that* $s + s^* \equiv \gamma = \frac{2n+t}{n(2-t)} > 1$ *is an evolutionary equilibrium.*

Proof : $\Pi_D = 1$ defines a locus with $\frac{ds^*}{ds} = -1$ by the implicit function theorem, and $\gamma = s + s^*$. For $t = t^*$, $\Pi_D = 1$ and $\Pi_D^* = 1$ define the same locus.■

The equal profit loci are linear when nations have identical tax rates that are independent of the state variables (s, s^*). If both tax rates are zero then both the home and foreign loci are: $s^* = 1 - s$. Any pattern of specialization is obtainable since any $s + s^* = 1$ is an EE. When the (equal) taxes are greater than zero the equal profit loci are shifted to towards the $s = s^* = 1$ corner of the unit box. In this case there is a greater aggregate prevalence of clean firms $s + s^* = \gamma = \frac{2n+t}{n(2-t)} > 1$. When the tax rate is constant in s, s^* the equal profit loci will not intersect (other than linear dependence if $t = t^*$). However, if the tax rates differ there is a unique pattern of specialization.

Proposition 5: If home and foreign have different pollution tax rates that are independent of s, s^* *then the nation with the higher tax rate is completely specialized in the clean good. The nation with the lower tax is incompletely specialized and produces all the dirty output.*

Proof*:* The simultaneous solution to $\Pi_D = 1$ and $\Pi_D^* = 1$ is:

$$\begin{aligned} s &= \frac{1 - t^* + n(t - t^*)}{n(t - t^*)} = 1 + \frac{1 - t^*}{n(t - t^*)} \qquad (12) \\ s^* &= \frac{1 - t + n(t^* - t)}{n(t^* - t)} = 1 + \frac{1 - t}{n(t^* - t)} \end{aligned}$$

Recall that $t, t^* < 1$ or the market for the dirty good ceases to exist. Suppose $s, s^* \in (0, 1)$. Equation (12) shows if $s \in (0, 1)$ then $t < t^*$and if $s^* \in (0, 1)$ then $t > t^*$.■

An alternative demonstration of the intuition behind Propositions 4 and 5 can be seen by recognizing that the $\Pi_D = 1$ and $\Pi_D^* = 1$ loci imply:[13]

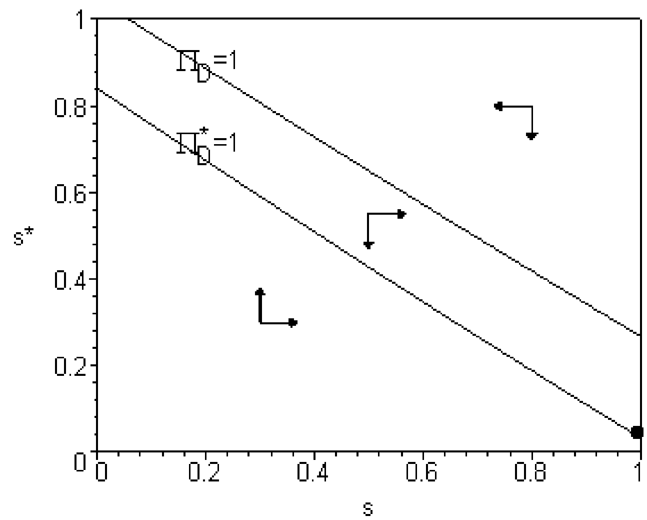
$$\begin{aligned} \frac{n_d + n_d^* + 1}{n_c + n_c^* + 1} &= n_d^* (t^* - t) + 1 - t \qquad (13) \\ \frac{n_d + n_d^* + 1}{n_c + n_c^* + 1} &= n_d (t - t^*) + 1 - t^* \end{aligned}$$

[13] I am grateful to an anonymous referee for suggesting this form and intuition.

An interior equilibrium requires the loci intersect in the unit square. By (13) this requires $n_d^* (t^* - t) + 1 - t = n_d (t - t^*) + 1 - t^*$, or $(n_d^* + n_d + 1)(t^* - t) = 0$. Thus, if $t \neq t^*$ it is not possible for both nations to be incompletely specialized. If $t = t^*$, then the loci are identical and show the global proportion of dirty firms is less than 1/2.

