ENVIRONMENTAL POLICY, AGGLOMERATION AND FIRM LOCATION

A theoretical study of environmental regulation with endogenous firm location

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ABSTRACT

This thesis considers the related policy challenges of deindustrialisation and 'leakage' which can arise when environmental regulation is differentiated across regions. A dynamic two-region 'New Economic Geography' (NEG) model is adopted in which agglomeration forces (which encourage firms to locate together) may make firms tolerant of regulatory disadvantage (Chapter 3). Each region ratifies an international environmental agreement (IEA) which requires it to tax transboundary pollution created by local firms. The tax rates may be differentiated. It is assumed that the IEA is the only policy instrument available. In contrast to previous NEG models used in this context, the model adopted is considerably more tractable, which enables comparative static analysis to be undertaken analytically rather than through computer simulation.

The model is extended to consider the relationship between the prescribed tax rates and deindustrialisation caused by the relocation of firms (Chapter 4). Firm relocation in response to a given tax differential depends crucially on trade costs and the initial location (configuration) of industry. For some industry configurations, agglomeration forces are strong and a set of tax differentials exist which cause no international relocation of polluting firms. For other initial industry configurations in which agglomeration forces are weaker, the same set of tax differentials may cause complete international relocation to the less stringently regulated region.

The model is further extended to consider the issue of carbon leakage, which arises in the regulation of greenhouse gas (GHG) emissions (Chapter 5). Agglomeration forces are a double-edged sword. For relatively low tax differentials, agglomeration forces create rents which tend to anchor industry in the higher taxing region, avoiding carbon leakage. If the tax differential is too great, however, agglomeration forces cause all firms to relocate to the lower taxing region where they optimally emit more GHGs. Environmental outcomes may therefore be improved by reducing the tax rate in the higher taxing region in order to discourage industry relocation. I show that in the presence of agglomeration forces, trade liberalisation can make industry less (rather than more) likely to relocate in response to a regulatory disadvantage. When industry is diversified between regions, firms respond to higher (lower) relative domestic taxes by increasing (decreasing) output and polluting more (less). The model suggests that carbon leakage in response to a policy shift may be far higher in the long-run than it is in the short-run due to the importance of firm relocation.

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GLOSSARY

CGE .... Computable general equilibrium

CL .... Carbon leakage

CP .... Core-periphery

CPN .... Core-in-the-north

CPS .... Core-in-the-south

CRS .... Constant returns to scale

EU .... Europe Union

EU-ETS .... European Union Emissions Trading Scheme

FC .... Footloose capital

FE .... Footloose entrepreneurs

GDP .... Gross domestic product

GHG .... Greenhouse gas

IEA .... International environmental agreement

IRS .... Increasing returns to scale

NEG .... New economic geography

PHE .... Pollution haven effect

PHH .... Pollution haven hypothesis

UNFCCC .... United Nations Framework Convention on Climate Change

VL .... Vertical linkages

WTO .... World Trade Organization

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1 INTRODUCTION

This thesis considers the related policy challenges of deindustrialisation and 'leakage' which can arise when environmental regulation is differentiated across regions. A dynamic 'New Economic Geography' (NEG) model is adopted in which agglomeration forces may make firms tolerant of regulatory disadvantage.

1.1 Motivation

Under very general conditions, regulation of transboundary pollution will only be optimal with international policy coordination. When countries fail to cooperate, the potential for free riding on the actions of others results in higher than optimal levels of pollution.

Given this regulatory challenge, it is unsurprising that almost every nation has agreed that cooperation, as opposed to unilateral action, should be the approach adopted towards the regulation of the greenhouse gases (GHGs) which contribute to climate change.[1] This consensus is demonstrated in the numerous international environmental agreements which have emerged over the past two decades that deal with the regulation of GHGs.[2]

Despite agreement on the general approach to regulating GHGs, the precise nature and degree of international cooperation in relation to regulation remains subject to significant debate. The principle of 'common but differentiated' responsibilities is a cornerstone of the two most important international treaties governing climate change, namely the United Nations Framework Convention on Climate Change (UNFCCC) and the Kyoto Protocol. In practice, however, there has not been agreement amongst signatories on how 'differentiated' the respective nations' responsibilities should be.

Evidence of this lack of clarity is provided by comparing two major international agreements drafted twelve years apart. The Kyoto Protocol (1997) committed forty industrialised countries to legally binding reductions in their national GHG emissions, while imposing little or no constraint on any other countries. More recently, however, many of those forty industrialised parties have insisted that any global climate agreement include commitments to reduce GHG

1 'Carbon leakage' is used as shorthand for carbon dioxide leakage. I follow most policy analysis and use the terms 'carbon' and 'greenhouse gas' interchangeably as carbon dioxide is the greenhouse gas which contributes most to climate change.

2 An example of which is the Kyoto Protocol (1997), a legally binding international treaty which at the end of 2009 had been signed and ratified by 187 UN member states.

emissions by major industrialising countries such as China and India. This shift in apportionment of responsibility is reflected in the recent (and non-binding) Copenhagen Accord (2009), under which both China and India (countries which had previously made no commitment to curtail their GHG emissions) committed to reduce their carbon dioxide emission intensity per unit of gross domestic product (GDP).[3]

The lack of consensus on the degree of each nation's responsibility arises partly because of the significant complications to which differentiation gives rise. The most obvious complication is in determining an equitable allocation of responsibility between countries. This is a problem for which the field of economics can provide useful tools of analysis, but which I explore no further in this thesis.

A second complication, which is the focus of this thesis, arises because regions which are required to significantly economise on their emission of GHGs may find their polluting firms become less competitive relative to polluting firms in regions in which the same degree of economisation is not mandated. As a consequence of this loss of international competitiveness, the less competitive firms may alter their size or relocate from regions that are more stringently regulated to regions that are less stringently regulated. In this thesis, the theory that polluting industry relocates in response to changes in the relative stringency of environmental policy is referred to as the Pollution Haven Effect (PHE).[4] There is currently strong empirical support for the PHE.[5]

The PHE poses an important policy challenge, especially for industrialised countries, with two concerns being particularly prominent. The first concern relates to welfare losses resulting directly from a relocation of industry, including unemployment, terms of trade losses and the social unrest which often results. This concern tends to be put forward by trade unions and business groups as an argument against stringent regulation. The second concern is carbon leakage, which occurs if relocation of polluting activity (as a consequence of tighter environmental

[3] China has committed to reduce the carbon dioxide emission intensity per unit of its GDP by 40 to 45 percent against 2005 levels; increase the proportion of non-fossil fuels in the country's total primary energy mix to 15 percent; increase its forest by 40 million hectares and increase its forest volume by 1.3 billion cubic meters on 2005 levels, all by 2020. India has commited to cut its emissions intensity per unit of GDP by 20 to 25 percent from 2005 levels, by 2020.

[4] The literature has been inconsistent in its use of the term PHE, which is often used interchangeably with the related pollution haven hypothesis (PHH). To avoid any ambiguity in this thesis I adopt the terminology from Copeland and Taylor (2004). The authors describe the PHE as follows: 'The PHE implies that a (unilateral) tightening up of pollution regulation will, at the margin, have an effect on plant location decisions and trade flows.' The authors describe the PHH as follows: '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.'

[5] See Jeppessen et al. (2002) for a review of recent literature in this area.

policy) induces relocation of GHG emissions rather than their reduction.[6,7] Carbon leakage makes environmental regulation less effective or even counterproductive.

These concerns have been expressed in the EU, USA and many other industrialised countries facing the question of how to regulate GHG emissions. A typical example of these two related concerns converging in public policy discourse is provided by the Australian Senate Economics Legislation Committee (which comprises representatives from all major political parties) regarding a bill to introduce a GHG limit to Australian GHG emitting industries:

> *The committee remains satisfied that carbon leakage is a legitimate concern ... the committee sees no virtue in the elimination of an emissions intensive industry in Australia if that industry simply relocates to another jurisdiction where it is allowed to pollute more heavily.*

Australian Senate Economics Legislation Committee,

Carbon Pollution Reduction Scheme Bill 2009 and related bills, p17.

While both policy challenges (direct welfare losses due to industry relocation and carbon leakage) are often invoked as noble masks to more traditional protectionist concerns, they have also found support in public policy circles and economic literature. As a result, an understanding of the conditions under which these concerns are likely to have the largest welfare consequences is of practical importance for the design of effective international environmental agreements.

This thesis explores the issues of industry relocation and carbon leakage which can result from internationally differentiated environmental regulation. It does so by extending the current NEG literature, establishing conditions under which these concerns are minimised and suggesting how best to design international environmental agreements to ensure they are more acceptable to all parties. In Chapter 4 I address the first concern and ask the first key question: *How does the degree of differentiation of environmental policy influence the extent of firm relocation?* In

[6] Economic analysis tends to consider carbon leakage as it arises through three channels. The first is a factor price channel (or factor market channel), whereby tighter regulation in one region reduces demand for polluting inputs, which in turn depresses the world price and encourages increased use of these inputs in regions where regulation is less stringent. The second is a market share channel (or goods market channel), whereby plants in stringently regulated regions reduce output in response to regulation, while plants located in less stringently regulated regions increase output in response. The third is a firm relocation channel, whereby plants which produce polluting goods relocate to less stringently regulated regions. See International Energy Association (2008) for a detailed discussion of these channels.

[7] In this thesis, the carbon leakage rate is defined as the change in foreign emissions in response to a one unit (regulation-induced) reduction in domestic emissions.

Chapter 5 I address the second concern and ask the second key question: *How does the degree of differentiation of environmental policy influence the extent of carbon leakage?*

1.2 Contribution

This thesis contributes to the existing literature by reconsidering two related environmental issues: the PHE and carbon leakage. I introduce the NEG framework to the issue of carbon leakage and extend previous NEG analysis of the PHE.

The model adopted (Forslid and Ottaviano's (2003) 'footloose entrepreneurs' (FE) model) comprises two regions (north and south), two sectors (perfectly competitive agriculture and monopolistically competitive manufacturing), and two factors of production (one which is mobile between regions and the other which is immobile). In addition, I assume that each region is committed to an international agreement which fixes the level of a tax on the production of pollution in the manufacturing sector within its region. The pollution tax may be differentiated across regions.

1.2.1 Contribution to the theory of the PHE (Chapter 4)

Venables (1999) has already considered the first key question (*How does the degree of differentiation of environmental policy influence the extent of firm relocation?*) using an NEG model.[8] Chapter 4 extends Venables' (1999) analysis on two fronts. First, the FE model in this thesis is easier to work with analytically than the vertical linkages (VL) model of Venables (1999).[9] Second, assumptions about the type of regulation and the way polluting firms respond to regulation in the model in this thesis may better reflect reality in the case of the regulation of GHG emissions.

The added tractability provided by the FE model yields several modelling benefits. First, the VL model in Venables (1999) poses difficulties for policy analysis as it is often impossible to identify the role of individual parameters in determining outcomes. This can obscure the exact mechanisms at work. Second, the tractability of the model in this thesis enables results to be

8 In contrast to the FE model in this thesis, Venables (1999) adopts a vertical linakges (VL) model of the type first developed in Venables (1996).

9 There is little or no cost of this added tractability, which arises due to the incorporation of the non-homothetic Flam-Helpman (1987) functional form. Baldwin et al. (2003, p91) claim: 'the (FE) model displays all the key features of the Core-Periphery (and therefore the VL) model while still remaining amenable to analytic reasoning.'

derived which can be shown to hold generally, rather than ascertained as simulated regularities. Third, in a model with discontinuities, as in the NEG models of Venables (1999) and this thesis, tractability enables the tipping points in the model to be determined analytically. Fourth, the model developed in this thesis is more readily extended to a competitive environmental policy setting in which governments select pollution tax rates by maximising an objective function.[10] In the NEG tax competition literature, the FE model has already been used to consider tax policies by competing governments.[11]

As a consequence of the improved tractability, the model presented in this thesis yields the main conclusions of Venables (1999) as well as a number of further conclusions which cannot be demonstrated with the model adopted in his paper.

The model in this thesis is also more realistic for a situation in which GHGs are regulated. In contrast to Venables (1999), this thesis considers a situation in which: (i) both regions impose an environmental tax (rather than just one region); (ii) the environmental tax is levied on the use of polluting variable inputs (rather than on total firm costs); (iii) the production function adopted is non-homothetic (which allows for substitution between fixed and variable costs in response to environmental regulation); and (iv) firm size is a function of the level of the pollution tax (rather than being fixed).[12]

Using this model, a number of properties of the relationship between environmental regulation and firm location are established which challenge the predictions of non-NEG models of the environment and trade. The two main results are set out below.

