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**WHY WE CAN'T CONFIRM THE POLLUTION HAVEN
HYPOTHESIS: A MODEL OF CARBON LEAKAGE WITH
AGGLOMERATION**

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Why we can't confirm the pollution haven hypothesis: A model of carbon leakage with agglomeration

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Abstract

The literature on carbon leakage has not yet benefitted from many of the insights of the ‘New Economic Geography’ (NEG). Most studies assume both an absence of agglomeration forces and that factors do not move inter-regionally. This paper develops a 2-region NEG model with factor mobility to study the impact of regionally-differentiated environmental regulation on the location of polluting firms. There are three main results: (i) trade liberalisation can reduce firms’ incentives to relocate in response to a regulatory disadvantage; this arises because trade liberalisation increases the agglomeration forces attracting firms to a given location, and may explain why the pollution haven hypothesis (PHH), which is a common prediction of standard trade models of environmental regulation, has been so difficult to detect empirically; (ii) unilaterally tightening environmental regulation by one region may increase global pollution; and (iii) if industry is dispersed between regions, individual firms respond to higher (lower) relative domestic pollution taxes by polluting more (less).

Jel codes: F18, Q56

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1 Introduction

The principle of ‘common but differentiated’ responsibilities is a cornerstone of the two most important international treaties governing greenhouse gas (GHG) emissions: (i) the United Nations Framework Convention on Climate Change (UNFCCC); and (ii) the Kyoto Protocol. In practice, however, there has not been agreement amongst signatories on how ‘differentiated’ the participating nations’ responsibilities should be.

One major complication arises because regions which are required to significantly reduce their emissions may find that their polluting firms become less competitive relative to polluting firms in regions with less stringent environmental policy. As a consequence, the less competitive firms may alter their scale or relocate to less stringently regulated regions.

In this paper, the theory that polluters relocate in response to changes in the relative stringency of environmental policy is referred to as the Pollution Haven Effect (PHE).¹ Recent literature provides empirical support for the PHE.²

The PHE poses an important policy challenge, especially for industrialised countries. Two related concerns, which are the focus of this paper, are particularly prominent. The first concern relates to welfare losses resulting directly from deindustrialisation, including unemployment and deterioration of the terms of trade. The second concern is ‘carbon leakage’, which occurs if relocation of polluting activity induces an international relocation of GHG emissions in addition to their domestic reduction.³ Carbon leakage reduces the effectiveness of GHG regulation.

This paper develops a theoretical New Economic Geography (NEG) model of international environmental agreements (IEAs) to investigate when both concerns, deindustrialisation and carbon leakage, are likely to be most important in the presence of agglomerated polluting industries. A study of environmental regulation

¹ The literature has been inconsistent in its use of the term PHE. The term PHE is often used interchangeably with the related pollution haven hypothesis (PHH). To avoid any ambiguity in this paper, the terminology from Copeland and Taylor (2004) is adopted: ‘The PHE implies that a tightening up of pollution regulation will, at the margin, have an effect on plant location decisions and trade flows’ while ‘the PHH implies that a reduction in trade barriers will lead to a shifting of pollution-intensive industry from countries with stringent regulations to countries with weaker regulations.’

² Examples of recent papers which detect a strong PHE include Kellenberg (2009), Wagner and Timmins (2008), Levinson and Taylor (2008) and Ederington and Minier (2003). Copeland and Taylor (2004) includes a relatively recent and widely cited review of literature on the PHE. Jaffe et al. (1995) and Jeppesen et al. (2002) summarise early literature on the PHE.

³ ‘Carbon leakage’ is used as shorthand for carbon dioxide leakage. In this paper, I use the terms ‘carbon’ and ‘greenhouse gas’ interchangeably. See Reinaud (2008) for a detailed definition of carbon leakage.

with agglomerated industries is timely in light of the dominance of models featuring constant returns to scale (CRS) and immobile factors of production in the literature.⁴ The model developed in this paper, which differs from previous NEG models of regulation because regulation is imposed upon pollution output rather than profit or revenue, is also likely to be relevant to policy makers considering non-environmental regulation of agglomerated industries.⁵

Section 3 focusses purely on the first concern, deindustrialisation, and asks this paper's first key question: *How does the degree of differentiation of environmental policy influence firm relocation incentives?* Section 4 considers carbon leakage and asks this paper's second key question: *How does the degree of differentiation of environmental policy influence the extent of carbon leakage?*

Section 3 is closely related to the literature on the PHE in the presence of increasing returns to scale (IRS). Two prominent approaches in this literature are international oligopoly of the Brander and Spencer (1985) variety and NEG of the Krugman (1991) and Venables (1996) varieties. Markusen *et al.* (1993) provides a typical example of an international oligopoly model.⁶ The authors show that when competition is imperfect, critical levels of environmental policy variables exist at which small policy changes can cause large jumps in the levels of pollution and welfare as firms relocate. The existence of such tipping points contrasts with earlier perfectly competitive CRS models, which predict that marginal changes in policy variables always lead to marginal changes in the location of production and of welfare.⁷

Section 3 of this paper is similar in purpose to Venables (1999), which is amongst the first NEG papers to consider the effect of environmental regulation on the location of polluting firms.⁸ Unlike the present paper, which adopts Forslid and Ottaviano's (2003) Footloose Entrepreneurs (FE) model, in which factor mobility drives agglomeration, Venables (1999) adopts a vertical linkages (VL) model, in which input-output linkages between firms can make profits an increasing function of the number of firms in a given location. Venables (1999) draws two main

⁴ Babiker (2005) provides an influential critique of the dominant CRS approach used to examine the nature of carbon leakage.

⁵ A prominent example is the recent proposal of a tax on financial transactions. A letter from the French and German heads of state informing the EU President of this proposal can be found at the following URL: <http://media.ft.com/cms/1e93f294-c8df-11e0-a2c8-00144feabdc0.pdf>

⁶ Motta and Thisse (1994) and Ulph (1994) provide studies of firm location in response to exogenous environmental policies using a similar framework.

⁷ See Pethig (1976) for an early example of a perfectly competitive CRS model.

⁸ Neary (2006) adopts a similar NEG approach albeit using more general functional forms. Elbers and Withagen (2004) and Pflueger (2001) consider competitive environmental policy in an NEG model.

conclusions. First, marginal changes in environmental regulation can cause highly non-linear and even catastrophic relocation of firms. Second, agglomeration forces can give rise to multiple equilibria; regulation-induced relocation of firms between equilibria may not be reversed simply by restoring the regulation parameters to their initial values.

A two region setting is used to derive results encompassing those of Venables (1999), and extending them in two important directions. First, the assumptions regarding the way in which the tax is levied, with both regions imposing a tax which is proportional to pollution produced, are more applicable to the context of regulating GHGs. Second, the model is more analytically tractable, which enables derivation of proofs of the simulated conjectures from Venables (1999), as well as several new closed-form results. The main contributions of Section 3 to the PHE literature are set out below.

If all polluting firms are agglomerated in one region (a so-called ‘core-periphery’, or CP, equilibrium), a reduction in trade costs may make relocation in response to a given environmental tax disadvantage less desirable for polluting firms. This result contrasts with most previous theoretical analysis of environmental regulation and firm location in which trade liberalisation unambiguously makes firms more footloose. As a consequence, in this framework, the pollution haven hypothesis (PHH), which predicts that trade liberalisation between regions with differentiated environmental regulation leads to industry relocation, only holds under certain conditions. Indeed, trade restriction that makes industry more footloose may also lead to relocation of firms from stringently regulated regions, thereby reversing the PHH. This result may explain the relatively weak empirical support for the PHH compared to the PHE.⁹

A further contribution is an analytical derivation of the effects of changes in environmental tax levels on the location of industry. As this is amongst the first papers to consider output taxation within the FE model, some detail is taken to show the equilibrium locations of firms as a function of the tax rates. The effects of taxation on firm location are shown to depend on whether all firms are agglomerated in one region or dispersed across both prior to the tax change. Firms agglomerated in one region do not relocate in response to a small tax disadvantage, whereas firms which are dispersed across both regions do. Key tipping points at which agglomerations relocate between regions are determined analytically.

Section 4 of this paper is closely related to the economic literature on carbon leakage. Ulph (1994) is amongst the first papers to consider how the extent of pol-

⁹ For example, two prominent studies, Ederington, Levinson and Minier (2004) and Kahn and Yoshino (2004) find no evidence of the PHH.

lution leakage responds to the regulation differential between regions. Calibrating a model to the fertilizer industry, Ulph (1994) finds that assumptions of IRS and imperfect competition tend to increase the level of leakage relative to a scenario of CRS and perfect competition. Babiker (2005) draws a similar conclusion using a computable general equilibrium model.