Figure 1 illustrates the EE when the home tax is greater. For $t > t^*$ the EE, denoted by a solid dot, is at the intersection of the $\Pi_D^* = 1$ locus and the $s = 1$ edge of the unit simplex. Proposition 5 shows that the pattern of trade corresponds to the pollution haven hypothesis, where the nation with the lower tax rate produces all of the global dirty output. The home country is completely specialized in the clean good, the foreign country is incompletely specialized and producing all of the dirty good output. This result would also be obtained in a model with constant but asymmetric marginal costs, and no pollution damage.

Figure 1: Greater Home Tax Equal Profit Loci



This result is a theoretical explanation for the pollution-haven hypothesis in which the polluting firms locate in the nation with the lower environmental standard. The evolution is driven by differences in pollution taxes across nations and is consistent with profit-maximizing behavior by firms. However, these tax rates do not respond to the level of output and pollution. Propositions 4 and 5 assume passive governments, that is: $\frac{dt}{ds} = \frac{dt^*}{ds^*} = 0$.

This raises the possibility that governments announcing a single tax rate have an incentive to leapfrog each others' tax rate. If the foreign nation raises its tax above the home tax then the pattern of specialization is reversed. In what follows we will show that the home and foreign tax rates are strategic complements (if pollution damage is sufficiently convex) in the neighborhood of the equilibrium. Both nations have an incentive to increase taxes until the marginal welfare gain from reducing pollution is equal to the marginal welfare loss from exacerbating the market imperfection. In other words, a race to the top in which both nations increase their tax rates. This is a non-cooperative tatônement process, not the social planner's solution to maximizing global welfare.

4 Endogenous pollution policy

To this point the equal profit loci assume a fixed tax rate in the state space. This is not problematic if pollution damage is linear, or governments do not respond to the level of pollution. However, if pollution damage is convex, then the tax should be a function of domestic pollution. The tax rate is state dependent, changing the loci slopes and generating an interior EE.[14]

Two endogenous tax policies are investigated and compared to the Pigouvian rate. First, the Nash equilibrium of the non-cooperative tax game between governments is presented. Next, the social planner's solution, where a free trade agreement also contains environmental policy provisions that harmonize tax policy. The social planner's solution is lower than the Nash equilibrium tax, which in turn is lower than the Pigouvian tax.

Under perfect competition the socially optimal tax is the Pigouvian rate. In partial equilibrium imperfect competition models the optimal pollution tax is less than marginal damage since the tax exacerbates the existing market imperfection distortion (Markusen 1975). Single sector imperfect competition trade models show that the Nash equilibrium of a tax game between nations results in a tax that is lower than the socially optimal level (Kennedy, 1994, Bagwell and Staiger, 2001).

This paper reverses the ordering. The socially optimal tax is less than the Nash equilibrium of the tax game between governments. This occurs because the planner's objective function contains the impact of the tax on the other nation. The planner chooses a lower tax since the reduction in pollution and consumer surplus dominates the increase in profit in the other nation. The pollution haven hypothesis is not obtained in either endogenous tax regime. Both regimes result in intra-industry trade, with both nations incompletely

[14] This is similar to the state dependent cost externality in Friedman and Fung (1996), causing the equal profit loci to cross in the unit box. Friedman and Fung (1996) model a positive externality where a firm's relative cost advantage increases in the prevalence of its type.

specialized at the EE. There is a stable, unique, interior EE of a two population game, which is surprising given both the orthodox evolutionary game perspective (Weibull, 1995), and some of Fisher and Kakkar's (2004) results. This EE is obtained since each firm competes directly or indirectly against all other firms, rather than the standard assumption that a firm from one population is matched against a randomly drawn firm from the other population. The matching assumption results in "purification" (Friedman 1996, Fisher and Kakkar 2004), where at least one nation is completely specialized. We now establish the relative magnitudes of the tax rates.