1. Agglomerated industries facing high trade costs may be less likely to relocate in response to an environmental tax disadvantage than those with lower trade costs. Trade liberalisation may therefore decrease the level of relocation from high taxing to low taxing regions for a given tax differential. This result contrasts with most previous theoretical analysis of regulation and firm location. In this thesis the PHH, which predicts that trade liberalisation between regions with differentiated environmental regulation leads to industry relocation,

[10] Elbers and Withagen (2004) consider competitive environmental policy in a less tractable NEG model (Krugman's (1991) CP model which is as difficult to work with analytically as the VL model). In order to derive many of the paper's main results the authors must either make strict assumptions on parameter values (such as an assumption of zero trade costs which eliminates agglomeration forces) or employ computer simulation.

[11] See Baldwin and Krugman (2004).

[12] The fact that firm size responds to regulation is important for analysis undertaken in Chapter 5 in which I consider the effect of regulation on the amount of pollution firms produce. If firms do not respond to regulation by changing their scale, some results derived in this thesis no longer hold.

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.[13]

2. The effect of changes in environmental tax levels on the location of industry depends on whether industry is agglomerated in one region (i.e. all firms are located in the same region) or dispersed across both. Agglomerated industry does not relocate in response to a small tax disadvantage whereas dispersed industry does.

1.2.2 Contribution to the theory of carbon leakage (Chapter 5)

To my knowledge, no paper has evaluated the relationship between environmental policy and carbon leakage in an NEG framework.[14] 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.[15] A theoretical NEG model of carbon leakage is thus well overdue.

As noted above, this thesis applies the NEG methodology and makes several new predictions about the nature of carbon leakage. The main results are set out below.

1. The extent of carbon leakage for a given IEA varies significantly depending on the initial location of industry. If all industry is initially agglomerated in one region, an increase in the tax differential can either increase or decrease the level of global emissions depending on the level of trade costs.[16] Taxing agglomerated industries may cause no carbon leakage if agglomeration forces are strong enough to preclude firm relocation. If industry is dispersed between regions, an IEA which specifies differentiated taxation must cause carbon leakage.
2. The potential existence of multiple equilibria is demonstrated. I show that the implication of this is that reversing policy decisions may not reverse changes in the level of global

[13] See Copeland and Taylor (2004) for a discussion of the empirical support for the PHH.

[14] Ishikawa and Okubo (2009) consider the relationship between trade liberalisation and carbon leakage in an NEG framework but do not consider the effect of the degree of differentiation of environmental policy. Their paper is discussed in Chapter 2.

[15] For a review of policy literature see International Energy Agency (2008). For recent theoretical work on carbon leakage with IRS see Fowlie (2009) and Ritz (2009). For recent empirical literature see Ben Kheder and Zugravu (2008). For a recent CGE study of carbon leakage with increasing returns to scale that reviews the literatue see Babiker (2005). For empirical evidence that agglomeration forces determine the location of polluting industries see Giarratani et al. (2007).

[16] In the model presented in this thesis, the level of global emissions refers to the combined level produced in both regions.

pollution. Once the carbon leakage genie is out of the bottle, it may be difficult to put it back in.

3. If industry is dispersed between regions, firms in the region with the higher tax rate are larger than those in the region with the smaller tax rate. This effect arises because the region with the higher tax rate produces less varieties of manufactures. Skilled workers in the higher taxing region thus require a higher nominal wage to compensate for the higher price index associated with having to import consumption from abroad. Firm size must be larger to provide this higher nominal wage.

1.3 Outline

This thesis proceeds as follows: Chapter 2 contextualises this thesis within the literature; Chapter 3 presents a theoretical model of pollution taxation with endogenous firm location and derives the equilibrium when firm location is fixed (the short-run equilibrium); Chapter 4 extends the model to consider the relationship between environmental regulation and firm location; Chapter 5 extends the model to consider the relationship between environmental regulation and carbon leakage; Chapter 6 concludes the thesis by summarising its main results, proposing an agenda for future research and outlining key policy implications.

2 LITERATURE REVIEW

This thesis extends and combines two related strands of the literature, those on the PHE and carbon leakage.[17] In this chapter I demonstrate the importance of the two central questions asked in Chapters 4 and 5, and justify the adoption of the NEG approach in answering those questions, by briefly surveying the literature relating to both strands.

In section 2.1 I review the literature on the PHE (particularly that which relates to firm relocation) and in section 2.2 I review the literature on carbon leakage.[18]

2.1 The PHE

In this section I discuss three theoretical approaches used to analyse the PHE. While a discussion of the existing literature is important in and of itself, the main purpose of this section is to demonstrate that the NEG framework is likely to shed light on aspects of the PHE which other models do not. In addition, this section demonstrates how the analysis undertaken within this thesis contributes to the current body of NEG literature on the PHE.

Perfectly competitive constant returns to scale (CRS) models The earliest papers on the PHE adopt perfectly competitive CRS general equilibrium models in either a Ricardian or Heckscher-Ohlin framework. Factors of production (of which pollution is one) are immobile between regions. The PHE is therefore driven by changes in output specialisation which are determined by the price (set by government) of the polluting factor of production.

Pethig (1976) was amongst the first to consider the PHE by using the perfectly competitive CRS framework. Theorem 4 of Pethig's paper is a standard Heckscher-Ohlin theorem stating that the jurisdiction with the least restrictive environmental policy (either a tax or an environmental standard) specialises in production of the pollution intensive good. This is a typical property of perfectly competitive CRS models. In Pethig's model, trade liberalisation causes production of the polluting good to migrate to the region with less stringent environmental regulation.

[17] This thesis contributes specifically to the portion of the literature on the PHE which considers the relationship between firm location and regulation.

[18] Carbon leakage is a term used almost exclusively in the context of climate change. However, an analysis of the literature which addresses other transboundary pollutants is also relevant to this thesis. Much of the non-climate change related literature uses more general language. Where necessary, in referring to relevant but non-climate change related studies, I adopt the term 'pollution leakage' as opposed to carbon leakage.

There are two major drawbacks with using perfectly competitive CRS models to analyse the PHE. First, polluting industries often exhibit increasing returns to scale, thus making such models unrealistic. Second, factor and firm relocation in response to environmental regulation is generally not possible in such models, yet relocation of factors and firms as a major cause of the PHE has received strong empirical support.[19]

Two approaches which assume increasing returns to scale (IRS) and imperfect competition (in part to address the two concerns expressed above) are international oligopoly of the Brander and Spencer (1985) variety and NEG of the interregional factor mobility (Krugman (1991)) and vertical linkages (Venables (1996)) varieties.[20]

International oligopoly models Markusen et al. (1993) provide a typical example of an international oligopoly model and their paper was amongst the first to consider the relationship between environmental regulation and firm location.[21] 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. This result contrasts with perfectly competitive CRS models, which predict that marginal changes in policy variables always lead to marginal changes in the location of production and welfare. In Markusen et al.'s (1993) model a reduction in trade costs makes locating a firm in the low taxing region more attractive.

New economic geography models The NEG framework provides a second avenue to explore the PHE as it arises due to firm relocation. NEG models introduce positive linkages (which give rise to agglomeration forces) between co-located firms. This can cause operating profits to be an increasing (rather than a decreasing) function of the number of firms in a given location.

A number of aspects of the NEG framework distinguish it from most other approaches used to consider the PHE (including international oligopoly models).[22] First, agglomeration forces (which encourage firms to locate close together) can make otherwise mobile (footloose) factors of production considerably less willing to relocate in response to stricter regulation. Second, the

[19] See Jeppesen et al. (2002) for a review of 11 studies on the relationship between polluting plant location and environmental regulation.

[20] This thesis adopts an NEG model of the interregional factor mobility type.

[21] Motta and Thisse (1994) and Ulph (1994) also provide studies of firm location in response to exogenous environmental policies.

[22] See Fujita et al. (1999) and Baldwin et al. (2003) for extensive summaries of the unique properties of NEG models.

willingness to relocate as the level of trade costs increases is hump-shaped (with the willingness increasing in trade costs before eventually decreasing) rather than monotonically decreasing. Third, over some ranges of the parameter space, multiple equilibria are possible.[23]

There is emerging empirical evidence that agglomeration forces are important determinants of the extent of the PHE, which means that an NEG analysis of the PHE is likely to provide important insights. Ben Kheder and Zugravu (2008) suggest that agglomeration forces are statistically significant in determining the extent of firm relocation in response to environmental regulation. Giarratani et al. (2007) suggest that agglomeration forces play an important role in determining the location of investment in the U.S. steel industry.

Chapter 4 of this thesis is closest in content and purpose to Venables (1999), which is amongst the first NEG papers to consider the effect of environmental regulation on the location of polluting firms.[24] Venables (1999) adopts a VL model and draws two main conclusions. First, unilateral changes in environmental regulation can cause highly non-linear and even catastrophic relocation of firms.[25] Second, agglomeration forces can give rise to multiple equilibria for certain parameter combinations, making the effects of a policy change which shifts industry location from one equilibrium to another difficult to reverse.

The model in this thesis yields both conclusions of Venables (1999) and extends his analysis in two important directions. First, assumptions are altered in order to make them more applicable to the context of regulating GHGs. Second, the model is more analytically tractable, yielding important results additional to those in Venables' paper.

A second paper which also considers exogenous environmental regulation in an NEG model is Ishikawa and Okubo (2009). The authors compare taxes and permits for the regulation of GHGs in the 'footloose capital' (FC) model of Martin and Rogers (1995). The FC model is a more tractable model than the VL model of Venables (1999). Use of the FC model allows the authors to analytically compare taxes with permits for the purposes of regulating GHGs, however much of the richness of the NEG framework is lost. The FC model features neither of Venables' (1999) key results, namely, irreversibility of the effect of policy changes and potentially catastrophic relocation of industry in response to policy changes.[26] As both the speed and irreversibility of

[23] Multiple equilibria arise because agglomeration forces depend on the number of co-locating firms but not on where the co-location actually occurs.

[24] Another paper, Neary (2006), adopts a more general version of the model adopted in Venables (1999) and produces similar results.

[25] This generalises the main prediction of Markusen et al. (1993) to an NEG framework.

[26] See Baldwin et al. (2003, Chapter 5) for a summary of the properties of the FC model adopted in Ishikawa and Obuko (2009).

industry relocation are critical policy issues, the FC model is too simple to yield many of the results of this thesis which are most relevant for policy makers.

2.2 Carbon leakage

The contribution of this thesis to the theory of carbon leakage is its consideration of the relationship between differentiated environmental regulation and carbon leakage in a theoretical model with agglomeration forces. In this section I survey the literature on carbon leakage with the aim of highlighting three important themes in the literature. First, firm relocation is an important channel of carbon leakage which may not have been adequately addressed. Second, there currently exists no model featuring agglomeration forces which considers the extent of carbon leakage as the tax differential between regions changes. Third, empirical analysis of carbon leakage is difficult to undertake at present for a variety of reasons. These three observations, combined with the literature in section 2.1 which suggests that agglomeration forces are likely to characterise polluting industries, indicate that the analysis undertaken in Chapter 5 of this thesis on carbon leakage is likely to be a worthwhile endeavour.

Computable general equilibrium (CGE) literature Most of the economic literature on carbon leakage has adopted multi-region, multi-sector CGE models, which almost exclusively assume perfect competition and constant returns to scale.[27] Most (or all) of the leakage in perfectly competitive CRS models occurs through changes in factor prices rather than through firm relocation.[28]

One exception is Babiker (2005), which adopts a CGE model with imperfectly competitive markets and free entry and exit of firms. Babiker (2005) suggests that earlier perfectly competitive CRS models are likely to understate the degree of leakage because they fail to consider the impact of firm relocation.[29] This thesis sets out conditions under which firm relocation may play a large role in determining the extent of carbon leakage.

[27] Examples include OECD (1992), Felder and Rutherford (1993), Weyant (1999) and Burniaux and Martins (2000).

[28] This is discussed in Babiker (2005). In his paper he states: 'Given the restrictive nature of the modeling assumptions, the scope for leakage tends to be quite limited in these (perfectly competitive CRS) models.'

[29] When calibrated to consider regulation levels agreed under the Kyoto Protocol, perfectly competitive CRS CGE models have predicted carbon leakage rates in the range of 5%-25%. Babiker shows that accounting for IRS and imperfect competition increases predictions of the rate of carbon leakage to as high as 130%.

Theoretical literature Markusen (1975) is amongst the earliest papers to consider transboundary pollution in an economic model. The welfare maximising policy of a large country which can influence the level of foreign pollution, requires a Pigouvian tax on domestic polluting output (equal to marginal environmental damage) and an import tariff. The optimal tariff reflects both the terms of trade motive of a large exporter exercising market power and the negative externality caused by foreign pollution. Markusen does not explicitly consider the level of pollution leakage as a consequence of the optimal policy, however the large country takes it into account in setting policy.