To my knowledge, no paper has evaluated the relationship between environmental policy differentials and carbon leakage in an NEG framework.¹⁰ However, firm location decisions, increasing returns to scale and agglomeration forces, all of which characterise the NEG framework, have been shown to be important determinants of the extent of carbon leakage.¹¹

The two key results of Section 4 are set out here. First, the presence of agglomeration forces implies that the extent of carbon leakage for a given IEA is highly non-linear in the tax differential and depends on the pre-IEA location of industry. If industry is initially agglomerated in a CP equilibrium, unilateral increases in the core's carbon tax will cause no carbon leakage provided agglomeration forces are strong enough to preclude firm relocation. In such a scenario, unilateral tax increases in the core are highly effective environmentally. If agglomeration forces are not strong enough to preclude firm relocation, carbon leakage exceeds 100%. If industry is dispersed between regions (the 'dispersed' equilibrium), an IEA which specifies differentiated taxation must cause some carbon leakage. Conditions are derived, for both CP and dispersed equilibria, for which a unilateral increase in the carbon tax causes a net increase in global carbon emissions.

Second, if industry is dispersed between regions, firms in the region with the higher tax rate are larger and pollute more than those in the region with the smaller tax rate. This general equilibrium result arises in a model of output taxation because relatively stringent local regulation implies that firm size must be larger in order to provide the internationally mobile fixed factor with a sufficient return.¹²

A further contribution is a demonstration of the existence of multiple equilibria

¹⁰ Ishikawa and Okubo (2011) consider the effect of trade liberalisation on firm location when pollution is regulated by a single region in the footloose capital model of Martin and Rogers (1995).

¹¹ For theoretical work on carbon leakage with IRS in an oligopolistic setting see Fowlie (2009) and Ritz (2009). For an empirical paper on the importance of agglomeration forces for environmental regulation induced firm relocation see Ben Kheder and Zugravu (2008). For a calibrated CGE simulation of carbon leakage with increasing returns to scale see Babiker (2005). For empirical evidence that agglomeration forces determine the location of polluting industries see Giarratani et al. (2007). Finally, for a review of non-economic literature on the determinants of carbon leakage see Reinaud (2008).

¹² This is a generalisation of an earlier result, Proposition 2 in Lawrence and Spiller (1983), to an NEG model.

in the level of global emissions.¹³ For certain parameter combinations there exist both high and low global emissions equilibria. An implication of this is that reversing policy decisions may not reverse changes in the level of global emissions. Once the carbon leakage genie is out of the bottle, it may be difficult to put it back in.

This result also has implications for the way in which environmental regulation increases are staged across regions and through time. With multiple equilibria, it is not just the final regulation levels that matter, but also the process by which they are achieved. Regions which move slowly enough are rewarded with a permanent increase in their industrial base.

While this paper adopts a simple NEG model, which is tractable enough to yield analytic results and in which agglomeration forces arise through factor mobility, the key results hinge on properties that hold in a wide range of NEG models.¹⁴ I therefore conjecture that the paper's main results hold in many NEG models.

The remainder of this paper proceeds as follows: Section 2 presents a theoretical model of pollution taxation and derives the equilibrium when firm location is fixed (the short-run equilibrium); in Section 3, firm relocation is permitted (the long-run) and the relationship between the tax levels in each region and firm location is considered; Section 4 extends the model to consider the relationship between the respective tax levels and carbon leakage; and Section 5 concludes the paper.

2 A Model of Agglomerated Polluting Industry

2.1 Model assumptions

The economy consists of two regions: north and south. It assists intuition to think of these regions as either separate countries or separate political entities: (i) which have each ratified an international agreement prescribing potentially different environmental tax policies; and (ii) between which, barriers to the free flow of unskilled labour exist. To reduce notation, only expressions for northern variables are shown provided no generality is lost. Southern expressions, where included, are denoted with an asterisk.

The model is populated by two types of labour: (i) interregionally immobile unskilled workers; and (ii) skilled workers who are interregionally mobile in the

¹³ This is not a major result in the sense that it follows naturally from the well-established properties of NEG models. Establishing hysteresis in global emission level is warranted in this paper, however, both because such a proof is lacking in the literature and because the result is of policy relevance.

¹⁴ See Robert-Nicoud (2004) for an explanation of the general properties of models of the type used in this paper.

long-run. Each worker (skilled or unskilled) produces one unit of labour. The quantity of unskilled (skilled) workers in the north and south are equal to L and L^* (H and H^*) respectively, and the population of unskilled (skilled) workers across both regions is denoted L^w (H^w). H and H^* are determined endogenously as a consequence of skilled worker migration to the region offering the highest real wage.

Preferences of skilled and unskilled workers are identical and defined over two goods: (i) horizontally differentiated manufacturing; and (ii) a homogeneous non-manufacturing good. The utility function of a representative consumer over the two consumption goods is:

$$U = C_M^\mu C_A^{1-\mu}, \quad C_M = \left(\int_0^{n+n^*} c_i^{1-\frac{1}{\sigma}} di \right)^{\frac{1}{1-\frac{1}{\sigma}}}; \quad 0 < \mu < 1, \sigma > 1 \quad (1)$$

C_M and C_A denote consumption of a CES composite of all manufacturing goods varieties and consumption of non-manufacturing goods respectively, c_i denotes consumption of manufacturing variety i , and n and n^* represent the mass of varieties of the manufacturing good produced in the north and south respectively. μ is a preference parameter. σ denotes both the elasticity of demand for any particular variety and elasticity of substitution between any two varieties.

Utility maximisation yields the following indirect utility functions for skilled and unskilled workers:

$$\omega = \eta \frac{w_H}{P}, \quad \omega_L = \eta \frac{w_L}{P}, \quad (2)$$

$$P \equiv p_A^{1-\mu} P_M^\mu, \quad \eta = \mu^\mu (1-\mu)^{1-\mu}, \quad P_M \equiv \left(\int_0^{n^w} p_i^{1-\sigma} di \right)^{\frac{1}{1-\sigma}}$$

Consumers derive all of their income from wages, where w_H and w_L denote the wages of skilled and unskilled workers respectively. The true cost of living index is denoted by P . P_M is the price index for the manufacturing good.

Both regions ratify an IEA which sets a tax rate on transboundary pollution, which is generated in the production of manufactures. The tax rate is set equal to an exogenous constant t (t^* in the south) per unit of pollution and, without loss of generality, it is assumed that $t \geq t^*$.

Tax revenue does not enter consumer welfare. This assumption, which is similar to Ossa (2011), enables this paper to focus on the first order effects of pollution taxation on the location of firms and the level of pollution generated as simply as possible.¹⁵

¹⁵ An alternative interpretation, which does not alter the analysis which follows, could assume that abatement of pollution in the production process is possible (for example, by using cleaner production processes) and that the IEA sets environmental standards in each region

The non-manufacturing good is produced in a perfectly competitive market with a CRS technology and only unskilled labour is used in its production. The cost of producing each unit of output is $a_A w_L$, where a_A is the unskilled labour input required to produce one unit of the non-manufacturing good.

Manufactures are produced in a monopolistically competitive market with increasing returns to scale. Each firm requires F units of skilled labour as a fixed input in addition to a_M units of unskilled labour per unit of output produced. Each firm can produce at most one variety. In addition, pollution is generated in the manufacturing process at a rate of γ units of pollution per unit of manufactures produced. A manufacturing firm's total cost function is therefore:

$$TC = w_H F + (w_L a_M + t\gamma) x \quad (3)$$

x is the output level. Manufacturing firms face iceberg trade costs when selling to foreign consumers. It costs $\tau - 1$ units of manufactures to ship one unit of manufactures between regions.

2.2 Short-run equilibrium

In this sub-section, a series of equations are derived, which define the model's equilibrium if skilled workers, and therefore firms, are interregionally immobile (the 'short-run'). This intermediate step is taken prior to solving for the long-run location of skilled workers in order to demonstrate the effect of pollution taxes on firm prices, output and profit, before introducing the added complexity of skilled worker migration.

2.2.1 Non-manufacturing sector

The Cobb-Douglas specification implies that the north's consumption of the non-manufacturing product, C_A , is equal to:

$$C_A = (1 - \mu) \frac{E}{p_A} \quad (4)$$

E is nominal expenditure in the north. The south has an analogous demand function. Perfect competition in the non-manufacturing market and the assumption that all pollution produced in the sector is not taxed, ensures marginal cost pricing such that $p_A = a_A w_L$ and $p_A^* = a_A w_L^*$.

rather than the level of a pollution tax. In this case, t should be interpreted as the increase in the marginal cost of production due to the imposition of an environmental standard and the government earns no revenue.