4.1 Nash Equilibrium of the tax game

The Nash equilibrium of the tax game has each government choosing a pollution tax to maximize national welfare, taking the other nation's tax rate as given. With trade, home welfare is:

$$W = CS_c + CS_d + \Pi_c + \Pi_d + TR - E(2n_d q_d) \tag{14}$$

Consumer surplus depends on output of domestic and foreign firms sold in the home market, and profit for home firms is generated by domestic and foreign sales. Tax revenue and the externality depend only on domestic dirty output, $2n_d q_d$. Thus, $CS_d = \frac{1}{2}(n_d q_d + n_d^* q_d^*)^2$, $\Pi_d = n_d \pi_d = 2n_d\,(q_d)^2$, $TR = 2tn_d q_d$. Equation (11) shows that $CS_c(n_c q_c + n_c^* q_c^*)$ and Π_c are independent of the tax in the short run. The home optimal tax solves:

$$\frac{\partial W}{\partial t} = \frac{\partial CS_d}{\partial t} + \frac{\partial \Pi_d}{\partial t} + \frac{\partial TR}{\partial t} - \frac{\partial E(2n_d q_d)}{\partial t} = 0 \tag{15}$$

The four components are:

$$\begin{aligned}
\frac{\partial CS_d}{\partial t} &= \frac{-n_d\left[n_d(1-t) + n_d^*(1-t^*)\right]}{\Delta^2} < 0 \\
\frac{\partial \Pi_d}{\partial t} &= \frac{-4n_d\left(n_d^*+1\right)\left[1-t+n_d^*(t^*-t)\right]}{\Delta^2} < 0 \\
\frac{\partial TR}{\partial t} &= \frac{2n_d\left[1-2t+n_d^*(t^*-2t)\right]}{\Delta} \gtreqless 0 \text{ for } t \lesseqgtr \frac{t^* n_d^* + 1}{2\left(n_d^*+1\right)} \\
-\frac{\partial E}{\partial t} &= \frac{2n_d\left(n_d^*+1\right)E'}{\Delta} > 0
\end{aligned} \tag{16}$$

Where $\Delta \equiv n_d + n_d^* + 1$ and $E' \equiv \frac{\partial E}{\partial 2n_d q_d}$ is the marginal damage of a unit of dirty output, so $\frac{\partial E}{\partial t} = \frac{\partial E}{\partial 2n_d q_d}\frac{\partial 2n_d q_d}{\partial t} = -\frac{2n_d(n_d^*+1)E'}{\Delta}$. The tax decreases domestic profit and pollution. Consumer surplus is decreasing in the tax even though foreign output is increasing in the home tax. The home reaction function is:

$$t(t^*) = \frac{t^* n_d^* \left[2\left(n_d - n_d^*\right) - 1\right] + 2\left(n_d^* + 1\right)\left(n_d + n_d^* + 1\right)E' + n_d - 3n_d^* - 2}{n_d\left(4n_d^* + 3\right)} \tag{17}$$

The slope of the home reaction function depends on the cross-tax effect on the externality. The impact of the foreign tax on home marginal damage is: $\frac{\partial E'}{\partial t^*} = \frac{\partial E'}{\partial 2n_d q_d}\frac{\partial 2n_d q_d}{\partial t^*} = \frac{2n_d n_d^* E''}{\Delta} > 0$, for all convex pollution damage. The slope of the home reaction function is:

$$\frac{\partial t(t^*)}{\partial t^*} = \frac{n_d^* \left[2\left(n_d - n_d^*\right) - 1\right] + 4n_d n_d^* \left(n_d^* + 1\right)E''}{n_d\left(4n_d^* + 3\right)} \tag{18}$$

Given the symmetry assumptions the Nash equilibrium will be along the main diagonal, where $s = s^*$ and $n_d = n_d^*$. Along the main diagonal the home reaction function slope is: $\frac{\partial t(t^*)}{\partial t^*} = \frac{4n_d(n_d+1)E''-1}{(4n_d+3)}$. The reaction function has a positive slope for all $E'' > \frac{1}{4n_d(n_d+1)}$. Only a very small degree of convexity is required for the tax rates to be strategic complements in equilibrium. If pollution damage is concave or linear then the taxes are strategic substitutes in equilibrium.