Hoel (2001) considers the use of import and export tariffs to prevent carbon leakage in a model with many sectors. The model assumes CRS and perfect competition in each sector, in addition to the ratification of an IEA which mandates a differentiated reduction in emissions across two regions. The optimal policy, if environmental policy is the only instrument available, is to vary the level of the pollution tax across sectors.[30] If trade policy is also available, the tax rate is optimally equalised across sectors but is supplemented by an import/export tariff based on how the import/export of the good affects the level of foreign emissions.

Neither Markusen (1975) nor Hoel (2001) allow for increasing returns to scale and firm relocation. Ulph (1994) (who adopts a similar model to Markusen et al. (1993)) is amongst the first to consider how the extent of pollution leakage responds to the regulation differential between regions. By calibrating his model to the fertilizer industry, Ulph draws a similar conclusion to Babiker (2005), finding that assumptions of IRS and imperfect competition tend to increase the level of carbon leakage relative to a scenario of CRS and perfect competition.

Ritz (2009) introduces a theoretical model to consider the interaction between market structure, carbon leakage and environmental regulation. Ritz finds that market structure is likely to be a critical determinant of the extent of carbon leakage.

Ishikawa and Okubo (2009) consider carbon leakage due to trade liberalisation under imperfect competition and IRS in a simple, tractable NEG model (the FC model). The authors show that a carbon emissions quota reduces the extent of carbon leakage more than an equivalent emissions tax.[31] The authors do not consider how the size of the differential in regulatory stringency between regions affects the relocation of polluting industry. Because the WTO restricts the

[30] The author does not find a simple relationship between the optimal tax rate and the pollution intensity of an industry.

[31] The tax is equivalent in the sense that it achieves the same level of domestic emissions as the quota prior to trade liberalisation.

extent to which trade freeness can be altered for environmental purposes, the tax differential is arguably a more important policy variable to consider.[32] This thesis considers carbon leakage resulting from both trade liberalisation and changes in the tax differential in this thesis.

Empirical literature I am not aware of any paper published in an economic journal which seeks to estimate the extent of carbon leakage empirically. I conjecture three main reasons for this lack of empirical work.[33] First, there are very few GHG regulatory regimes in operation from which to draw data. Second, those which are in operation, including the European Union Emissions Trading Scheme (EU-ETS), have not been operating long enough for the effects of differentiated regulation on firms' investment decisions to be observed. Third, an estimate of the level of carbon leakage requires estimation of the counter-factual: how much pollution would there have been, both domestically and in the non-regulating region, had there been no regulation?

[32] Article XX of the General Agreement on Tariffs and Trade (GATT) provides for environmentally motivated trade protection. However, the article has rarely been successfully invoked and it has never been invoked on grounds of reducing GHG emissions.

[33] In doing so I intend to demonstrate why a theoretical study of carbon leakage is a reasonable avenue of exploration.

3 THE GENERAL MODEL

This chapter develops a theoretical NEG model with pollution taxation. This chapter comprises two sections. In section 3.1 I outline the assumptions underlying the model. In section 3.2 I solve the model for its short-run equilibrium in which firm location is fixed. An analysis of the long-run equilibrium, in which firms are mobile, is deferred until Chapter 4.

3.1 Model assumptions

I adopt a variant of Krugman's (1991) CP model, namely the FE model of Forslid and Ottaviano (2003). Notation is kept as similar as possible to Baldwin et al. (2003, Chapter 4). In the FE model (as in the CP model), agglomeration is driven by labour mobility between regions, however, the FE model is more tractable, allowing analytical expressions for most of its important endogenous variables.

The economy consists of two regions: north and south. In the context of this thesis 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 tax policies and (ii) between which barriers to the free flow of unskilled labour exist.[34] In order to reduce notation in the analysis that follows, only expressions for northern variables are shown (but only to the extent that no generality is lost). Southern expressions are denoted with an asterisk.

The model is populated by two types of labour: (i) inter-regionally immobile unskilled workers and (ii) skilled workers who are inter-regionally mobile in the long-run.[35,36] Each worker (skilled or unskilled) produces one unit of labour. The quantity of unskilled workers in the north and south are equal to L and L^* respectively and the population of unskilled workers across both regions is denoted L^w. The total population of the mobile factor of production (skilled workers)

[34] Fujita, Krugman and Venables (1999, Chapter 14) provide evidence to suggest that labour mobility may be less important in generating agglomeration forces across national borders than some other causes (notably input-output linkages between firms such as those captured by VL models). Despite this, I adopt the FE model in order to simplify analysis. I appeal to the significant mathematical similarities between labour mobility models and VL models (see Robert-Nicoud (2005) for a summary of these) in order to generalise the findings of this thesis to situations in which vertical linkages are more likely to explain agglomeration forces.

[35] Empirical evidence on labour mobility by skill type is scarce. Shields and Shields (1989) and Lowell and Findlay (2001) are frequently cited papers which provide empirical support for the assumption that skilled workers tend to be more mobile inter-regionally than unskilled workers.

[36] An alternative interpretation, which recognises that capital is significantly more mobile internationally than labour, would be to consider the mobile factor to be capital. This requires a slightly unsatisfactory additional assumption that the return to capital must be spent where that capital is employed but it may be applicable in certain circumstances.

is equal to H^w and their geographic distribution between regions, represented by H and H^*, is determined endogenously as a consequence of movement to the region offering the highest indirect utility.

3.1.1 Demand side

Preferences of skilled and unskilled workers are identical and defined over two goods: horizontally differentiated manufactures and homogeneous agriculture. The utility function of a representative consumer over the two consumption goods is:

$$U = C_M^{\mu} C_A^{1-\mu} - f\left(\Gamma + \Gamma^*\right) \tag{1}$$

$$C_M = \left(\int_0^{n+n^*} c_i^{1-\frac{1}{\sigma}} di \right)^{\frac{1}{1-\frac{1}{\sigma}}} ; 0 < \mu < 1, \sigma > 1 \tag{2}$$

C_M and C_A denote consumption of manufactures and agricultural products, c_i denotes consumption of manufactures variety i, and n and n^* represent the mass of varieties of manufactures produced in the north and south respectively. μ is a preference parameter which, as a consequence of the Cobb-Douglas specification, is equal to the expenditure share spent on manufactures (similarly $(1-\mu)$ is agriculture's share of expenditure). The disutility of pollution is expressed as an increasing monotonic function of the level of transboundary pollution, $f\left(\Gamma + \Gamma^*\right)$, where Γ and Γ^* are the levels of pollution produced in the north and south respectively. σ denotes both the elasticity of demand for any particular variety and elasticity of substitution between any two varieties. σ also reflects the representative consumer's love of varieties; lower σ denotes a greater affinity for variety.

Allowing I to denote total income and p_i to denote the consumer price per unit of output of variety i of manufactures, a consumer's budget constraint is:

$$\int_0^{n+n^*} p_i c_i di + p_A C_A \leq I \tag{3}$$

Maximisation of (2) subject to (3) yields the following indirect utility functions for skilled and unskilled workers:

$$\begin{gathered}\omega = \eta \tfrac{w_H}{P}, \omega_L = \eta \tfrac{w_L}{P} \\ P \equiv p_A^{1-\mu} P_M^{\mu}, \eta = \mu^{\mu} (1-\mu)^{1-\mu}, P_M \equiv \left(\int_0^{n^w} p_i^{1-\sigma} di \right)^{\frac{1}{1-\sigma}} \end{gathered} \tag{4}$$

I assume that 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 and is true in the sense that it takes account of inter-commodity substitution as well as prices themselves. P_M is the manufactures price index. The parameter η can be set equal to one to reduce notation as it has a linear effect on utility.

3.1.2 Government

Each government ratifies an IEA which sets a tax rate on each unit of a transboundary pollutant generated in the production of manufactures. The tax rate is set equal to an exogenous constant t (t^* in the south) and, without loss of generality, it is assumed that $t \geq t^*$. This is the way in which responsibilities for controlling the transboundary pollutant can be differentiated in this model. Both t and t^* are assumed to be equal (potentially to zero) prior to ratifying the agreement.

Tax revenue does not enter consumer welfare. This assumption enables this thesis 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.[37]

I assume that the only policy instrument available to both regions is the IEA. In the current multilateral trading scheme an assumption of the absence of trade measures such as tariffs and subsidies used for environmental purposes appears to be a reasonable assumption.[38]

[37] 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 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.

[38] As discussed in Chapter 2, Article XX of the GATT provides exceptions to the sanction on protectionism for trade measures necessary to the protection of human, animal or plant life or health (ArtXX(b)) or relating to the conservation of exhaustible natural resources (Art XX(g)). However, such sanctions have rarely been invoked on environmental grounds.

3.1.3 Supply side

Agricultural products are produced in a perfectly competitive market with a CRS technology and unskilled labour is used exclusively in their production. The cost of producing each unit of output is therefore $a_A w_L$, where a_A denotes the unskilled labour input required to produce one unit of agriculture.

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. I assume that 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 can therefore be expressed as:

$$TC = w_H F + (w_L a_M + t\gamma)\, x \tag{5}$$

x is the output level. Equation (5) demonstrates the sense in which this is a model of environmental regulation rather than a more general model of taxation. Pollution can be treated as a variable factor of production, with the tax rate representing the factor price. This assumption arguably makes this model more realistic than previous NEG models of pollution regulation for a number of industries.[39]

Manufacturing firms face iceberg trade costs when selling to foreign consumers. It costs $\tau - 1$ units of manufactures to ship a unit of manufactures between regions.

3.2 Deriving the short-run equilibrium

In this section, a series of equations are derived, which define the model's equilibrium if skilled workers (and therefore firms) are immobile. I adopt Krugman's (1991) terminology and refer to this as the short-run equilibrium. 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.

[39] Both Venables (1999) and Elbers and Withagen (2004) assume firms are taxed proportionally to their total costs. For polluting industries in which a firm's pollution increases with the level of variable inputs (such as fuels, chemicals and electricity) used this may be an unrealistic assumption.

3.2.1 Agriculture

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

$$C_A = (1 - \mu)\,\frac{E}{p_A} \tag{6}$$

E is nominal expenditure in the north. The south has an analogous demand function.

Perfect competition in the agricultural market and the assumption that all pollution produced in the agricultural sector is not taxed ensures marginal cost pricing such that:[40]

$$\begin{aligned} p_A &= a_A w_L \\ p_A^* &= a_A w_L^* \end{aligned} \tag{7}$$

An assumption of zero trade costs for the agricultural product ensures $p_A = p_A^*$ and therefore $w_L = w_L^*$.[41,42] Treating agriculture as the numeraire good I set p_A equal to 1. Supply and demand for the agricultural product must match but I use Walras' law to drop this market clearing condition.

3.2.2 Manufacturing

By a full employment assumption, the total number of firms is equal to the number of skilled workers divided by the number of skilled workers required per firm to cover fixed costs:

$$n^w = \frac{H^w}{F} \tag{8}$$

As firms and workers are co-located, the number of firms in each region is proportional to the number of skilled workers in that region. Migration of skilled workers therefore occurs at the

[40] The assumption of no regulation in the agricultural sector is realistic when considering the regulation of GHGs. The EU-ETS and current proposal to regulate GHGs in Australia and the USA exempt the agricultural sector almost entirely.

[41] Free trade in the agricultural sector is clearly an assumption of convenience, however it is not a pivotal one. Fujita et al. (1999, Chapter 7) consider a CP model (which has virtually identical properties to the FE model) in which the agricultural sector has both IRS and transport costs and the predictions of the model are not altered significantly from the costless trade case.

[42] Technically unskilled wage equalisation also requires a non-full specialisation (NFS) condition to ensure that both regions are active in agricultural production. I assume that this condition holds for the remainder of this thesis.

same rate as relocation of firms. Utility maximisation yields the standard constant elasticity of substitution (CES) demand and inverse demand functions for variety j:

$$c_j = p_j^{-\sigma}\left(\frac{\mu E}{P_M^{1-\sigma}}\right) \tag{9}$$

$$E = w_H H + w_L L \tag{10}$$

$$p_j = \frac{c_j^{-\frac{1}{\sigma}}}{C^{1-\sigma}}\mu E,\ C = \left(\int_0^{n+n^*} {c_i}^{1-\frac{1}{\sigma}}\, di\right)^{\frac{1}{1-\sigma}} \tag{11}$$

Isomorphic demand and inverse demand functions exist for southern varieties. Three comments are in order here. First, expenditure in the north, E, is equal to the sum of skilled and unskilled worker income. Profits do not enter expenditure as free entry ensures that they are equal to zero. Second, varieties are differentiated, precluding direct strategic interaction between firms. This is a standard result in models of monopolistic competition. Third, the combination of a CES sub-utility function for manufactures and the assumption of an infinite number of atomistic firms precludes competition effects; each firm rationally ignores the impact of its price on $P_M^{1-\sigma}$.