An assumption of zero trade costs for the non-manufacturing product ensures $p_A = p_A^*$ and therefore $w_L = w_L^*$.¹⁶ Treating the non-manufacturing good as the numeraire, p_A is set equal to 1. Supply and demand for the non-manufacturing good must match, however, Walras' law is used to drop this market clearing condition.

2.2.2 Manufacturing sector

As firms and skilled workers are co-located, and by a full employment assumption, the number of firms in each region is proportional to the number of skilled workers in that region ($n^w = H^w/F$). Utility maximisation yields the standard constant elasticity of substitution (CES) demand function for variety j :

$$c_j = p_j^{-\sigma} \left(\frac{\mu E}{P_M^{1-\sigma}} \right), \quad E = w_H H + w_L L \quad (5)$$

Allowing superscripts to reflect the location of production and subscripts to denote the location of consumption, firms charge a consumer price equal to:

$$\begin{aligned} p_N &= \frac{w_L a_M + t\gamma}{1 - \frac{1}{\sigma}}, \quad p_S = \tau \frac{(w_L a_M + t\gamma)}{1 - \frac{1}{\sigma}} = \tau p_N \\ p_S^* &= \frac{w_L a_M + t^*\gamma}{1 - \frac{1}{\sigma}}, \quad p_N^* = \tau \frac{(w_L a_M + t^*\gamma)}{1 - \frac{1}{\sigma}} = \tau p_S^* \end{aligned} \quad (6)$$

Free entry ensures firms make zero pure profit. As skilled labour is the only fixed input, all operating profit accrues to skilled workers.

As the variable cost of producing each unit is constant and as a fixed mark-up over variable costs is charged, operating profit for a firm producing variety j in the north can be expressed as:

$$\pi_j = \frac{p_N x_j}{\sigma} = \frac{w_L a_M + t\gamma}{\sigma - 1} x_j \quad (7)$$

Firm output levels in the north and the south are:

$$\begin{aligned} x &= w_H F \frac{\sigma - 1}{w_L a_M + t\gamma} \\ x^* &= w_H^* F \frac{\sigma - 1}{w_L a_M + t^*\gamma} \end{aligned} \quad (8)$$

Next, equilibrium nominal skilled wages are derived. This requires the introduction of the market clearing condition to close the model:

$$p_N x_j = p_N c_{j,N} + p_S c_{j,S} \quad (9)$$

¹⁶ Unskilled wage equalisation also requires a non-full specialisation condition to ensure that both regions are active in non-manufacturing production. I assume that this condition holds for the remainder of this paper.

Combining expressions for skilled wages ($w_H = \pi/F$), operating profit ($\pi = p_N x/\sigma$) and the market clearing condition (equation (9)), then substituting in equations (5) and (6) yields the following nominal skilled wage in each region:

$$\begin{aligned} w_H &= bB \frac{E^w}{n^w} \\ w_H^* &= brB^* \frac{E^w}{n^w} \end{aligned} \quad (10)$$

where:

$$\begin{aligned} b &\equiv \frac{\mu}{\sigma}, B \equiv \left[\frac{s_E}{\theta} + \phi \frac{1-s_E}{\theta^*} \right], B^* \equiv \left[\phi \frac{s_E}{\theta} + \frac{1-s_E}{\theta^*} \right], \phi \equiv \tau^{1-\sigma}, \\ \theta &\equiv s_n + \phi(1-s_n)r = \frac{P_M^{1-\sigma}}{p_N^{1-\sigma} n^w}, \theta^* \equiv (1-s_n)r + \phi s_n = \frac{P_M^{*1-\sigma}}{p_N^{1-\sigma} n^w}, \\ E^w &\equiv E + E^*, n^w \equiv n + n^*, r \equiv \left(\frac{w_L a_M + t\gamma}{w_L a_M + t^* \gamma} \right)^{\sigma-1} \geq 1 \end{aligned} \quad (11)$$

There are a number of new terms in these wage equations. r , which I refer to as the ‘tax differential’, is the first of two key parameters for the analysis that follows. Taxes only appear in the expressions for nominal wages through their effect on r . This implies that r is the critical parameter for determining international competitiveness; r is the ‘true tax differential’. The assumption that the north is the higher taxing region implies that $r \geq 1$.

The second key parameter is ϕ , which (following Baldwin *et al.* (2003)) I refer to as the ‘freeness of trade’. When $\phi = 1$, trade is completely free and when $\phi = 0$, trade costs are infinite.

E^w denotes total global expenditure such that $E^w = E + E^*$. s_E denotes the north’s share of total global expenditure. b is a bundling term for exogenous preferences which combines expenditure on manufactures (μ) and consumers’ love of variety (σ).

Analysis of B and rB^* illustrates the model’s only dispersion force, the ‘local competition effect’. To provide intuition, if taxes are equalised, holding expenditure shares (s_E) constant and relocating a firm from, say, the north to the south, reduces each southern firm’s domestic market share. This encourages southern firms to relocate back to the less competitive northern market.

If a tax differential exists ($r > 1$) and trade is possible between regions ($\phi > 0$) the local competition effect is not symmetric. Relocation of firms from the north to the south decreases domestic competition in the north (via a trade composition effect), however, it also increases the number of firms operating at a regulatory advantage in the low-taxing south; which increases competition for northern firms (a cost composition effect). Holding expenditure constant, movement of firms from the north to the south has an ambiguous effect on northern competition and increases southern competition, while moving firms from the south to the north decreases southern competition and has an ambiguous effect on northern

competition.

2.2.3 Spatial distribution of expenditure

To simplify notation, units of skilled labour are selected such that $F = 1$. Operating profit for all manufacturing firms is a constant margin, $1/\sigma$, multiplied by total expenditure on manufactures, μE^w . Total operating profit is therefore equal to bE^w . As all operating profit is paid to skilled workers, it is possible to express world expenditure, $E^w = w_L L^w + w_H H + w_H^* H^*$ as:

$$E^w = \frac{w_L L^w}{1 - b} \quad (12)$$

The north's share of expenditure is therefore:

$$s_E = \left[\frac{\frac{(1-b)}{2} + b\phi \frac{1}{\theta^*} s_H}{1 - b\frac{1}{\theta} s_H + b\phi \frac{1}{\theta^*} s_H} \right] \quad (13)$$

A useful property of equation (13) is that for a given distribution of skilled workers between regions (s_H), increasing the tax differential (r) will increase the expenditure share in the south ($1 - s_E$). Holding s_H fixed, $\frac{\partial s_E}{\partial r} < 0$ for all s_H except when $s_H = 1$ or $s_H = 0$, at which values $\frac{\partial s_E}{\partial r} = 0$.

Equation (13) illustrates the first of two agglomeration forces in the model: the 'market size effect'. Relocation of skilled workers to the northern market increases (decreases) the northern (southern) market size. Through the home market effect, this makes the north relatively more attractive to skilled workers and the south relatively less attractive.

3 Long-Run Equilibrium

This section addresses the first key question of this paper: *How does the degree of differentiation of environmental policy influence the extent of firm relocation?* To consider this, skilled workers, and therefore firms, are permitted to move freely between regions and the equilibria of the model are derived analytically.

3.1 Normalisations

Normalisations are undertaken to remove clutter and focus on the two key parameters r and ϕ . Units of non-manufacturing output are selected such that $a_A = 1$. With free trade of the non-manufacturing good, perfect competition in production and non-manufacturing as numeraire good, unskilled wages in both

regions are equal to 1. In the manufacturing sector units of output and pollution are selected such that $a_M = 1$ and $\gamma = 1$.

The total number of skilled workers is set equal to one ($H^w = 1$), which implies that $n^w = 1$. This normalisation ensures the equivalence of skilled labour shares and skilled labour populations: $n = H = s_n = s_H$ and $n^* = H^* = 1 - s_n = 1 - s_H$. I normalise the population of unskilled workers such that $L^w = 1 - b$. This ensures that $E^w = 1$, and consequently, that regional expenditure and regional expenditure shares are equivalent ($E = E/E^w = s_E$ and $E^* = E^*/E^w = 1 - s_E$).

3.2 Equilibrium and stability conditions

Skilled workers move to the region offering the highest real wage. This gives intuition for the model's second agglomeration force: a 'cost of living effect'. As consumers bear the cost of trade, skilled workers prefer to locate where many varieties are produced. Migration of skilled workers from, say, the south to the north, increases the attractiveness of locating in the north for skilled workers via a trade composition effect (more varieties are now produced domestically in the north, reducing the northern price index), however, the north's attractiveness decreases via a cost composition effect (more varieties are now produced in the high-taxing region, which are consequently sold at a higher price). The effect on the cost of living in the north is therefore ambiguous. The cost of living in the south is unambiguously higher as more varieties are imported from the high-taxing north.