Symmetry allows for an analytic solution to the Nash equilibrium of the governments' tax game. Demand, cost and the number of firms is assumed to be equal across nations. The Nash equilibrium of the tax game results in equal tax rates and thus an equal number of a given type of firm in each nation. The Nash equilibrium of the tax game is:

$$t^{ne} = \frac{\left(2n_d + 1\right)E' - 1}{2n_d} \tag{19}$$

The Nash tax rates are positive, provided the marginal damage from the externality is sufficiently large, $t^{ne} > 0$ for all $E' > \frac{1}{2n_d+1}$. Otherwise, the loss of profit and consumer surplus dominate the pollution damage and tax revenue, making the welfare maximizing tax zero. The tax rule in (19) is not a reduced form. The number of dirty firms is a function of s which in turn is a function of the tax rates, and E' is a function of both.

4.2 Social planner's solution

The social planner is faced with two distortions, imperfect competition and a negative production externality. The first-best policy would be a Pigouvian tax on the externality combined with a subsidy to correct the output distortion. Assuming a subsidy is not allowed (i.e. a violation of a free trade agreement), the pollution tax must address both distortions, and will therefore be below the Pigouvian level. The solution to the planner's problem is a second-best tax.

The social planner chooses a t, t^* pair to maximize the sum of home and foreign welfare. This is a reasonable outcome if the two governments can coordinate environmental policy within a free trade agreement. The first-order condition of the planner's problem with respect to the home tax contains all four terms in (15), as well as three additional terms that reflect the impact of the home tax on foreign welfare: $\frac{\partial W^*}{\partial t} = \frac{\partial CS_d^*}{\partial t} + \frac{\partial \Pi_d^*}{\partial t} - \frac{\partial E^*(2n_d^* q_d^*)}{\partial t}$.

$$\begin{aligned} \frac{\partial CS_d^*}{\partial t} &= \frac{-n_d\left[n_d(1-t)+n_d^*(1-t^*)\right]}{\Delta^2} < 0 \qquad (20) \\ \frac{\partial \Pi_d^*}{\partial t} &= \frac{4n_d n_d^*\left[1-t^*+n_d(t-t^*)\right]}{\Delta^2} > 0 \\ -\frac{\partial E^*(2n_d^* q_d^*)}{\partial t} &= \frac{-2n_d n_d^* E^{*\prime}}{\Delta} < 0 \end{aligned}$$

The sum of the planner's three additional terms along the main diagonal is:

$$\frac{\partial W^*}{\partial t} = \frac{2n_d^2\left[1-t-(2n_d+1)E^{*\prime}\right]}{(2n_d+1)^2} \qquad (21)$$

The optimal tax pair (t, t^*) is the solution to the planner's problem.

$$t^p = \frac{(2n_d+1)E' - 1}{n_d(2n_d+3)} \qquad (22)$$

The planners' tax is positive for all $E' > \frac{1}{2n_d+1}$, which indicates $\frac{\partial W^*}{\partial t} < 0$ in equilibrium. The planner recognizes that foreign welfare is decreasing in the home tax and therefore the planner chooses a lower tax than the Nash equilibrium of the governments' tax game. Consequently, the planner's equal profit loci are lower than the Nash tax loci.

Next, we can compare the Nash and planner's taxes recognizing that q_d and $E'(2n_d q_d)$ are different in (19) and (22) since both are functions t. Both the planner and the governments take the initial condition n_d and n_d^* as given. A direct comparison of (19) and (22) reveals:

Proposition 6: The Nash equilibrium of the governments' pollution tax game exceeds the planner's tax.