The inverse demand function implies the following marginal revenue function for variety j:

$$MR = \left(1 - \frac{1}{\sigma}\right)p_j \tag{12}$$

The marginal cost of supplying domestic and foreign consumers is found by differentiating the manufacturing total cost function (5) with respect to x and adding any trade costs:

$$\begin{aligned} MC_d &= w_L a_m + t\gamma \\ MC_f &= \tau\left(w_L a_m + t\gamma\right) \end{aligned} \tag{13}$$

Equating marginal cost and marginal revenue yields four pricing equations, which reflect the price paid per unit of manufactures by consumers:

$$p_N = \frac{w_L a_M + t\gamma}{1-\frac{1}{\sigma}},\ p_S = \tau\frac{(w_L a_M + t\gamma)}{1-\frac{1}{\sigma}} = \tau p_N$$
$$p_S^* = \frac{w_L a_M + t^*\gamma}{1-\frac{1}{\sigma}},\ p_N^* = \tau\frac{(w_L a_M + t^*\gamma)}{1-\frac{1}{\sigma}} = \tau p_S^* \tag{14}$$

Superscripts reflect the location of production. Subscripts denote the location of consumption. For example, p_N^* is the price paid by northern consumers for one unit of a manufactures variety produced by a southern firm.

Firms optimally charge a fixed mark-up over their marginal cost of production in their domestic markets. This is reflected in Figure 1, the so-called Chamberlinian tangency condition. Fixed mark-up pricing is a standard result when consumers possess CES utility functions. All manufacturing firms act as monopolists facing a demand curve for their variety with elasticity equal to σ.

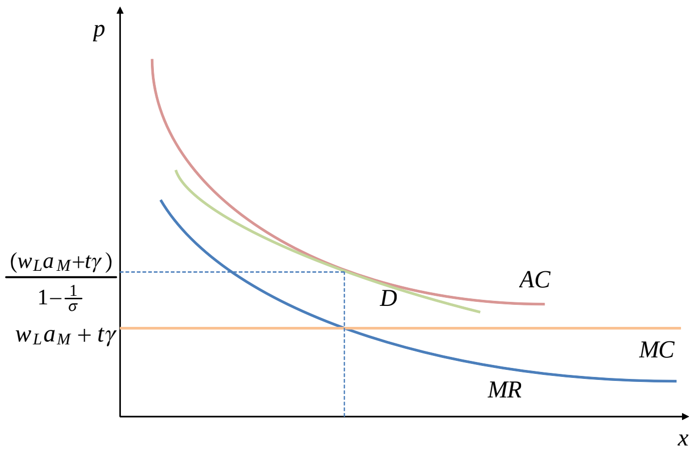

Figure 1: The fixed mark-up condition

As equation (14) makes explicit, the combination of fixed mark-up pricing and iceberg trade costs implies that firms undertake ‘mill pricing’; that is, they charge consumers in the foreign market the domestic price plus trade costs. Mill pricing implies that producers receive the same price per unit sold regardless of whether they sell to the domestic or the foreign market.

Differentiated pollution taxation causes the price of both domestic and imported varieties to differ between regions by altering the variable cost of production. Firms in the region imposing the higher pollution tax are subject to a larger variable cost of production and consequently optimally charge higher domestic and export prices.

Firm size can be ignored in establishing the equilibrium properties of the system, however, it is important for the analysis of carbon leakage undertaken in Chapter 5. As a consequence, I digress briefly to derive the firm size conditions.

Skilled labour is used only and exclusively as a fixed input for manufactures and free entry ensures firms make zero pure profit. This implies that all operating profits accrue to the skilled workers of each firm. In the north this can be expressed as $w_H F = \pi$ where π is the operating profit.

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:

$$\pi_j = \frac{p_N x_j}{\sigma} = \frac{w_L a_M + t\gamma}{\sigma - 1} x_j \tag{15}$$

Combining these two conditions and removing the subscript implies the following firm output levels in the north and the south:

$$\begin{aligned} x &= w_H F \tfrac{\sigma-1}{w_L a_M + t\gamma} \\ x^* &= w_H^* F \tfrac{\sigma-1}{w_L a_M + t^*\gamma} \end{aligned} \tag{16}$$

The non-homothetic cost function ensures that firm size is a function of the ratio of fixed to variable input prices. In particular, firm size is decreasing in both the unskilled workers' wage and the cost of polluting and is increasing in the skilled workers' wage. In order to earn the operating profit required to pay higher skilled worker wages, firms must sell more output, while a high unskilled wage increases variable costs and discourages production.

The pollution tax affects firm size through two channels. First, through its effect on the variable cost of producing manufactures. Second, through its effect on the skilled wage. These channels are considered at greater length in Chapter 5.

The firm size obtained in equation 16 contrasts with that in Venables (1999) and Elbers and Withagen (2004) which adopt a homothetic cost function (in which the same factor is used as both a fixed and a variable input) and assume environmental taxation is ad valorem on total costs. In their models, the firm does not respond to tax rate changes by expansion or contraction because the tax rate does not change the ratio of fixed to variable costs.

Next I derive equilibrium skilled wages. This requires the introduction of the market clearing condition to close the model. I define the market clearing condition for manufactures varieties in terms of value as opposed to quantities, however, either could be used. Specifically, market clearance implies that the value of production at producer prices is equal to the value of consumption at consumer prices:

$$p_N x_j = p_N c_{j,N} + p_S c_{j,S} \tag{17}$$

The LHS term is equal to the value of output at northern prices for the firm producing variety j in the north. The RHS is equal to the value of consumption of variety j in both regions at consumer prices. An isomorphic condition is required for southern firms.

Utilising the market clearing condition, nominal skilled wages can be expressed as a function of exogenous variables and the distribution of skilled workers. Combining expressions for skilled wages ($w_H = \frac{\pi}{F}$), operating profit ($\pi = \frac{p_N x}{\sigma}$) and the market clearing condition (equation (17)), then substituting in equations (9), (10) and (14) yields the following (nominal) skilled wage in each region:

$$\begin{aligned} w_H &= bB\tfrac{E^w}{n^w} \\ w_H^* &= brB^*\tfrac{E^w}{n^w} \end{aligned} \tag{18}$$

where:

$$\begin{gathered} b = \tfrac{\mu}{\sigma}, \phi = \tau^{1-\sigma}, B = \left[\left(\tfrac{s_E}{\theta}\right) + \phi\left(\tfrac{1-s_E}{\theta^*}\right)\right], B^* = \left[\phi\left(\tfrac{s_E}{\theta}\right) + \left(\tfrac{1-s_E}{\theta^*}\right)\right], \\ \theta \equiv s_n + \phi\left(1-s_n\right) r = \tfrac{P_M^{1-\sigma}}{p_N^{1-\sigma} n^w}, \theta^* = \left(1-s_n\right) r + \phi s_n = \tfrac{{P_M^*}^{1-\sigma}}{p_N^{1-\sigma} n^w}, \\ E^w = E + E^*, n^w = n + n^*, r = \left[\tfrac{w_L a_M + t\gamma}{w_L a_M + t^*\gamma}\right]^{\sigma-1} \geq 1 \end{gathered} \tag{19}$$

Steps taken in the derivation of this expression are in Appendix 3.3. These expressions (the 'wage equations') are crucial in determining the long-run location of firms and require some explanation.

There are a number of new terms in these wage equations. r, which I refer to henceforth as the 'tax differential', is a critical parameter for the analysis that follows. r is a linear transformation of the ratio of (tax inclusive) variable costs.[43] Interestingly, taxes only appear in the expressions for nominal wages through their effect on r. This result 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 critical 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 world expenditure. b is a bundling term for exogenous preferences which combines expenditure on manufactures (μ) and consumers' love of variety (σ). Clearly, b is higher for a larger expenditure share on manufactures (μ) and for a greater love of variety by consumers (low σ). The nominal skilled wage is increasing in b. B and rB^* are bias terms in the sense that $s_n B + (1 - s_n) rB^* = 1$.

3.2.3 Channels through which environmental regulation affects nominal wages

Analysis of B and rB^* illustrates the two forces (one being a centripetal or agglomeration force and the other, a centrifugal or dispersion force) in the model which operate through the nominal wage. These are a local competition effect and a market size effect.[44] On the one hand, greater domestic concentration of firms increases competition in the domestic market, reducing each domestic firm's market share and encouraging firms to relocate to the less competitive foreign market. This is the local competition effect and it is the model's only dispersion force. On the other hand, those regions with more firms have more skilled workers and therefore tend to have larger expenditure. This encourages firms to co-locate in order to maximise the size of the market they can service domestically without having to meet trade costs. This is the market size effect. The existence of these two opposing forces is well documented in the NEG literature, however, the introduction of a pollution tax alters the relative magnitude, and potentially the direction, of these forces.

The two forces are non-linear and do not operate in isolation. However, the thought experiments

[43] As a consequence of fixed mark-up and mill pricing, r can equally be considered to be the same linear transformation of p_S/p_N^* or p_N/p_S^*.

[44] The third force, a cost of living effect, operates through the real wage and is examined in Chapter 4 once factor migration is introduced into the model.

below provide intuition as to how each works and of their relative sizes.

Effect 1: Local competition effect To investigate the local competition effect, hypothesize a situation in which both regions have equal expenditure ($s_E = \frac{1}{2}$) and both have an equal number of firms ($s_n = \frac{1}{2}$).[45] In order to abstract from any cost of living effects on migration decisions, assume also that workers make migration decisions on the basis of nominal (rather than real) wages. Now consider the effect of a small migration of skilled workers (and therefore firms) from the north to the south (represented by a small decrease in s_n) while assuming market size, s_E, is fixed (for example by assuming that the wages of the migrating skilled workers are remitted back to the north) and that skilled wages are fixed for those relocating firms. I make the latter two assumptions in order to abstract from any expenditure shifting effects, thereby focussing purely on competition effects of the movement of skilled workers and firms.

θ^* (which reflects the degree of competition in the south) unambiguously increases ($-\frac{\delta\theta^*}{\delta s_n} = r - \phi \geq 0$), while θ (which reflects the degree of competition in the north) either increases (if $\phi r > 1$) or decreases (if $\phi r < 1$) as $-\frac{\delta\theta}{\delta s_n} = r\phi - 1$. The increase in θ^* is of a greater magnitude than any decrease in θ (as $r - \phi > r\phi - 1$). This implies that the effect of the relocation of skilled workers is to reduce southern nominal skilled wages, while having an ambiguous effect on northern nominal wages (see equation (18)). This result can be further decomposed into two composition effects which illustrate the effect of the tax.

The first effect, which I call the 'trade composition effect', is well established in the literature and arises because of the existence of positive trade costs (it occurs in the absence of pollution taxation). To examine this effect I further assume that taxation is equalised across regions ($r = 1$) to abstract from the cost composition effect described below. Firms in the north must cover both trade costs and production costs when they sell to the south. When $\phi < 1$, moving a firm from the north to the south decreases the southern manufactures price index (increases ${P_M^*}^{1-\sigma}$) and increases the northern manufactures price index (decreases $P_M^{1-\sigma}$). Higher ${P_M^*}^{1-\sigma}$ with constant southern expenditure (E^*) implies that firms in the south will each sell less (see equation (9)) and therefore earn less operating profit. In order to break even, southern firms must decrease nominal wages for skilled workers, which makes the south relatively less attractive and the north relatively more attractive for skilled workers.

[45] As will be demonstrated, this can never be a long-run equilibrium when $t \neq t^*$ and $\phi > 0$. For the purposes of this thought experiment the assumptions help as symmetry ensures several terms cancel.

The trade composition effect has an equal effect for a migration of skilled workers in both directions and its strength is decreasing in the freeness of trade. When $\phi = 1$ there is no trade composition effect.

The second effect, which I call the 'cost composition effect', is a consequence of a difference in the variable cost of production across regions which results from differentiated pollution tax rates. To isolate this effect, now assume a tax differential exists ($r > 1$) and there are no trade costs ($\phi = 1$). When firms move from north to south they have lower (tax inclusive) production costs and therefore optimally charge lower prices and sell more output (see equation (16) and recall that skilled wages of those relocating firms are assumed fixed). As trade is free, the presence of more firms in the south tends to decrease both northern and southern manufactures price indices (increasing both $P_M^{1-\sigma}$ and $P_M^{*1-\sigma}$). Assuming constant expenditure in both regions, the north to south migration thus causes all firms to sell less output and earn less operating profit. All firms must now pay lower skilled wages in order to break even.