A standard but ad-hoc migration equation is assumed:

$$\dot{s}_H = (\omega - \omega^*) s_H (1 - s_H) \quad (14)$$

$\dot{s}_H$ denotes the instantaneous rate of change of the proportion of skilled workers in the north.

An equilibrium distribution of skilled workers is defined as one in which $\dot{s}_H = 0$. There are two types of equilibrium: (i) a dispersed equilibrium, which occurs when real wages are equalised across regions ($\omega = \omega^*$) and neither region hosts all skilled workers ($0 < s_H < 1$); and (ii) a core-periphery (CP) equilibrium, which occurs when all skilled workers are located in one of the two regions. There are two candidates for CP equilibria: the core-in-the-north (CPN) equilibrium in which all skilled workers (and firms) are located in the north and the core-in-the-south (CPS) equilibrium.

A stability condition is added to reduce the number of potential equilibria to those for which a perturbation in the distribution of workers will lead to self-

correcting (as opposed to self-reinforcing) forces which bring the distribution of workers between regions back to its original state.

This definition of stability can be formalised for the dispersed, CPN and CPS equilibria respectively as follows:

$$\begin{aligned}\frac{d(\omega - \omega^*)}{ds_H} &< 0 \text{ if } (0 < s_H < 1) \\ \omega &> \omega^* \text{ if } s_H = 1 \\ \omega &< \omega^* \text{ if } s_H = 0\end{aligned}\tag{15}$$

In the analysis that follows, it is often algebraically neater to work with the log real wage ratio, which I denote Ω , rather than the real wage difference $(\omega - \omega^*)$.

3.3 Equilibrium with no taxation

With zero taxation, the log real wage ratio is:

$$\Omega = \log \left[\frac{\theta^* s_E + \phi \theta (1 - s_E)}{\phi \theta^* s_E + \theta (1 - s_E)} \right] + a \log \left(\frac{\theta}{\theta^*} \right), \quad a \equiv \frac{\mu}{\sigma - 1}\tag{16}$$

The properties of the no-taxation base case have been considered in significant detail in the literature.¹⁷ In this sub-section, only those properties of the base case which are of importance for the purposes of this paper are restated.

First, the only stable dispersed equilibrium possible is one in which $s_n = 1/2$. This is a consequence of the three symmetric forces acting in the model in the absence of differentiated taxation.

Second, as trade freeness decreases from a level at which trade is perfectly free ($\phi = 1$), stability properties of the model move through three stages. For high levels of trade freeness, agglomeration forces dominate the centrifugal market-crowding effect, and only the two CP equilibria are stable. For intermediate trade freeness, the dispersed equilibrium is stable in addition to the CPN and CPS equilibria. For relatively low trade freeness, the market crowding effect dominates and only the dispersed equilibrium is stable. The properties of Ω as trade costs and the distribution of firms vary are illustrated in Figures 1 and 2.

The function in Figure 1, which is referred to as $\Omega(s_n)$, maps out the combinations of Ω and s_n which represent short-run equilibria for a given set of parameters μ, σ and ϕ . It can be shown that the slope of $\Omega(s_n)$, which is denoted $\Omega'(s_n)$, changes sign at most twice.¹⁸

Figure 2, the ‘bifurcation’ diagram, plots the share of workers/firms in the north (s_n) against trade freeness at all stable equilibria (represented by the thick solid

¹⁷ Forslid and Ottaviano (2003) provide a thorough explanation of the properties of the zero tax base case of the FE model.

¹⁸ See Baldwin et al. (2003) for a proof of this result.

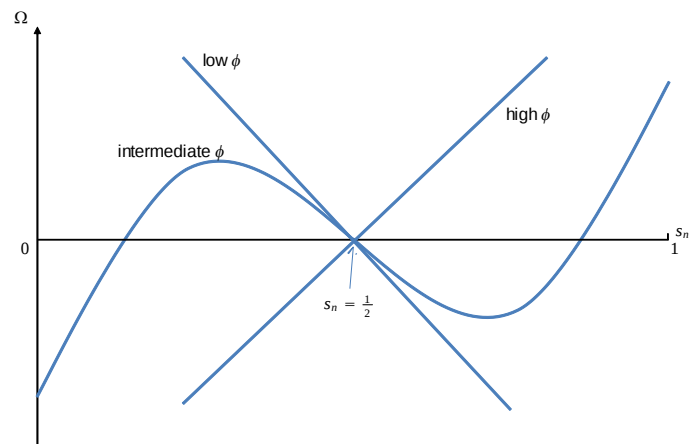


Figure 1: Log real wage ratio with no taxation

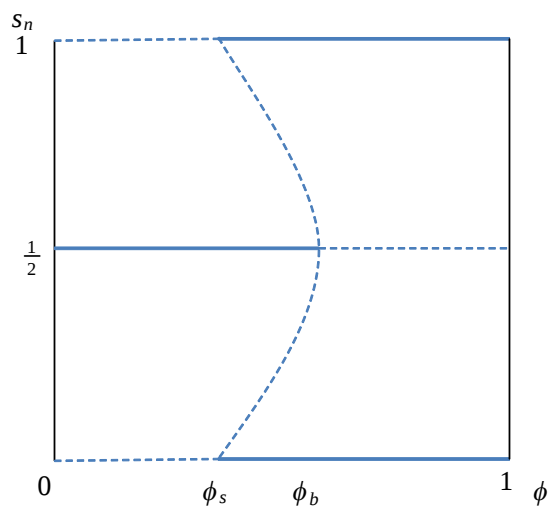


Figure 2: Bifurcation diagram with no taxation

lines) and at unstable equilibria (represented by the dashed lines). Two threshold levels of trade costs are of particular interest. First, the level of trade freeness above which the dispersed equilibrium is unstable (this is known as the break point), ϕ_b .¹⁹ Second, the level of trade freeness below which both CP equilibria are unstable (this is known as the sustain point), ϕ_s .

3.4 Equilibrium with harmonised taxation ($t = t^* = \bar{t} \geq 0$)

Recall from Section 2 that taxes affect nominal wages through the ratio of variable costs (reflected by the tax differential parameter r) only. As $r = 1$ whenever taxes are harmonised, nominal wages are identical to those in the zero tax case.

Price indices, however, are affected by the level of the harmonised tax. The northern true cost of living index when taxes are harmonised is equal to:

$$P \equiv p_N^\mu \theta^a = \left(\frac{1 + \bar{t}}{1 - \frac{1}{\sigma}} \right)^\mu [s_n + (1 - s_n) \phi]^a \quad (17)$$

Increases in the harmonised tax rate imply that manufacturing firms face higher variable costs and produce and sell less output at a higher price. While this leaves operating profit unchanged, the price indices increase and the real wage of skilled workers declines equally in both regions.

Despite the effect on real wages, changes in the harmonised tax rate do not alter the set of parameter values for which each type of equilibrium is stable. Evaluating the log real wage ratio, Ω , when $t = t^* > 0$, yields an expression which is identical to that established for the zero tax case (see equation (16)), as the effects of changing the tax rate on the northern and southern true cost of living indices cancel each other out.

One consequence of this result is that the stability properties of the harmonised tax equilibria are also summarised in Figures 1 and 2. Trade liberalisation (represented by an increase in ϕ) can lead to relocation of firms, however, changes in the harmonised tax rate cannot.

3.5 Equilibrium with unharmonised taxation ($t > t^* \geq 0$)

Unharmonised taxation breaks the symmetry of Figures 1 and 2 by the introduction of the asymmetric market crowding and cost of living effects. The CPN and CPS equilibria do not have identical properties and the dispersed equilibrium is no

¹⁹ For the remainder of this paper I impose the condition that $\phi_b > 0$, which ensures that agglomeration forces are never so strong that the diversified equilibrium is not stable for any ϕ .

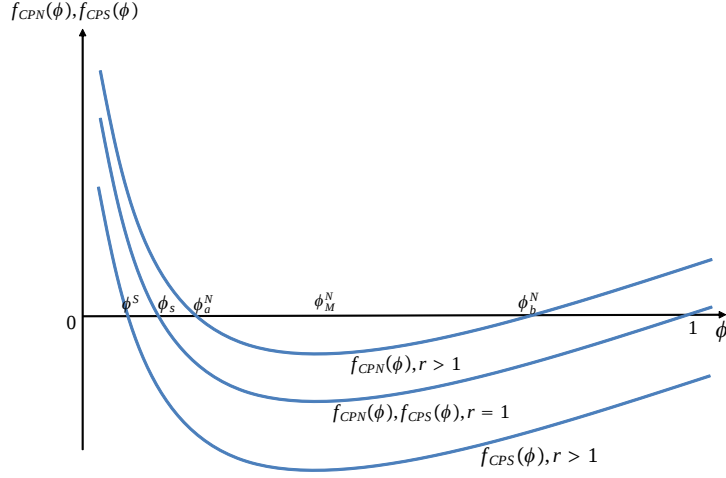


Figure 3: f_{CPN} and f_{CPS} for $r = 1$ and $r > 1$

longer symmetric. As the response of firms to exogenous parameter changes differs significantly at each of the three stable equilibria (CPN, CPS and dispersed), it assists intuition to consider each of these separately.