Proof: Fix n_d and suppose the opposite is true: $t^p - t^{ne} > 0$. This implies $E'_p < E'_{ne}$ due to the strict convexity of $E(2n_d q_d)$ and since $\frac{\partial q_d}{\partial t} < 0$. $t^p - t^{ne} = \frac{(2n_d+1)E'_p-1}{n_d(2n_d+3)} - \frac{(2n_d+1)E'_{ne}-1}{2n_d}$. Define the difference in marginal damage as $\epsilon > 0$, so that $E'_p + \epsilon = E'_{ne}$. Then $t^p - t^{ne} = \frac{(2n_d+1)[E'_{ne}-\epsilon]-1}{n_d(2n_d+3)} - \frac{(2n_d+1)E'_{ne}-1}{2n_d}$. Given a common denominator: $t^p - t^{ne} = \frac{2(2n_d+1)[E'_{ne}-\epsilon]-2-[(2n_d+1)(2n_d+3)E'_{ne}-(2n_d+3)]}{2n_d(2n_d+3)}$, and factoring a common term: $\phi = \frac{2n_d+1}{2n_d(2n_d+3)} > 0$, $t^p - t^{ne} = \phi\left[-E'_{ne}(2n_d+1) - 2\epsilon + 1\right]$. Finally, from (19) $E'_{ne} > \frac{1}{2n_d+1}$ for a positive level of taxation, thus for all $\epsilon > 0$, $t^p - t^{ne} < 0$, a contradiction.■

Next, we compare the Nash equilibrium tax with the Pigouvian rate.

Proposition 7: The Nash equilibrium tax rate is less than marginal damage.

Proof: $t^{ne} = E' + \frac{E'-1}{2n_d}$, where the second term is negative since $E' < 1$, otherwise the tax is such that the dirty market ceases to exist.■

The final issue is a comparison of the tax rates at the EE's that they generate. At an interior EE $\Pi_D = 1$ and $\Pi^*_D = 1$. Both the Nash and the planner's taxes are symmetric equilibria ($t = t^*, s = s^*$), so we get:

$$s = \frac{2n+t}{2n(2-t)} \tag{23}$$

Thus far we have an undetermined system $t^p(s, n, E'(s, n, t))$, $t^{ne}(s, n, E'(s, n, t))$ and $s(t)$ given by (23) so an analytic comparison of the Nash and planner's taxes at the EE's they generate requires a functional form for pollution damage.

4.3 Pollution damage function

Consider the simple convex form for pollution damage: $E = \frac{(2n_d q_d)^2}{2}$. Marginal damage is a ray from the origin with slope one in domestic dirty output, $E' = 2n_d q_d$ and $E'' = 1$, so the tax rates are strategic complements in equilibrium. The tax rules in (19) and (22) become:

$$\begin{aligned} t^{ne} &= \frac{2n_d-1}{4n_d} \\ t^p &= \frac{2n_d-1}{n_d(2n_d+5)} \end{aligned} \tag{24}$$

Using (23) to eliminate s in $n_d \equiv (1-s)n$, and using the fact that $E' = 2n_d^{ee} q_d^{ee} = \frac{2n(1-t)-t}{2(n+1)}$, the Nash tax evaluated at the EE is:

$$t^{ne}_{|ee} = \frac{n-1}{2n+1} \tag{25}$$

The planners tax is non-linear in s, and slightly more complicated. The relevant solution is:

$$t^{p}_{|ee} = \frac{n^2+6n+1-\sqrt{\Gamma}}{2n^2+7n+3} \tag{26}$$

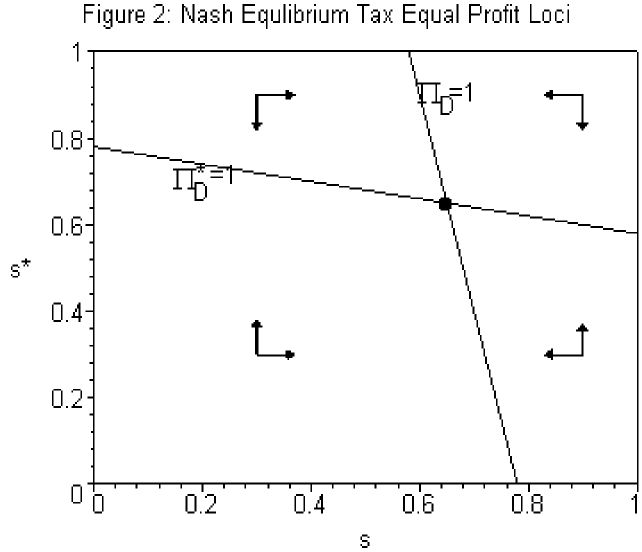
where $\Gamma = (n^2+2n+13)(n+1)^2$. A direct comparison of the two tax rates evaluated at the EE's that they generate shows:

$$t^{ne}_{|ee} - t^{p}_{|ee} = \frac{\sqrt{\Gamma}-4(n+1)}{2n^2+7n+3} > 0 \ \forall \ n > 1 \tag{27}$$