The cost composition effect operates in only one direction and is a cause of asymmetry in the model. Firm migration from the high taxing north to the low taxing south increases competition for all firms, regardless of location, through the cost composition effect. Alternatively, firm migration from the low taxing south to the high taxing north, decreases competition for firms in both regions as the relocating firms pay a higher pollution tax, charge higher prices and are thus less competitive. The strength of the cost composition effect is increasing in r. When $r = 1$, pollution taxes are equalised and there is no cost composition effect.

Effect 2: Market size effect (demand-linked circular causality) Firms with a large domestic market have an advantage over firms with a small domestic market due to the transport costs involved with servicing customers in foreign markets. This results in an agglomeration force associated with greater concentration of firms and skilled workers (and therefore expenditure) in one region. To gain intuition into the effect of a change in the size of the domestic market, consider again an equal distribution of skilled labour and expenditure between regions. By moving a small amount of expenditure from the south to the north (an increase in s_E) and holding worker location fixed B increases and B^* decreases. Specifically, taking the derivative of B with respect to s_E, evaluating it assuming skilled labour and expenditure are equally distributed across regions, and holding s_n fixed, yields $\frac{dB}{ds_E} = \frac{r\left(1-\phi^2\right)}{(1+r\phi)(r+\phi)}$. $\frac{dB}{ds_E}$ is positive for $\phi < 1$. Similarly $\frac{dB^*}{ds_E} = \frac{\left(\phi^2-1\right)}{(1+r\phi)(r+\phi)}$, which is negative for $\phi < 1$. Increasing the size of a region while holding firm location constant therefore makes that region relatively more attractive to skilled workers.

3.2.4 Spatial distribution of expenditure

The final short-run endogenous variable required to derive the long-run equilibrium location of firms is the share of expenditure in the north, s_E. To simplify notation, I select units of skilled labour such that $F = 1$. One fortunate consequence of the combination of fixed mark-up and mill pricing is the ability to express operating profit for all manufacturing firms as a constant margin $\frac{1}{\sigma}$ 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[46]:

$$E^w = \frac{w_L L^w}{1-b} \tag{20}$$

E^w is the denominator for the expenditure shares in both the north and the south, s_E and $(1 - s_E)$ respectively. The numerators are $E = w_L L + w_H H$ and $E^* = w_L L^* + w_H^* H^*$ respectively. Combining numerator and denominator, northern and southern shares of expenditure are:

$$\begin{gathered} s_E = (1-b)\, S_L + bBs_H,\ s_L \equiv \tfrac{L}{L^w},\ s_H \equiv \tfrac{H}{H^w} = s_n \\ (1-s_E) = (1-b)\,(1-S_L) + brB^*\,(1-s_H) \end{gathered} \tag{21}$$

Equation (21) demonstrates the relationship between production shifting and expenditure shifting which drives the market size agglomeration force in this model. When a skilled worker moves, she takes her expenditure with her, increasing the size of her new market and decreasing the size of the market she has left. If this move makes firms in her new market more profitable, other firms will follow, which will ultimately lead to an agglomeration of firms in one region.[47]

Rearranging (21), substituting in (18) and, for simplicity, assuming a symmetric distribution of

[46] To see this note that: $w_H H + w_H^* H^* = H^w \left[bB \frac{E^w}{n^w} s_n + brB^* \frac{E^w}{n^w} (1-s_n) \right] = bE^w$ as $Bs_n + rB^*(1-s_n) = 1$ and $n^w = H^w$.

[47] This is also a significant point of departure from Ishikawa and Okubo (2009). In their model, all mobile factor earnings are remitted to the factor's initial region and as a consequence, production shifting does not lead to expenditure shifting, eliminating the circular causality which causes catastrophic agglomeration and multiple equilibria in the model in this thesis.

unskilled labour between regions ($L = L^*$) enables expression of the distribution of expenditure as a function of the distribution of skilled workers:

$$s_E = \left[\frac{\frac{(1-b)}{2} + b\phi\frac{1}{\theta^*}s_H}{1 - b\frac{1}{\theta}s_H + b\phi\frac{1}{\theta^*}s_H} \right] \tag{22}$$

Derivations of (21) and (22) are in Appendix 3.4.

Equation (22) has two properties which assist with analysis in the following chapter. First, $s_E|_{s_H=0} = \frac{1-b}{2}$ and $s_E|_{s_H=1} = \frac{1+b}{2}$ for all r. If a region has no (all) skilled workers it has an expenditure share equal to $\frac{1-b}{2}$ $(\frac{1+b}{2})$. The second property is stated in Proposition (1).

Proposition 1 *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* $\frac{\delta s_E}{\delta r} = 0$

Proof. See Appendix 3.5. ■

Proposition 1 implies 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 ($1 - s_E$). To illustrate Proposition 1, Figure 2 plots s_H on the vertical axis and s_E on the horizontal axis for various values of r.

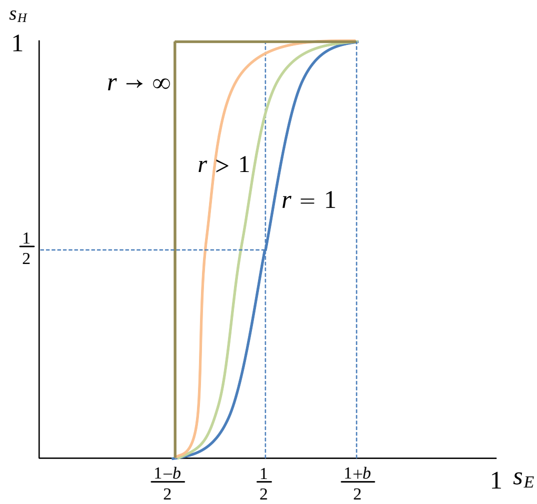

Figure 2: Expenditure share as a function of skilled population share

The short-run equilibrium number of firms, prices, nominal wages and distribution of expenditure, were all established as functions of the distribution of skilled workers in this chapter (see equations (8), (14), (18) and (22)). Building on this, in order to consider the first key question of this thesis (*How does the degree of differentiation of environmental policy influence the extent of firm relocation?*), Chapter 4 analyses a situation in which skilled workers (and firms) are mobile between regions.

3.3 Appendix 1: Derivation of nominal skilled wages (equation (18))

Combining the expression for firm profit obtained in equation (15) with the market clearing condition in equation 17 enables derivation of an expression for the profit of the northern firm which produces a typical variety j, as a function of consumption in the north and the south ($c_{j,N}$ and $c_{j,S}$ respectively) and consumer prices ($p_{j,N}$ and $p_{j,S}$).

$$\pi_j = \frac{1}{\sigma}\left[c_{j,N}p_{j,N} + c_{j,S}p_{j,S}\right] \tag{23}$$

Inverse demand functions for variety j in north and south respectively are:

$$c_{j,N} = p_{j,N}^{-\sigma}\left(\frac{\mu E}{P_M^{1-\sigma}}\right) \text{ and } c_{j,S} = p_{j,S}^{-\sigma}\left(\frac{\mu E^*}{P_M^{*\,1-\sigma}}\right) \tag{24}$$

Substituting these inverse demand functions into the market clearing conditions yields:

$$\pi = \frac{\mu}{\sigma}p_N^{1-\sigma}\left[\left(\frac{E}{P_M^{1-\sigma}}\right) + \phi\left(\frac{E^*}{P_M^{*\,1-\sigma}}\right)\right] \tag{25}$$

Dividing the numerator and denominator by the total number of firms, n^w, yields:

$$\pi = \frac{\mu}{\sigma}p_N^{1-\sigma}\left[\left(\frac{s_E}{\frac{P_M^{1-\sigma}}{n^w}}\right) + \phi\left(\frac{1-s_E}{\frac{P_M^{*\,1-\sigma}}{n^w}}\right)\right]\frac{E^w}{n^w} \tag{26}$$

s_E is the northern share of E^w, the total expenditure by both regions combined.

Expanding the denominators inside the square brackets yields:

$$\pi = \frac{\mu}{\sigma} p_N^{1-\sigma} \left[\left(\frac{s_E}{s_n p_N^{1-\sigma} + \phi \left(1 - s_n\right) p_S^{*1-\sigma}} \right) + \phi \left(\frac{1 - s_E}{\left(1 - s_n\right) p_S^{*1-\sigma} + \phi s_n p_N^{1-\sigma}} \right) \right] \frac{E^w}{n^w} \tag{27}$$

Simplification yields:

$$\pi = \frac{\mu}{\sigma} \left(w_L a_M + t\gamma\right)^{1-\sigma} \left[\begin{array}{c} \left(\frac{s_E}{s_n (w_L a_M + t\gamma)^{1-\sigma} + \phi (1-s_n)(w_L a_M + t^*\gamma)^{1-\sigma}} \right) \\ + \phi \left(\frac{1-s_E}{(1-s_n)(w_L a_M + t^*\gamma)^{1-\sigma} + \phi s_n (w_L a_M + t\gamma)^{1-\sigma}} \right) \end{array} \right] \frac{E^w}{n^w} \tag{28}$$

Simplification yields:

$$\pi = \frac{\mu}{\sigma} \left[\left(\frac{s_E}{s_n + \phi \left(1 - s_n\right) \left[\frac{w_L a_M + t^*\gamma}{w_L a_M + t\gamma} \right]^{1-\sigma}} \right) + \phi \left(\frac{1 - s_E}{\left(1 - s_n\right) \left[\frac{w_L a_M + t^*\gamma}{w_L a_M + t\gamma} \right]^{1-\sigma} + \phi s_n} \right) \right] \frac{E^w}{n^w} \tag{29}$$

Which can be expressed as:

$$\pi = bB \frac{E^w}{n^w}, \tag{30}$$

with:

$$\begin{gathered} b = \tfrac{\mu}{\sigma}, B = \left[\left(\tfrac{s_E}{\theta} \right) + \phi \left(\tfrac{1-s_E}{\theta^*} \right) \right], \\ \theta \equiv s_n + \phi \left(1 - s_n\right) r, \theta^* = \left(1 - s_n\right) r + \phi s_n, r = \left[\tfrac{w_L a_M + t^*\gamma}{w_L a_M + t\gamma} \right]^{1-\sigma} \end{gathered} \tag{31}$$

For southern firm profits, following identical steps to those above yields:

$$\pi^* = brB^* \frac{E^w}{n^w}, \tag{32}$$

with:

$$B^* = \left[\phi\left(\frac{s_E}{\theta}\right) + \left(\frac{1-s_E}{\theta^*}\right)\right] \tag{33}$$

3.4 Appendix 2: Derivation of expenditure shares

Begin with the definition of north's expenditure share, s_E:

$$s_E = \frac{E}{E^w} \tag{34}$$

Substitute in $E = w_L L + w_H H$ and $E^w = \frac{w_L L^w}{1-b}$:

$$s_E = \frac{w_L L + w_H H}{\frac{w_L L^w}{1-b}} \tag{35}$$

Substitute in skilled wages w_H:

$$s_E = (1-b)\, S_L + \frac{w_H H\,(1-b)}{w_L L^w}, s_L \equiv \frac{L}{L^w} \tag{36}$$

Expand and simplify:

$$s_E = (1-b)\,S_L + bBs_H, s_H \equiv \frac{H}{H^w} \tag{37}$$

Substitute in B:

$$s_E = (1-b)\,S_L + b\left[\frac{s_E}{\theta} + \phi\frac{1-s_E}{\theta^*}\right]s_H \tag{38}$$

Set $s_L = \frac{1}{2}$ and rearrange so that s_E is on the RHS:

$$s_E = \frac{\frac{(1-b)}{2} + b\phi\frac{1}{\theta^*}s_H}{\left[1 - b\left(\frac{1}{\theta} - \phi\frac{1}{\theta^*}\right)s_H\right]} \tag{39}$$

3.5 Appendix 3: Proof of Proposition 1.

The north's expenditure share can be expressed as:

$$s_E = \left[\frac{\frac{(1-b)}{2} + b\phi\frac{1}{\theta^*}s_H}{1 - b\frac{1}{\theta}s_H + b\phi\frac{1}{\theta^*}s_H}\right] \tag{40}$$

As $s_E \leq 1$ by definition:

$$\frac{(1-b)}{2} + b\phi\frac{1}{\theta^*}s_H \leq 1 - b\frac{1}{\theta}s_H + b\phi\frac{1}{\theta^*}s_H \tag{41}$$

Final terms in LHS and RHS are equal, $\frac{\partial\theta}{\partial r} > 0$ and $\frac{\partial\theta^*}{\partial r} > 0$. Therefore:

$$\frac{\partial\left[\frac{(1-b)}{2} + b\phi\frac{1}{\theta^*}s_H\right]}{\partial r} < \frac{\partial\left[1 - b\frac{1}{\theta}s_H + b\phi\frac{1}{\theta^*}s_H\right]}{\partial r} \tag{42}$$

The numerator is less than the denominator in equation (40) and I showed in equation (42) that the numerator declines in r faster than the denominator. The result follows.