3.5.1 Properties of the CPN equilibrium

The set of stable CPN equilibria are derived by evaluating $\Omega|_{s_n=1}$ and applying the standard stability condition for CPN equilibria ($\Omega > 0$). This yields the following condition for stability:

$$\phi^a \left(\phi \frac{1+b}{2} + \frac{1}{\phi} \frac{1-b}{2} \right) - \frac{1}{r} < 0 \quad (18)$$

Therefore, the solutions to the equality $f_{CPN}(\phi) = 0$ determine the level of ϕ at which the CPN equilibrium changes between stable and unstable, where $f_{CPN}(\phi)$ is defined as:

$$f_{CPN}(\phi) \equiv \phi^a \left(\phi \frac{1+b}{2} + \frac{1-b}{2\phi} \right) - \frac{1}{r} \quad (19)$$

$f_{CPN}(\phi)$ for $r = 1$ and $r > 1$ are illustrated as the top two functions in Figure 3.²⁰

²⁰ Six properties of the function $f_{CPN}(\phi)$ are worth noting as they are necessary for the results derived in this section: (i) $f_{CPN}(1) = 1 - 1/r \geq 0$; (ii) $f'_{CPN}(1) > 0$; (iii) $f_{CPN}(0) > 0$; (iv) $f'_{CPN}(0) < 0$; (v) $\phi^a [\phi(1+b)/2 + (1-b)/(2\phi)] > 0$ for $\phi \in [0, 1]$; and (vi) $f_{CPN}(\phi)$ has a unique minimum.

The equality $f_{CPN}(\phi) = 0$ has at most two solutions which I refer to in order of increasing size as ϕ_a^N and ϕ_b^N (where they exist). For sufficiently high r , $f_{CPN}(\phi) = 0$ has no solutions and for some intermediate value of r , $f_{CPN}(\phi) = 0$ has one solution. Due to the existence of non-integer powers in $f_{CPN}(\phi)$, no analytical solution is, in general, possible for ϕ_a^N and ϕ_b^N .

A number of the stability properties of the model under output taxation can be derived analytically. First, for values of ϕ below ϕ_a^N and above ϕ_b^N , the CPN equilibrium is not stable. For $\phi_a^N \leq \phi \leq \phi_b^N$, the CPN equilibrium is stable.²¹ This implies that for values of ϕ such that $\phi_a^N < \phi < \phi_b^N$, the real wage in the north is greater than the real wage in the south given the CPN equilibrium occurs. This is a consequence of the agglomeration rents which all skilled workers receive at a CP equilibrium.²² The rents are hump-shaped in trade freeness, as the real wage is higher in the core than in the periphery for an intermediate level of ϕ .

Figure 3 illustrates the hump-shaped agglomeration rents with pollution taxation. The distance between the ϕ -axis and $f_{CPN}(\phi)$ for $\phi \in [\phi_a^N, \phi_b^N]$ reflects the size of the agglomeration rent received by skilled workers in the core in the presence of a tax per unit of pollution.

In the zero tax and harmonised tax cases, no level of trade freeness above ϕ_s will make the CPN equilibrium unstable. If neither region has a cost advantage brought about by pollution taxation, regulators in the core can pursue a policy of trade liberalisation without fear of loss of industry. In the presence of differentiated pollution taxation, trade liberalisation *can* make the CPN equilibrium unstable.

A second property of the set of stable CPN equilibria is that for values of r at which the equality $f_{CPN}(\phi) = 0$ has two solutions, ϕ_a^N (ϕ_b^N) is increasing (decreasing) in r .²³ As the tax differential increases, the range of values of ϕ over which the higher taxing north can sustain an agglomeration of industry decreases (both from above and below).

A third property is that a value of r exists such that $\phi_a^N = \phi_b^N$ and the CPN equilibrium is stable at only one level of ϕ . For larger values of r , the CPN equilibrium is unstable for all ϕ .²⁴ This implies that if the tax differential is

²¹ To obtain this result, observe that ϕ_a^N and ϕ_b^N are the roots of $f_{CPN}(\phi)$ and that $f_{CPN}(\phi) > 0$ only for $\phi < \phi_a^N$ or $\phi > \phi_b^N$. The result follows by the stability condition in equation (18).

²² Ludema and Wooton (2000), Andersson and Forslid (2003) and Kind, Midelfahrt-Knarvik and Schjelderup (1998) demonstrate the taxability of these agglomeration rents.

²³ To see this, observe that increases in r shift the function $f_{CPN}(\phi)$ upwards at all points, that $f'_{CPN}(\phi) < 0$ when $\phi = \phi_a^N$, $f'_{CPN}(\phi) > 0$ when $\phi = \phi_b^N$ and that $f_{CPN}(\phi)$ is convex. The result follows.

²⁴ To see this, observe that increases in r shift the function $f_{CPN}(\phi)$ upwards at all points and that $f_{CPN}(\phi)$ has a unique minimum. The result follows.

sufficiently high, no stable equilibrium is possible in the higher taxing region. It is possible to establish the value of r at which the CPN equilibrium becomes unstable for a given value of ϕ . I state this value of r in Proposition 1.

Proposition 1 *If for some ϕ the CPN equilibrium with symmetric taxation is stable, with differentiated taxation, the minimum level of r which makes the CPN equilibrium unstable (denoted by r^N) is equal to $(2\phi^{1-a}) / (2 - (1+b)(1-\phi^2))$.*

Proof. Solve $f_{CPN}(\phi) = 0$ for r . ■

Proposition 1 illustrates the interdependence of trade freeness, ϕ , and the tax rate differential, r , for the determination of stability. For example, at a level of ϕ that is slightly larger than ϕ_a^N , a relatively small increase in r causes the CPN equilibrium to become unstable. Whereas for a larger level of ϕ , an identical increase in r has no effect on the stability of the CPN equilibrium. Clearly, the value of r^N is of significant interest to a policy maker seeking to regulate agglomerated polluting industry without causing relocation of firms.²⁵

The level of trade freeness which allows the tax differential between regions to be maximised without firm relocation is referred to as ϕ_M^N .

Proposition 2 ϕ_M^N is equal to $\sqrt{[(1-a)(1-b)] / [(1+a)(1+b)]}$.

Proof. Observe that ϕ_M^N occurs at the unique minimum of $f_{CPN}(\phi)$. Solving $f'_{CPN}(\phi) = 0$ for ϕ yields the result. ■

Propositions 1 and 2 demonstrate the non-linear and non-monotonic effect of trade liberalisation on the footlooseness of firms in the presence of differentiated pollution taxation. I state this effect in Corollary 1.

Corollary 1 *Beginning from a value of ϕ less (greater) than ϕ_M^N , trade liberalisation makes the CPN equilibrium more (less) stable in the sense that a larger (smaller) tax differential, r , is required to make the CPN equilibrium unstable.*

Proof. Evaluate $\frac{\partial r^N}{\partial \phi}$ and observe that it is positive for $\phi < \phi_M^N$ and negative for $\phi > \phi_M^N$. ■

Corollary 1 reveals the first main result of the paper: The introduction of agglomeration forces implies that the PHH, which suggests that trade liberalisation makes firms more likely to relocate in response to a pollution tax disadvantage, does not always hold. In the presence of agglomeration forces, trade liberalisation can actually make firms less willing to relocate in response to an increase in the tax differential by strengthening the agglomeration forces holding them together.

²⁵ Trade freeness and pollution intensity are currently two of the most commonly adopted measures by policy makers to indicate an industry's propensity to relocate abroad in response to more stringent environmental regulation.

3.5.2 Properties of the CPS equilibrium

The solutions to the equality $f_{CPS}(\phi) = 0$ determine the level of ϕ at which the CPS equilibrium changes from stable to unstable where $f_{CPS}(\phi)$ is defined as:

$$f_{CPS}(\phi) \equiv \phi^a \left(\phi \frac{1+b}{2} + \frac{1-b}{2\phi} \right) - r \quad (20)$$

Analysis of $f_{CPS}(\phi)$ reveals five properties which are useful in establishing the set of stable CPS equilibria: (i) $f_{CPS}(1) = 1 - r \leq 0$, (ii) $f'_{CPS}(1) > 0$, (iii) $f_{CPS}(0) > 0$, (iv) $f'_{CPS}(0) < 0$ and (v) $f_{CPS}(\phi)$ has a unique minimum.