Thus, (27) confirms Proposition 6 at the EE. Following this procedure for other convex forms yields the same result. There is no pollution haven, and since the EE is along the main diagonal both nations are incompletely specialized. Tax rates are equal and there exists intra-industry trade.

As an illustration, Figure 2 presents the Nash tax loci when $n = 10$. With endogenous pollution policy the equal profit loci intersect and generate a unique interior EE, unlike the exogenous policy in Figure 1. This illustration highlights the role of endogenous taxation in generating an interior EE. The Nash tax and EE are: $t^{ne}_{|ee} = 0.429$ and $s = s^* = 0.65$. For $n = 10$ the planner's tax and EE are: $t^{p}_{|ee} = 0.125$ and: $s = s^* = 0.54$.

Figure 2: Nash Equlibrium Tax Equal Profit Loci



5 Conclusion

Nations in a free trade area have an incentive to coordinate environmental policy. With Cournot competition between oligopolists that operate in one of two sectors there need not be the fear of a "race to the bottom" of environmental standards. Coordinating environmental policy prevents a race beyond the top, since the non-cooperative Nash equilibrium of the governments' tax game exceeds the social planner's tax. This result is obtained with convex pollution damage where the pollution shifting effect dominates the profit and consumer surplus effects.

Evolutionary game theory provides a natural framework to analyze the differences between short and long run outcomes. Under autarky the tendency of firms to flee the taxed sector increases the incentive for a welfare maximizing government to tax pollution since the output restriction in the taxed sector is mitigated by an expansion in the number of firms, and hence output, in the other sector. The dynamics follow profit advantage and allow for adjustments to the long run equilibrium that are not instantaneous. The standard Cournot model is a single population Hawk-Dove game under autarky where there is a stable mix of each type of firm. With trade the model becomes a two population Hawk-Dove game where each firm competes against all other firms, domestic and foreign.

If the tax rate is exogenous then the nation with the lower tax becomes a pollution haven. This outcome is analogous to asymmetric integration in the absence of externalities. When pollution policy is endogenous there is intra-industry trade and no pollution haven. The planner's tax results in fewer clean firms than the Nash equilibrium of the tax game between governments, which in turn has fewer than a Pigouvian policy. These results rely on the strong assumption of symmetry. With symmetric nations the tax rates are strategic complements in the neighborhood of the equilibrium. Relaxing the symmetry assumption might reverse some of the results. If nations are strongly asymmetric in demand, cost, or pollution damage functions then the tax rates might become strategic substitutes and the Nash equilibrium of the tax game may lie below planner's tax pair.

There are a number of directions that the model could be extended. Future work could investigate different demand and cost structures other than the standard Cournot framework. Another possible avenue is analyzing mergers within and across borders, or endogenizing firm location. Allowing for abatement technology would provide the firm with a method of reducing tax liability other than reducing output. This would add the potential for trade to effect the technique with which output is produced.

A monopolistic competition model would be obtained by endogenizing the number of firms via fixed costs. This would eliminate profit from the social planners welfare function. The optimal tax would balance the consumer surplus loss with the reduction in pollution damage at an interior EE, where profit would be zero in both sectors. Allowing resources to flow to the non-taxed sector will increase output and subsequently consumer surplus. Thus a tax on the dirty sector that recognizes this effect will exceed the short run welfare maximizing tax, and the main point of Proposition 2 would remain. Similarly, with trade the magnitudes of the tax rates will change with an endogenous number of firms and zero profit, but the rank ordering (Proposition 6) will remain the same. Equations (20)-(22) illustrate this point, and show that eliminating profit at the EE will make the planner's two additional terms unambiguously negative.

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