4 ENVIRONMENTAL POLICY AND FIRM RELOCATION

The climate change agenda won't affect the amount of steel consumed, but it will determine where it's produced.

Ian Rodgers, director of UK Steel

Guardian Newspaper, 11 March 2010

4.1 Introduction

This chapter asks the first key question of this thesis: *How does the degree of differentiation of environmental policy influence the extent of firm relocation?* To address this I allow skilled workers (and therefore firms) to move freely between regions. I assume that both regions ratify an IEA which fixes the levels of t and t^* in the long-run, altering them from an initial level of zero.

In section 4.2 I make a number of normalisations to avoid unnecessary notation and to improve focus on the critical exogenous parameters of the analysis, r and ϕ. Section 4.3 defines the concepts of equilibrium and stability used in the remainder of this thesis. Section 4.4 considers the first (and simplest) of three tax scenarios, a base case in which tax rates are equal to zero in both regions ($t = t^* = 0$). Section 4.5 evaluates a scenario in which tax rates are positive but equal ($t = t^* > 0$). Section 4.6 considers the most general case; one in which output taxes are both weakly positive and differentiated ($t > t^* \geq 0$). Section 4.7 concludes the chapter.

4.2 Normalisations

Several normalisations are made in order to reduce notation. This allows a sharper focus on the two parameters of primary interest, r and ϕ. A consequence of this simplification is an inability to undertake comparative static analysis on those exogenous parameters which I normalise.

I select units of agricultural output such that $a_A = 1$. With free trade of the agricultural commodity, perfect competition in production and the assumption that $p_A = 1$, unskilled wages in both regions are equal to 1.

In the manufacturing sector, units of output are selected such that $a_M = 1$ and units of pollution are selected such that $\gamma = 1$. These two assumptions imply that prices can be expressed as:

$$\begin{array}{c} p_N = \frac{1+t}{1-\frac{1}{\sigma}},\ p_S = \tau\frac{1+t}{1-\frac{1}{\sigma}}, \\ p_S^* = \frac{1+t^*}{1-\frac{1}{\sigma}},\ p_N^* = \tau\frac{1+t^*}{1-\frac{1}{\sigma}}, \end{array} \tag{43}$$

The total number of skilled workers is set equal to one ($H^w = H + H^* = 1$), which implies that $n^w = n + n^* = 1$. This normalisation ensures the equivalence of skilled labour shares and skilled labour populations: $n = H = s_n = s_H$ and $n^* = H^* = 1 - s_n = s_H^*$. 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 ($E = \frac{E}{E^w} = s_E$ and $E^* = \frac{E^*}{E^w} = 1 - s_E$).

Given the equivalence of n, s_n, H and s_H after normalisation, in what follows, I simplify notation by using s_n to represent all four terms, but only in cases where the simplicity obtained outweighs the minor ambiguity caused.

4.3 Real wages, equilibrium and stability conditions

4.3.1 Deriving real wages

Real wages determine the migration of skilled labour in the model. For convenience, I restate the real skilled wages from (4) after accounting for normalisations:

$$\begin{array}{c} \omega = \eta\frac{w_H}{P},\ P \equiv P_M^{\mu}, P_M \equiv \left(\int_0^{n^w} p_i^{1-\sigma} di\right)^{\frac{1}{1-\sigma}} = p_N\left[s_n + (1-s_n)\,\phi r\right]^{\frac{1}{1-\sigma}} \\ \omega^* = \eta\frac{w_H^*}{P^*},\ P^* \equiv P_M^{*\mu}, P_M^* \equiv \left(\int_0^{n^w} p_i^{*1-\sigma} di\right)^{\frac{1}{1-\sigma}} = p_N\left[\phi s_n + (1-s_n)\,r\right]^{\frac{1}{1-\sigma}} \end{array} \tag{44}$$

This representation of real wages gives intuition for the third force in the model, the cost of living effect or 'cost linked' circular causality. Like the market crowding effect, with pollution taxation, the cost of living effect comprises a trade composition and a cost composition effect.

The trade composition effect arises because the price index tends to be lower when many varieties can be sourced domestically, avoiding the relatively high prices associated with imported varieties. To assist intuition, consider a case in which pollution taxes are equalised across regions

($r = 1$) and therefore that production costs are also equalised. Consider a small increase in s_n, the share of firms located in the north. This change decreases the true cost of living index for the north, P, which tends to increase the indirect utility from living in the north. Similarly, a movement of firms from the north to the south (a decrease in s_n) decreases the southern price index and tends to increase southern indirect utility. This is thus a symmetric force, with equivalent effects for migration in both directions, which encourages greater concentration of manufacturing firms.

The cost composition effect arises under differentiated taxes as a consequence of a production cost advantage in the lower taxing region. With fixed mark-up pricing, varieties produced in the low taxing south are cheaper than those produced in the north. Relocation of firms to the south therefore tends to decrease the price indices in both regions. To provide some intuition, assume trade is perfectly free in order to eliminate the trade composition effect ($\phi = 1$) and that taxes are differentiated ($r > 1$). A small increase in the number of firms in the south clearly decreases the true cost of living index in both regions, while an increase in the number of firms in the north increases the true cost of living index in both regions.

Combining the two composition effects, an increase in the share of firms in the south will unambiguously reduce the true cost of living index in the south and will increase (decrease) the true cost of living index in the north if $\phi r < 1$ ($\phi r > 1$). Similarly, an increase in the share of firms in the north will unambiguously increase the true cost of living index in the south and will decrease (increase) the true cost of living index in the north if $\phi r < 1$ ($\phi r > 1$).

4.3.2 Equilibrium and stability conditions

Skilled workers move to the region offering the highest real wage.[48] The dynamics between equilibria are not explicitly considered in this thesis and, as a consequence, the precise nature of the adjustment process is not material. I follow convention and assume the standard but ad-hoc migration equation:[49]

$$\dot{s}_H = (\omega - \omega^*)\, s_H\, (1 - s_H) \tag{45}$$

[48] Equivalently, they move to the region which grants them the highest indirect utility.

[49] Although the use of this function fails to take account of forward looking expectations, it has received some support through the concept of replicator dynamics in evolutionary game theory.

$\dot{s}_H$ 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 there is no movement between regions according to the law of motion defined in equation (45). Equation (45) implies that there are two types of equilibrium. The first type is a diversified equilibrium. Such an equilibrium occurs when real wages are equalised across regions ($\omega = \omega^*$) and neither region hosts all skilled workers ($0 < s_H < 1$). The second type is a core-periphery (CP) equilibrium. Such an equilibrium occurs when all skilled workers are located in one of the two regions. There are two candidates for such an equilibrium: the core-in-the-north (CPN) equilibrium in which all skilled workers (and firms) are located in the north ($s_H = s_n = 1$) and the core-in-the-south (CPS) equilibrium in which all skilled workers are located in the south ($s_H = s_n = 0$).

The definition of equilibrium provided by the law of motion for skilled workers (45) is unsatisfactory in the sense that equilibrium occurs when all skilled workers are in one region, for example the north, and the other region, the south, offers a higher real wage for any worker who migrates. Rather than altering the law of motion, which has become the standard for migration based NEG models, I add a stability condition to reduce the number of potential equilibria to those which survive a small perturbation in s_H; those equilibria for which a slight 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. I assume that only those equilibria which are stable could reflect long-run configurations on industry.

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

$$\begin{aligned} \tfrac{d(\omega-\omega^*)}{ds_H} &< 0 \text{ if } (0 < s_H < 1) \\ \omega &> \omega^* \text{ if } s_H = 1 \\ \omega &< \omega^* \text{ if } s_H = 0 \end{aligned} \tag{46}$$

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, $\omega - \omega^*$.[50] Substituting expressions for nominal wages (equation (18)) and the true cost of living indices into the real wage equations (44) and taking the log yields Ω as a function of the distribution of skilled workers and exogenous model parameters.[51]

[50] This is a consequence of the non-integer powers in the real wage equations.
[51] The price index ratio is derived in Appendix 4.8.

$$\Omega = \log\left(\frac{\theta^* s_E + \phi\theta\,(1 - s_E)}{r\,[\phi\theta^* s_E + \theta\,(1 - s_E)]}\right) + a\log\left(\frac{\theta}{\theta^*}\right), a = \frac{\mu}{\sigma - 1} \tag{47}$$

Clearly, the real wage is higher in the north (south) for $\Omega > 0$ ($\Omega < 0$).

Having established the basis on which equilibrium and stability are to be evaluated, I apply these definitions to three tax scenarios of increasing generality in Sections 4.4, 4.5 and 4.6 in order to derive the effect of the pollution tax rates on firm location.

4.4 Case 1: No taxation (base case)

A consequence of the assumption of zero taxation is the elimination of both the local competition and cost of living cost composition effects. The elimination of these asymmetric effects ensures the symmetry of the diversified equilibrium. With zero taxation, the log real wage ratio is:

$$\Omega = \log\left(\frac{\theta^* s_E + \phi\theta\,(1 - s_E)}{[\phi\theta^* s_E + \theta\,(1 - s_E)]}\right) + a\log\left(\frac{\theta}{\theta^*}\right) \tag{48}$$

The properties of the base case have been considered in significant detail in the literature.[52] In this section I restate only those properties of the base case which are of particular importance for the purposes of this thesis.

First, the only stable diversified equilibrium possible is one in which $s_n = \frac{1}{2}$. 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 diversified equilibrium is stable in addition to the CPN and CPS equilibria. For relatively low trade freeness, the market crowding effect dominates and only the diversified equilibrium is stable. The properties of Ω as trade costs and the distribution of firms vary are illustrated in Figures 3 and 4.

I follow convention and refer to Figure 3 as a 'wiggle' diagram. The functions in Figure 3, which

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

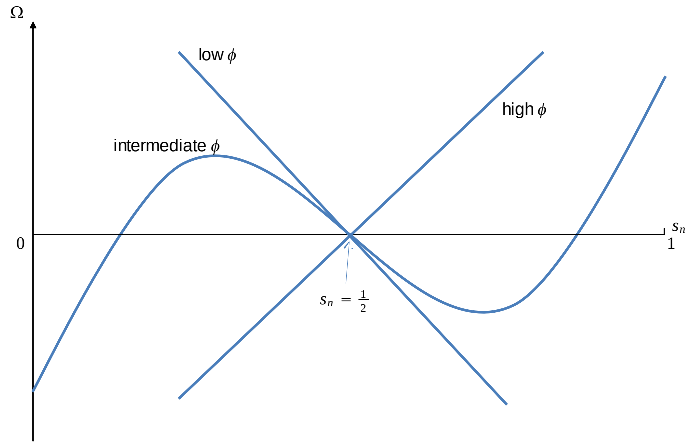

Figure 3: Wiggle diagram with no taxation

I refer to as $\Omega(s_n)$, map out the combinations of Ω and s_n which represent short-run equilibria for a given set of parameters μ, σ, t, t^* and ϕ. It can be shown that the slope of $\Omega(s_n)$ (which I denote $\Omega'(s_n)$) changes sign at most twice.[53]

In Figure 3, $\Omega(s_n)$ is illustrated for three values of ϕ representing high, medium and low trade freeness. As shown in Figure 3, these three levels of trade costs represent values of ϕ for which respectively: (i) only the CP equilibria are stable, (ii) both diversified and CP equilibria are stable and (iii) only the diversified equilibrium is stable.

Figure 4, 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 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 diversified equilibrium is unstable (this is known as the break point), ϕ_b, is expressed in equation (49).[54,55]

$$\phi_b = \left(\frac{1-b}{1+b}\right)\left(\frac{1-a}{1+a}\right) \tag{49}$$

Second, the level of trade freeness above which both CP equilibria are stable (this is known as

53 See Baldwin et al. (2003) for a proof of this.
54 For a derivation see Baldwin et al. (2003).
55 For the remainder of this thesis I impose the condition that $a < 1$. This ensures that agglomeration forces are never so strong that the diversified equilibrium is not stable for any ϕ. This is the so-called 'no-black-hole' condition of Fujita, Krugman and Venables (1999).