When $r > 1$, the equality $f_{CPS}(\phi) = 0$ has only one solution in the economically meaningful range $[0, 1]$. This implies that unlike in the case of the CPN equilibria, there is only one level of ϕ at which the CPS equilibrium changes between instability and stability.

The level of ϕ at which $f_{CPS}(\phi) = 0$ is designated ϕ^S and referred to as the sustain point for the CPS equilibrium. For values of ϕ less than ϕ^S , the CPS equilibrium is not stable, and for values of ϕ greater than ϕ^S and within the economically meaningful range $[0, 1]$, the CPS equilibrium is stable.²⁶ As r increases, the set of values of ϕ over which the CPS equilibrium is stable expands to include lower values of ϕ .

It is possible to determine the minimum level of r required to make the CPS stable for a given value of ϕ . This value is given in Proposition 3.

Proposition 3 *If for some ϕ the CPS equilibrium is not stable, the requisite value of r to achieve stability, denoted by r^S , is equal to $\frac{2-(1+b)(1-\phi^2)}{2\phi^{1-a}}$.*

Proof. Solve $f_{CPS}(\phi) = 0$ for r . ■

3.5.3 Properties of the dispersed equilibrium

I consider the effects of r and ϕ on the dispersed equilibrium in turn. Holding s_n fixed at any level in the economically meaningful interval $[0, 1]$, $\frac{\delta\Omega}{\delta r} < 0$. The implication of this result for the function $\Omega(s_n)$ is illustrated in Figure 4 for parameter values for which both CP and dispersed equilibria are stable.

The stable dispersed equilibrium, if it exists, does not comprise an equal distribution of firms between regions when r is greater than one. To demonstrate this result, recall that at any stable dispersed equilibrium, $\Omega'(s_n) < 0$. Therefore increasing r ensures that the new stable dispersed equilibrium (if one exists) will

²⁶ To establish this, observe by the five properties of $f_{CPS}(\phi)$ that ϕ^S is the smallest root of $f_{CPS}(\phi)$ and that no other roots exist in the economically meaningful range $\phi \in [0, 1]$. Note that $f_{CPS}(\phi) > 0$ for $\phi < \phi^S$ and $f_{CPS}(\phi) < 0$ for $\phi > \phi^S$. The result follows by the stability condition in equation (15).

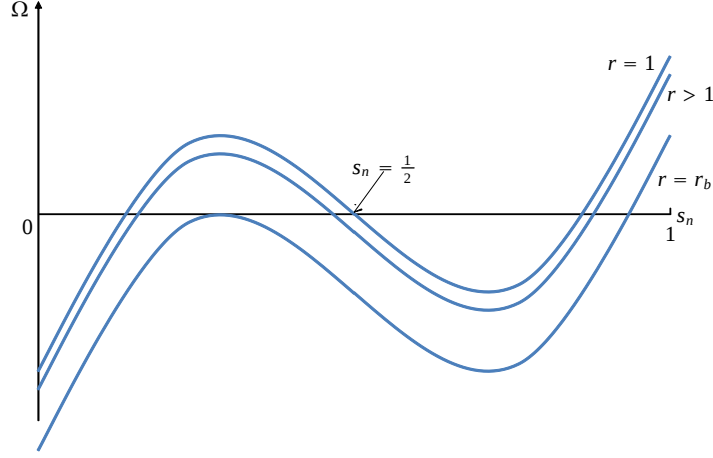


Figure 4: Log real wage with unharmonised taxation

occur for a lower value of s_n . This property reveals how the response of firm location to regulation differs quite dramatically depending on the initial industry configuration. If firms are agglomerated in a core they do not relocate in response to a small tax differential. At the dispersed equilibrium, however, any tax differential causes relocation of firms.

A second property of the stable dispersed equilibrium is that increasing r beyond the level at which the dispersed equilibrium is marginally stable, which I denote r_b , need not precipitate a catastrophic relocation of firms away from the dispersed equilibrium. The relocation can be smooth.

As in the harmonised tax case, in the unharmonised tax case there exists a range of values of ϕ from 0 to $\phi_b(r)$ for which there exists a stable dispersed equilibrium over the range $s_n \in (0, 1/2)$.²⁷ For $\phi > \phi_b(r)$, no stable equilibrium exists over the range $s_n \in (0, 1/2)$. This arises because the strength of the local competition effect (which encourages dispersion of firms between regions) falls approximately with the square of trade freeness, while the strength of the cost of living effect and the market size effect (which encourage firms to co-locate) increases roughly linearly with ϕ . Proposition 4 states formally that the range of ϕ for which the dispersed equilibrium is stable diminishes as the tax differential widens.

Proposition 4 *The unharmonised tax break point, $\phi_b(r)$, is decreasing in r .*

²⁷ To distinguish between the unharmonised and harmonised tax break points the unharmonised tax break point, which is a function of exogenous parameters μ and σ as well as r is written as $\phi_b(r)$. The harmonised tax break point, which is written as ϕ_b , is a function of μ and σ only.

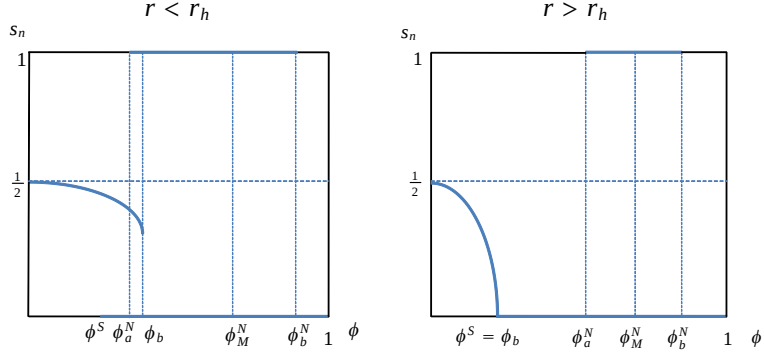


Figure 5: Asymmetric bifurcation diagram with catastrophic (left) and non-catastrophic (right) delocation

Proof. Consider an arbitrary stable dispersed equilibrium which is marginally stable such that $\phi = \phi_b(r^1)$. A small increase in the tax rate differential from r^1 to r^2 , holding $\phi = \phi_b(r^1)$ constant, ensures, by the fact that $\frac{\delta\Omega}{\delta r} < 0$, that the local maximum of $\Omega(s_n)$ for $s_n \in [0, 1/2]$ is now less than zero. Therefore, no stable equilibrium is now possible and $\phi_b(r^1) > \phi_b(r^2)$. This proves the proposition as ϕ , r^1 and r^2 are arbitrarily chosen. ■

For sufficiently large r , the break point, $\phi_b(r)$, is less than the northern sustain point ϕ_a^N . Unlike the harmonised tax case, there may be no values of ϕ for which both dispersed and CPN equilibria are stable.

3.5.4 Diagrammatic summary of the unharmonised tax case

The properties of the FE model with output taxation established in Section 3 are summarised in Figures 5 and 6, which demonstrate how the set of stable equilibria changes in response to changes in the parameters r and ϕ .

Figure 5 illustrates the effect of trade liberalisation on the set of stable equilibria. This is the unharmonised tax version of the bifurcation diagram in Figure 2. The left hand pane illustrates the case in which there is an interior break point. Trade liberalisation leads to catastrophic delocation of industry from the dispersed equilibrium. The right hand pane features a corner break point and delocation is smooth. The set of parameter values for which the CPN (CPS) equilibrium is stable is diminishing (increasing) in r .

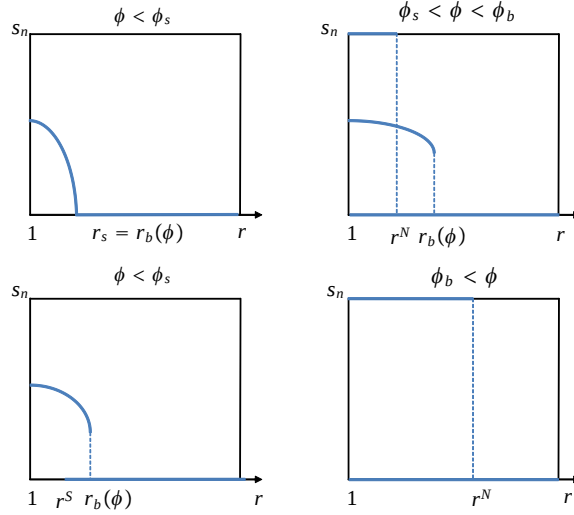


Figure 6: Stable equilibria as a function of r

Two qualifications for Figure 5 are in order. First, it is possible that $\phi_a^N > \phi_b(r)$ in the left hand pane.²⁸ Second, for r sufficiently large, it is possible that the CPN equilibrium is not stable for any level of ϕ . Both scenarios are omitted in order to present a simpler diagrammatic summary.