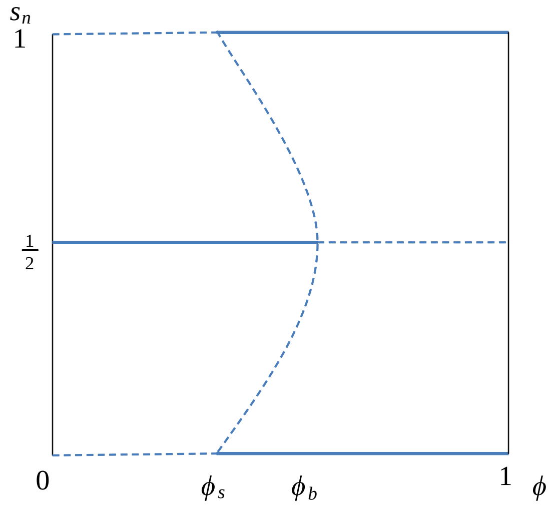

Figure 4: Bifurcation diagram with no taxation

the sustain point), ϕ_s, is defined implicitly by the value of ϕ which solves equation (50):[56]

$$f(\phi) = \phi^a \left[\phi \frac{1+b}{2} + \frac{1-b}{2\phi}\right] - 1 \tag{50}$$

In the absence of trade costs ($\phi = 1$), location plays no role in the determination of real wages and as a consequence, real wages are equalised across regions for any distribution of skilled workers.

4.5 Case 2: Harmonised taxation $\left(t = t^* = \bar{t} \geq 0\right)$

I now consider a more general case in which pollution taxes are positive and equal. This case is relatively straightforward, however, it is a logical intermediate step before considering the unharmonised tax case in section 4.6.

Recall from Chapter 3 that taxes affect nominal wages through the ratio of variable costs (reflected by the parameter r) only. As $r = 1$ whenever taxes are harmonised, nominal wages are identical to those in the zero tax case. I state this as Conclusion 1 .

Conclusion 1 *If taxes are harmonised, changes in the harmonised tax rate, $\bar{t}$, do not alter the*

[56] For a derivation see Baldwin et al. (2003).

nominal wage.

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

$$
\begin{aligned}
P &\equiv p_N^{\mu}\theta^{a} = \left[\frac{1+\bar{t}}{1-\frac{1}{\sigma}}\right]^{\mu}\left[s_n + (1-s_n)\,\phi\right]^{a} \\
P^{*} &\equiv p_N^{\mu}{\theta^{*}}^{a} = \left[\frac{1+\bar{t}}{1-\frac{1}{\sigma}}\right]^{\mu}\left[\phi s_n + (1-s_n)\right]
\end{aligned}
\tag{51}
$$

When taxes are harmonised, increasing the tax rate reduces the real wage in both regions equally. Increases in the harmonised tax rate imply that manufacturing firms face higher variable costs 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.

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 equation (47) when $t = t^{*} > 0$ yields an expression which is identical to that established for the zero tax case (see equation (48)) as the effects of changing the tax rate on the northern and southern true cost of living indices cancel each other out. Changes in the harmonised tax rate therefore never change the location of firms beginning from a stable equilibrium. I state this result as Conclusion 2.

Conclusion 2 *Under harmonised taxation the level of the harmonised tax rate, $\bar{t}$, does not alter the real wage ratio. The set of stable equilibria in the harmonised and zero tax cases are therefore identical.*

This result is sensitive to the assumption that revenue from the tax is not redistributed or used in the provision of a public good. Introduction of tax redistribution would increase the parameter set for which the CP equilibria are stable and decrease the range for which the diversified equilibrium is stable.[57]

One consequence of Conclusion 2 is that the stability properties of the harmonised tax equilibria

[57] See Andersson and Forslid (2003) for an analysis of the effect of public goods on agglomeration forces in this model. The authors show that the introduction of public goods (provided by tax on the wage of skilled workers) creates an additional force for agglomeration. Skilled workers tend to prefer locations where tax revenue (and consequently the provision of public goods) is highest.

are also summarised in Figures 3 and 4. Trade liberalisation (represented by an increase in ϕ) can lead to relocation of firms, however, changes in the harmonised tax rate cannot.

4.6 Case 3: Unharmonised taxation $(t > t^* \geq 0)$

Unharmonised taxation breaks the symmetry of Figures 3 and 4 by the introduction of the asymmetric market crowding and cost of living cost composition effects. The CPN and CPS equilibria do not have identical properties and the diversified equilibrium is no longer symmetric. As the response of firms to exogenous parameter changes differs significantly at each of the three stable equilibria (CPN, CPS and diversified), it assists intuition to consider each of these separately. First I consider the set of stable CPN equilibria in response to changes in the two exogenous parameters of interest r and ϕ. Second, I consider the set of stable CPS equilibria and finally the set of stable diversified equilibria. Comparison of Figures 10 and 11 at the end of this section to Figure 4 provides a concise illustration of the consequences of unharmonised taxation for firm location.

4.6.1 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:

$$\phi^a \left[\phi \frac{1+b}{2} + \frac{1}{\phi} \frac{1-b}{2} \right] - \frac{1}{r} < 0 \tag{52}$$

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

$$f_{CPN}(\phi) = \phi^a \left[\phi \frac{1+b}{2} + \frac{1-b}{2\phi} \right] - \frac{1}{r} \tag{53}$$

$f_{CPN}(\phi)$ for $r = 1$ and $r > 1$ are illustrated in Figure 5.

Six properties of the function $f_{CPN}(\phi)$ are important for the analysis which follows:

1. $f_{CPN}(1) = 1 - \frac{1}{r} \geq 0$

2. $f'_{CPN}(1) > 0$

3. $f_{CPN}(0) > 0$

4. $f'_{CPN}(0) < 0$

5. $\phi^a \left[\phi \frac{1+b}{2} + \frac{1-b}{2\phi}\right] > 0$ for $\phi \in [0, 1]$

6. $f_{CPN}(\phi)$ has a unique minimum.

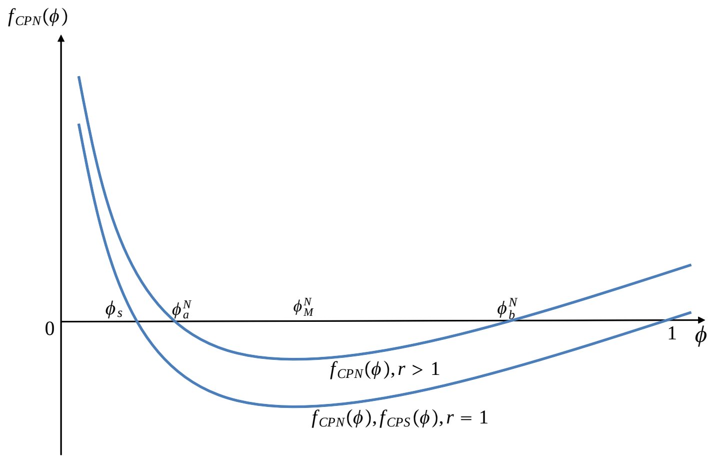

Figure 5: f_{CPN} for $r = 1$ and $r > 1$

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). The values of both ϕ_a^N and ϕ_b^N depend on r. 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. Unfortunately, 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.

The condition for stability in equation (52) and the six properties of $f_{CPN}(\phi)$ can be used to derive a number of properties of the set of stable CPN equilibria. 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.[58] 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 higher wage

[58] To obtain this result observe that ϕ_a^N and ϕ_b^N are the roots of $f_{CPN}(\phi)$. From the six properties of $f_{CPN}(\phi)$, note that $f_{CPN}(\phi) > 0$ only for $\phi < \phi_a^N$ or $\phi > \phi_b^N$. The result follows by the stability condition in (52).

in the core reflects 'agglomeration rents' which all skilled workers receive at a CP equilibrium. The rents are hump-shaped in transport costs in the sense that the real wage is significantly higher in the north than in the south for an intermediate level of ϕ and is only slightly higher for ϕ slightly above ϕ_a^N or slightly below ϕ_b^N.

Figure 5 illustrates the hump-shaped agglomeration rents. The portion of the function $f_{CPN}(\phi)$ below the ϕ axis reflects the range of values of ϕ for which the real wage in the northern core is higher than in the southern periphery. The distance between the axis and $f_{CPN}(\phi)$ reflects the size of the agglomeration rent received by skilled workers in the core.

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 equilibrium is that for values of r at which the equality $f_{CPN}(\phi) = 0$ has two solutions, the sustain point, ϕ_a^N (ϕ_b^N) for the core in the north equilibrium is increasing (decreasing) in r.[59] This property illustrates how a greater tax differential between regions decreases the range of values of ϕ (both from above and below) over which the higher taxing north can sustain an agglomeration of industry.

A third property is that for r sufficiently large that $\phi_a^N = \phi_b^N$, the CPN equilibrium is stable at only one level of ϕ. For larger values of r the CPN equilibrium is unstable for all ϕ.[60] This implies that if the tax differential is sufficiently high, no stable equilibrium is possible in the higher taxing region. It is possible to establish the precise value of r at which the CPN equilibrium becomes unstable for a given value of ϕ. I state this value of r in Proposition 2.

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

Proof. See Appendix 4.9. ■

Proposition 2 illustrates the interdependence of trade freeness, ϕ, and the tax rate differential,

59 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.

60 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.

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. For a higher level of ϕ, an identical increase in r has no effect on the stability of the CPN equilibrium.

It is possible to determine the level of trade freeness which allows the tax differential between regions to be maximised without firm relocation. This level of trade freeness coincides with the value of ϕ at which ϕ_a^N equals ϕ_b^N as r increases. I denote this value of ϕ to be ϕ_M^N.

Proposition 3 *ϕ_M^N is equal to $\sqrt{\left[\frac{(1-a)(1-b)}{(1+a)(1+b)}\right]}$.*

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 2 and 3 demonstrate the non-linear 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 illustrates how the introduction of agglomeration forces implies that the standard result in the international trade literature that trade liberalisation makes firms more footloose in response to a tax disadvantage may not always hold. In the FE model, trade liberalisation can actually make firms less likely to relocate in response to an increase in the tax differential by strengthening the agglomeration forces holding them together.

This result suggests two policy implications. First, policy makers seeking to protect 'trade exposed industries' (i.e. those most likely to relocate) from foreign competition when pollution regulation is differentiated should not rely on the trade costs of the industry's output to determine its likelihood of relocation in response to a regulatory disadvantage. The function r^N which first increases then decreases in ϕ, is the true measure of the footlooseness of agglomerated industries in this model. Second, the PHH, which suggests that trade liberalisation between regions with differentiated environmental policies encourages firm relocation away from the more stringently regulated region may only tell half the story. Restriction of trade may also lead to industry relocation from stringently regulated regions. In the model, from a CP equilibrium relocation of the core in response to changes in ϕ occurs if trade is liberalised (such that ϕ is greater than ϕ_b^N) and if trade is restricted (such that ϕ is less than ϕ_a^N). The potential for industry relocation in response to trade restriction turns the PHH, as described in Chapter 1, on its head. Agglomeration rents may therefore help explain Copeland and Taylor's (2004) observation that the PHH has received significantly less empirical support than the PHE.

The interaction between r and ϕ in determining the stability of equilibria indicates a potential extension to this thesis, which I discuss in Chapter 6. If northern regulators can unilaterally control trade freeness in addition to their own tax rate (for example by placing a border tariff on the import of manufactures) they can maximise their domestic pollution tax rate without inducing relocation of firms by setting $\phi = \phi_M^N$ and $r = r^N$.

4.6.2 Properties of the CPS equilibrium

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

$$\phi^a \left[\phi \frac{1+b}{2} + \frac{1-b}{2\phi} \right] - r < 0 \tag{54}$$

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

$$f_{CPS}(\phi) = \phi^a \left[\phi \frac{1+b}{2} + \frac{1-b}{2\phi} \right] - r \tag{55}$$

Analysis of $f_{CPS}(\phi)$ reveals five properties which are useful in establishing the set of stable CPS equilibria:

1. $f_{CPS}(1) = 1 - r \leq 0$
2. $f'_{CPS}(1) > 0$
3. $f_{CPS}(0) > 0$
4. $f'_{CPS}(0) < 0$

5. $f_{CPS}(\phi)$ has a unique minimum.

Figure 6 illustrates $f_{CPS}(\phi)$ for $r = 1$ and $r > 1$.

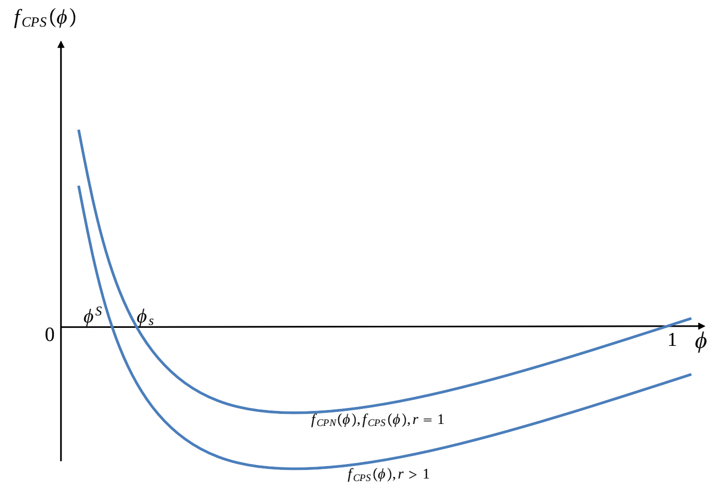

Figure 6: $f_{CPS}(\phi)$ for $r = 1$ and $r > 1$

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 from unstable to stable.