Figure 6 illustrates the effect of changes in the tax rate on firm location for four representative values of ϕ . Both panes on the left hand side demonstrate the effect of increasing r when ϕ is less than ϕ_s , the zero tax sustain point. The top left pane reflects a situation in which the transition from dispersed to CPS equilibrium is smooth as r rises. The bottom left pane reflects a situation in which the relocation of firms is catastrophic as r rises.

The top right pane illustrates the stable equilibria for ϕ greater than ϕ_s but less than the harmonised tax break point, ϕ_b (the intermediate ϕ case in Figure 1). In this scenario, both the dispersed and CP equilibria are stable for $r = 1$. As represented in the top right hand pane, the CPN equilibrium becomes unstable for a value of r which is lower than that for which the dispersed equilibrium becomes unstable. The opposite result is also possible, however, for simplicity, it is omitted.

The bottom right hand pane reflects values of ϕ for which only the CPN and CPS equilibria are stable when $r = 1$ (the high ϕ case in Figure 1). As r increases, the CPN equilibrium eventually becomes unstable.

In contrast to the effect of changes in trade freeness, the number of firms in

²⁸ This occurs for a higher tax differential than that represented.

the north is monotonically decreasing in the tax differential. This may explain why the PHE (which predicts firm relocation in response to changes in the tax differential) has received significantly more empirical support than the PHH.

4 Carbon Leakage

In this section the NEG model of Sections 2 and 3 is extended to consider the issue of carbon leakage. The second question introduced in Section 1 is addressed: *How does the degree of differentiation in environmental policy influence the extent of carbon leakage?* Conditions are derived under which unilaterally tightening environmental regulation increases global emissions. In addition, the region with the higher tax rate is shown to have larger firms at the dispersed equilibrium.

The level of carbon emissions in each region is equal to the product of: the number of firms located in the region, these firms' emission intensity and the level of output of each firm. The total emissions in the north, Γ , is given by:

$$\Gamma = s_n \gamma x \quad (21)$$

Changes in the tax parameters t and t^* alter the level of regional emissions by encouraging firms to relocate (a long-run effect reflected in the variable s_n , which I refer to as the 'firm relocation effect') and change their scale (an effect which operates in both the long-run and the short-run and is reflected in the variable x , which I refer to as the 'firm scale effect').

4.1 Carbon leakage with harmonised taxation

As carbon leakage can only occur when taxes are unharmonised, the harmonised tax case provides a zero leakage benchmark with which to compare the unharmonised tax case. The global level of emissions is denoted Γ^w , which is simply the sum of Γ and Γ^* . The harmonised tax rate is again denoted by $\bar{t}$ in both regions. As $r = 1$ when taxes are harmonised, there is only a firm scale effect and no relocation effect.

Because the response of both firm size and location to the IEA depends on the initial location of industry, I consider the CP and dispersed equilibria separately.

The level of emissions at the CPN and CPS equilibria are determined by evaluating Γ when $s_n = 1$ and Γ^* when $s_n = 0$. This yields a total level of emissions in the core (and therefore globally) of $b(\sigma - 1) / (1 + \bar{t})$ for both equilibria. Trade freeness, ϕ , plays no role in determining the level of emissions at either the firm,

region or global level.²⁹ Global emissions are thus monotonically decreasing in the harmonised tax rate, $\bar{t}$.

Recall from Section 3 that the dispersed equilibrium is always symmetric when taxes are harmonised. The global level of emissions is thus determined by setting $s_n = 1/2$ and evaluating Γ^w . This yields, $\Gamma = \Gamma^* = (1/2) b (\sigma - 1) / (1 + \bar{t})$ and therefore $\Gamma^w = b (\sigma - 1) / (1 + \bar{t})$. Global emissions at both dispersed and CP equilibria are declining in $\bar{t}$ at rate $b (\sigma - 1) / [(1 + \bar{t})^2]$.

As was the case for the CP equilibrium, ϕ plays no role in the determination of the level of global emissions. From a dispersed equilibrium, as trade is liberalised, the effect of greater access to the foreign market on firm scale is exactly offset by exposure to greater foreign competition.³⁰ Two obvious consequences of this are stated in Proposition 5.

Proposition 5 *When taxation is harmonised, the dispersed and CP equilibria yield identical levels of global emissions and the level of global emissions is independent of trade freeness.*

Proof. This follows immediately from the global levels of emissions at the CP and diversified equilibria derived above. ■

4.2 Carbon leakage with unharmonised taxation

Unlike in Section 3 (in which the values of t and t^* only affect the extent of firm relocation through their effect on the tax differential, r), the absolute level of each tax rate must be considered in undertaking comparative static analysis of the global level of emissions. This arises because the absolute levels of both t and t^* alter variable costs and therefore firm size, through the firm scale effect, even though it is only their ratio (via the parameter r) which alters firm location.

To abstract from complications arising from the need to consider both the absolute values of t and t^* and the resulting value of r , I assume that the environmental agreement leaves t^* fixed at its pre-agreement level and only increases t . This assumption ensures that r and t have a one-to-one mapping.

²⁹ This occurs because nominal expenditure on manufactures in the periphery is a constant fraction of unskilled worker income. Therefore, with mill pricing, trade costs determine the amount of manufactures consumed in the periphery and the amount used to cover transport costs. Trade costs do not, however, influence the level of manufactures actually produced in the core and therefore the level of global emissions.

³⁰ This a weak result, however, in the sense that it depends critically upon the collective assumptions of constant elasticity of substitution (CES) sub-utility, iceberg trade costs and the symmetry implied by harmonised taxation. Altering any of these will invalidate the result.

4.2.1 The CP equilibria

In this sub-section it is assumed that the core is initially in the north in order to ease exposition.³¹ The level of global emissions in the CPN and CPS equilibria are:

$$\Gamma^w = \Gamma + \Gamma^* = b \frac{\sigma - 1}{1 + t} + 0, \text{ for the CPN equilibrium} \quad (22)$$

$$\Gamma^w = \Gamma + \Gamma^* = 0 + b \frac{(\sigma - 1)}{1 + t^*}, \text{ for the CPS equilibrium} \quad (23)$$

Equations (22) and (23) suggest three important properties of the stable equilibria, which comprise the second major contribution of the paper. First, the global level of emissions is decreasing in the tax rate in the core, provided no relocation of firms occurs. Specifically, increasing t decreases the level of global emissions at rate $b(\sigma - 1) / [(1 + t)^2]$ regardless of the value of t^* provided the IEA is such that $r < r^N$. If the IEA induces catastrophic relocation of firms ($r > r^N$), the global emissions level increases catastrophically from $b(\sigma - 1) / (1 + t)$ to $b(\sigma - 1) / (1 + t^*)$. Second, of the two CP equilibria, the CP equilibrium with the higher domestic tax rate comprises smaller firms and results in a lower level of global emissions. Third, the tax rate in the periphery, t^* , has no effect on the global level of emissions provided the IEA is such that $r < r^N = (2\phi^{1-a}) / (2 - (1 + b)(1 - \phi^2))$.

An IEA which sets unharmonised taxes can be as effective at reducing global emissions as a harmonised tax IEA which has the same northern tax rate, provided the tax rates are not too differentiated. Γ^w declines in the northern tax rate until the tax differential is such that $r = r^N$. Beyond this level of differentiation, Γ^w catastrophically increases as all firms relocate to the south. The southern tax rate can now influence Γ^w . When such a relocation of firms occurs, the leakage rate is greater than unity and can be as large as $(1 + t) / (1 + t^*)$.³²

The existence of multiple equilibria implies that reversing the change in t mandated by the IEA will not necessarily reduce emissions to their original level. The model exhibits hysteresis in the level of global emissions.

Given hysteresis, the tipping point, r^N , also provides guidance on how increases in environmental regulations might be staged in order to achieve a targeted level

³¹ Some generality is lost through this assumption, as the case in which the core is initially in the south prior to the IEA is no longer considered. This scenario is uninteresting, however, as the IEA, which, by assumption, provides the south with a tax advantage, cannot induce firms to relocate from a CPS equilibrium.

³² The maximum leakage rate is calculated by dividing the reduction in emissions in the north ($b \frac{\sigma-1}{1+t}$) by the increase in emissions in the south ($b \frac{(\sigma-1)}{1+t^*}$) at the point at which catastrophic relocation occurs.

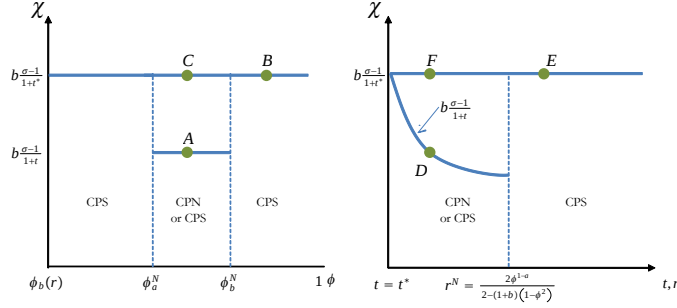


Figure 7: Global emissions at CP equilibria with unharmonised taxation

of regulation globally, while avoiding leakage by exploiting agglomeration forces.³³ If both t and t^* are increased at different rates, provided r^N is never breached, no leakage occurs. In general, it is possible to stage increases in t and t^* cooperatively so that the north leads but that the configuration of firms does not vary.³⁴

The level of ϕ can also influence Γ^w if it precipitates catastrophic relocation of firms. Both trade liberalisation (such that $\phi > \phi_b^N$) and restriction (such that $\phi < \phi_a^N$) can trigger a catastrophic increase in the level of emissions. This result contrasts with standard non-NEG predictions in which trade restriction unambiguously reduces leakage. Unlike in the harmonised tax case, trade liberalisation can also alter the global level of emissions in ways which may be difficult to reverse.

Figure 7 illustrates the responsiveness of global emissions to changes in ϕ and t . In the left hand pane (a situation in which taxes are differentiated such that $r > 1$), if industry is initially at the CPN equilibrium, both trade liberalisation (above $\phi = \phi_b^N$) and trade restriction (below $\phi = \phi_a^N$) lead to a catastrophic increase in global emissions. To demonstrate the potential difficulties in reversing

³³ Within international climate negotiations there appears to be some consensus that industrialised countries should regulate more stringently and earlier than developing nations, with the goal of convergence to a global carbon price at some point in the future.

³⁴ According to Ossa (2011), the objective of avoiding firm relocation underpins the world multilateral trading system's principle of reciprocity of tariff changes. The process to secure an international treaty on carbon emissions may learn from the multilateral world trading system by, for instance, discouraging unilateral reductions in environmental regulation by individual regions or countries by allowing others regions to reciprocally reduce their environmental regulation levels in response, eliminating any firm relocation benefits of the initial unilateral reduction in regulation.

the outcomes of policy changes, consider trade liberalisation from an initial level corresponding to the point A (at which the core is in the north and global emissions are equal to $b(\sigma - 1)/(1 + t)$) to point B . Reversing this change in trade costs moves the equilibrium back to point C and does not reduce global emissions back to their original level.

The right hand pane illustrates the consequences of increasing t beginning from a situation in which $t = t^*$. For small increases in t such that $r < r^N$, no relocation of firms occurs and global emissions decrease. The reduction in global emissions is equal to that of the harmonised tax case (with $\bar{t}$ set equal to the unharmonised value of t) and therefore no leakage occurs. Firms in the north simply reduce their scale, rather than relocating, in response to an increase in their domestic tax rate, t . If t increases above the level at which $r = r^N$, all industry relocates to the south and the global level of emissions increases catastrophically to its original level, $b(\sigma - 1)/(1 + t^*)$. Points D , E and F in Figure 7 demonstrate the effect of first increasing the tax differential (D to E) and then decreasing it (E to F). This illustrates how the environmental consequences of changes in the tax differential may be difficult to reverse and suggests a new and environmentally motivated rationale for avoiding highly differentiated environmental policies.

4.2.2 The dispersed equilibrium

As was the case in Section 3, when considering firm relocation, the level of global emissions, Γ^w , responds differently to increases in t from an initial dispersed equilibrium than it does from a CP equilibrium.

Proposition 6 *Beginning from the harmonised tax dispersed equilibrium (that is, if $t = t^*$ and $s_n = 1/2$), $\frac{\partial \Gamma^w}{\partial t} < 0$.*

Proof. Differentiate the expression for the total global emissions, $\Gamma^w = s_n \gamma x + (1 - s_n) \gamma x^*$, with respect to t . The result follows. ■

Proposition 6 implies that beginning from a symmetric dispersed equilibrium, as t increases, the global level of emissions initially declines.

There is a level of t above which $\frac{\partial \Gamma^w}{\partial t} > 0$. To see this, note that beginning from a dispersed equilibrium, if the IEA sets t sufficiently large, all firms locate in the south and $\Gamma^w = b(\sigma - 1)/(1 + t^*)$. Increasing t above t^* will reduce global emissions if the increase is sufficiently small, however, if the difference is too great, relocation of firms to the south restores the original level of global emissions. Therefore, a level of r exists at which increases in t do not reduce global emissions, the reduction in domestic emissions is more than offset by emissions abroad. This

level of r represents the maximum reduction in global emissions attainable by a region acting unilaterally from a dispersed equilibrium.

An interesting, and somewhat counterintuitive, general equilibrium result, which is the third and final main result of this paper, is that firms in the north, where environmental regulation is more stringent, are actually larger than those in the south for $t > t^*$.

Proposition 7 *At the dispersed equilibrium the higher taxing region has larger and therefore higher polluting firms than the lower taxing region.*

Proof. See appendix. ■

5 Conclusion

This paper considered the consequences of differentiated environmental policy in the form of an output tax for firm location and carbon leakage in an NEG model. Section 3, which dealt with firm location, proved previous conjectures from the NEG literature on environmental regulation, presented a theoretical model in which the PHH need not hold and enumerated its stability properties. Section 4 provided an examination of carbon leakage. It was shown that, in the presence of agglomeration forces, unilaterally tightening environmental regulation can be environmentally deleterious under a broad set of conditions.

This paper does not address a number of complications that are worth exploring in the future. In particular, strategic regulation setting is not considered as both regions are simply assumed to ratify the IEA. This is desirable for addressing the two key questions of this paper. However, a positive level of both leakage and deindustrialisation may be desirable for a welfare maximising government for which an IEA is its only policy instrument. A setting in which competitive governments maximise the welfare of their local unskilled labour force, perhaps incorporating welfare effects of pollution and public goods provided by tax revenue, would enable consideration of the trade-off between environmental and economic objectives in a model with agglomeration forces.

Finally, the paper presents two new empirically testable hypotheses. The first hypothesis is that industries with lower trade costs need not have a higher delocation elasticity in response to environmental regulation. The second hypothesis is that the delocation elasticity of more agglomerated industries is lower. Both of these hypotheses would benefit from empirical validation.

6 Appendix - Proof of Proposition 7

Expressions for the real wages in each region are:

$$\begin{aligned}\omega &= \eta \frac{w_H}{P}, P \equiv P_M^\mu, P_M \equiv \left(\int_0^{n^w} p_i^{1-\sigma} di \right)^{\frac{1}{1-\sigma}} = p_N [s_n + (1-s_n)\phi r]^{\frac{1}{1-\sigma}} \\ \omega^* &= \eta \frac{w_H^*}{P^*}, P^* \equiv P_M^{*\mu}, P_M^* \equiv \left(\int_0^{n^w} p_i^{*1-\sigma} di \right)^{\frac{1}{1-\sigma}} = p_N [\phi s_n + (1-s_n)r]^{\frac{1}{1-\sigma}}\end{aligned}\quad (24)$$

Subtracting the southern cost of living index from the northern cost of living index yields:

$$P_M - P_M^* = p_N [[1-\phi][s_n - [1-s_n]r]]^{\frac{1}{1-\sigma}} \quad (25)$$

Therefore the cost of living index is smaller in the larger region.

But $\omega = \omega^*$ at the diversified equilibrium. Therefore $w_H > w_H^*$ at a unharmonised diversified equilibrium as the south is larger.

Recall that firm size can be expressed as:

$$x = w_H \frac{(\sigma-1)}{1+t} \quad (26)$$

Therefore:

$$\frac{x}{x^*} = \left[r^\mu \frac{[s_n\phi + r[1-s_n]]}{[s_n + r\phi[1-s_n]]} \right]^{\frac{\mu}{\sigma-1}} \quad (27)$$

As $r > 1$ and the south is larger in the unharmonised diversified equilibrium:

$$r[1-s_n] > s_n \quad (28)$$

Alternatively, this can be expressed as:

$$r[1-s_n] = s_n + \Delta \quad (29)$$

Therefore in the expression for $\frac{x}{x^*}$ the numerator of the fraction inside the square brackets is:

$$s_n\phi + s_n + \Delta \quad (30)$$

The denominator in the fraction inside the square brackets is:

$$s_n + \phi[s_n + \Delta] = \phi s_n + s_n + \phi\Delta \quad (31)$$

Therefore, as $\phi < 1$ at any stable diversified equilibrium the firms in the higher taxing south are larger than those in the north.

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