I define the level of ϕ at which $f_{CPS}(\phi) = 0$, for a given level of r, to be ϕ^S. I refer to ϕ^S 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.[61] Therefore as r increases, the set of values of ϕ over which the CPS equilibrium is stable expands to include smaller values of ϕ.

Note also that ϕ^S asymptotes with 0 as $r \to \infty$.[62] Therefore, for any tax rate differential between regions (no matter how large) a level of ϕ exists such that the CPS equilibrium is not stable. Beginning from a CPS equilibrium, if trade becomes sufficiently closed, some skilled workers (and therefore firms) will move to the northern periphery in order to avoid the trade costs associated with serving the immobile unskilled workers located there.

[61] 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 (54).

[62] ϕ^S is the solution to the equality $\phi^a \left[\phi \frac{1+b}{2} + \frac{1-b}{2\phi}\right] = r$. As $r \to \infty$, $\phi^S \to 0$.

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 4.

Proposition 4 *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 $\frac{2-(1+b)\left(1-\phi^2\right)}{2\phi^{1-a}}$.*

Proof. *See Appendix 4.10.* ■

For some $\phi \in [0, \phi_s]$, as $\phi \to 0$, $r^S \to \infty$ and as $\phi \to \phi_s$, $r^S \to 1$.

4.6.3 Properties of the diversified equilibrium

In this section I consider the effects of r and ϕ on the diversified equilibrium separately.

The effect of r on the stable diversified equilibrium I establish firstly that increasing r shifts the function $\Omega(s_n)$ down. I state and prove this in Proposition 5.

Proposition 5 *Holding s_n fixed at any level in the economically meaningful interval* $[0,1]$, $\frac{\delta\Omega}{\delta r} < 0$.

Proof. See Appendix 4.11. ■

Proposition 5 implies that the short-run real wage ratio for a given distribution of firms (s_n) is decreasing in r. The implication of Proposition 5 for the function $\Omega(s_n)$ is illustrated in Figure 7 for parameter values for which both CP and diversified equilibria are possible.

Increases in r do not shift the function $\Omega(s_n)$ down uniformly. The level of s_n at which $\Omega(s_n)$ achieves an interior local maxima and minima changes with the value of r.[63]

The stability analysis which follows, relies on the property of the FE model that $\Omega(s_n)$ changes concavity at most once (alternatively that $\Omega'(s_n)$ changes sign at most twice). It can be proven that $\Omega(s_n)$ retains this property when taxation is unharmonised.[64]

[63] If Ω has a maximum or minimum at $s_n = 0$ or $s_n = 1$,(as is the case, for instance if ϕ is relatively low or high) changes in r may have no effect on the value of s_n at which this maximum or minimum occurs.

[64] For a detailed proof in the harmonised tax case see Baldwin et al. (2003). The unharmonised tax proof is almost identical and I do not reproduce it here.

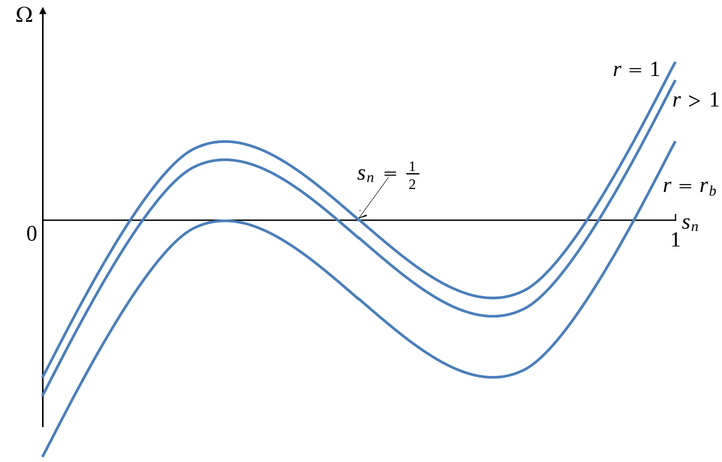

Figure 7: Wiggle diagram with unharmonised taxation

The first property of the stable diversified equilibrium that I establish is that for sufficiently high tax differentials, no stable diversified equilibrium is possible if $\phi > 0$.[65]

For a given level of ϕ, I denote the level of r at which the diversified equilibrium ceases to be stable, as r_b. r_b can therefore be thought of as the tax differential equivalent of the trade freeness break point, ϕ_b. The effect of setting $r = r_b$ is shown in Figure 7. As the local maximum of $\Omega(s_n)$ is equal to zero when $r = r_b$, any increase in the level of r above r_b will shift the function $\Omega(s_n)$ down, and no stable diversified equilibrium will exist. In general, no closed form solution for r_b is possible.[66]

A second property of the diversified equilibrium, which is implied by Proposition 5, is that the stable diversified 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 diversified equilibrium $\Omega'(s_n) < 0$. Therefore increasing r ensures that the new stable diversified

65 To see this observe that $\Omega \to -\infty$ as $r \to \infty$ for all s_n. If $\Omega(s_n)$ is negative over the entire range of s_n only the CPS equilibrium is stable.

Under autarky, when $\phi = 0$, $\Omega(s_n)$ asymptotes to ∞ if $s_n = 0$ and $\Omega(s_n)$ asymptotes to $-\infty$ if $s_n = 1$.

66 In general, two steps are required to solve for r_b . One must first solve for the value of s_n at which $\Omega(s_n)$ has a local maximum on the range $[0, 1]$. In general this is a function of r. Given this value of s_n, one must then solve for the value of r at which $\Omega = 0$ in order to obtain r_b. Non-integer powers in Ω ensure that it is in general not possible to obtain closed form solutions for r_b. One exception is when Ω is decreasing over the entire range of s_n. In this case $r_b = r^S$, which, as established previously, is equal to $\frac{2-(1+b)\left(1-\phi^2\right)}{2\phi^{1-\alpha}}$.

equilibrium (if one exists) will occur for a lower value of s_n.[67,68] 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 diversified equilibrium, however, any tax differential causes relocation of firms.

A third property of the stable diversified equilibrium is that increasing r beyond r_b need not precipitate a catastrophic relocation of firms away from the diversified equilibrium. In other words, the relocation can be smooth. The conditions under which both smooth relocation and catastrophic relocation occur are set out in Appendix 4.12.

The effect of ϕ on the stable diversified equilibrium First, I establish that under unharmonised taxation autarky ensures that a diversified equilibrium is stable regardless of the tax differential. To see this note that when $\phi = 0$, evaluating $\Omega(0)$ and $\Omega(1)$ reveals that $\Omega(0) > 0$ and $\Omega(1) < 0$ for all r less than ∞. This implies that $\Omega(s_n) = 0$ for some $s_n \in (0, 1)$.

Second, like the harmonised tax case, the unharmonised tax case must feature a break point, $\phi_b(r)$, however, it is a function of the tax differential. Proposition 6 states this:

Proposition 6 *There exists a range of values of ϕ from 0 to $\phi_b(r)$ for which there exists a stable diversified equilibrium over the range $s_n \in (0, \frac{1}{2})$.*[69] *For $\phi > \phi_b(r)$, no stable equilibrium exists over the range $s_n \in (0, \frac{1}{2})$.*

Proof. The strength of the local competition effect (which encourages dispersion of firms between regions) falls roughly with the square of trade freeness, while the strength of cost of living effect and the market size effect (which encourage firms to co-locate) increases roughly linearly with ϕ. This implies that above a certain value of ϕ, $\phi_b(r)$, the diversified equilibrium is no longer stable.[70] ■

[67] For an illustration, consider the symmetric stable diversified equilibrium in Figure 7 when $r = 1$. After the increase in r, the $\Omega(s_n)$ curve shifts down and the level of s_n at which the stable diversified equilibrium occurs is less than $\frac{1}{2}$.

[68] If the increase in r precludes the existence of a stable diversified equilibrium (i.e. $r > r_b$), a relocation of all firms to a stable CP equilibrium occurs.

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

[70] Technically, the same no-black-hole condition as required for the symmetric case must be assumed, in order to ensure that agglomeration forces are not so strong that there is no positive value of ϕ for which the diversified equilibrium exists.

It is possible to prove that the range of ϕ for which the diversified equilibrium is stable diminishes as the tax differential widens.

Proposition 7 *$\phi_b(r)$ is decreasing in r.*

Proof. Consider an arbitrary stable diversified 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 Proposition 5, that the local maximum of $\Omega(s_n)$ for $s_n \in \left[0, \frac{1}{2}\right]$ is now less than zero. Therefore, no stable equilibrium is now possible and $\phi_b(r^1) > \phi_b(r^2)$ by Proposition 6. This proves the proposition as ϕ, r^1 and r^2 are arbitrarily chosen. ■

For sufficiently large r, the break point $(\phi_b(r))$ can even be less than the smaller sustain point in the north (ϕ_a^N).[71] Unlike the harmonised tax case, there may be no overlap of values of ϕ for which both diversified and CPN equilibria are stable. This implies that in the unharmonised tax case (in contrast to the harmonised tax case in which trade liberalisation beyond ϕ_b could lead to a relocation of firms to either of the CP equilibrium) when r is sufficiently large, the relocation caused by trade liberalisation must be to the CPS equilibrium.

To progress further in determining the effect of ϕ on the stable diversified equilibrium I make a conjecture grounded in extensive simulation but without a formal proof. This approach is not uncommon within the NEG literature. The conjecture is not critical for many of the main messages of this thesis however I include it both for completeness and in order to identify an issue requiring further study.

Conjecture 1 *As ϕ increases from 0 to $\phi_b(r)$: (i) The level of s_n at which the stable diversified equilibrium occurs decreases; and (ii): $\Omega'(s_n)$ at the stable diversified equilibrium becomes less negative.*

Conjecture 1 is supported by extensive simulation over the economically meaningful parameter space in which it has been found to hold without exception.[72,73] Conjecture 1 is illustrated

[71] This can be proven simply by simulated counterexample.

[72] The economically meaning parameter space comprises those parameter values for which $\phi \in [0,1], r \geq 1, (1-\mu) > \frac{1}{2}(1-b)$ (the NFS condition), $a < 1$ (the no-black-hole condition) and all parameters are non-negative.

[73] Solving for the distribution of firms in the diversified equilibrium requires a solution to the condition $(\omega = \omega^*)$. Despite the FE model's relative tractability, the presence of non-integer powers in the price indices ensures that this is not possible analytically. This is not a significant problem when taxes are harmonised, as the symmetry of the model ensures that the diversified equilibrium always occurs for $s_n = \frac{1}{2}$. In the unharmonised tax case, however, symmetry can no longer be relied upon to determine the value of s_n at any stable diversified equilibrium.

in Figure 8. At the diversified equilibrium, the value of s_n decreases and the slope of $\Omega(s_n)$ becomes less negative as ϕ increases.[74] On the assumption that conjecture 1 is true for all parameter combinations, I proceed to analyse the effect of changing ϕ on the stability of the diversified equilibrium.

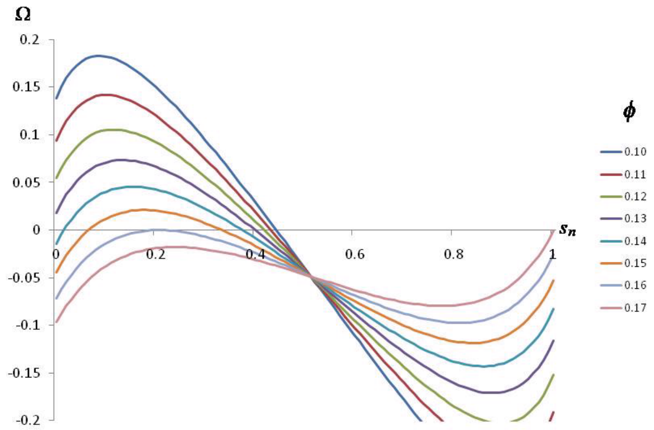

Figure 8: $\Omega(s_n)$ for various ϕ.

When $\phi = \phi_b(r)$ there are two possible types of break point: An interior break point for which $s_n > 0$ and $\Omega'(0) > 0$ and a corner breakpoint for which $s_n = 0$ and $\Omega'(0) \leq 0$. Both occur at local maxima of Ω when $\phi = \phi_b(r)$. Figure 9 illustrates both types. The blue function represents a level of r, r^*, at which there is an interior break point, while the grey function represents a level of r, r^{**}, at which there is a corner break point. The functions in Figure 9 are illustrated for values of ϕ equal to $\phi_b(r^*)$ and $\phi_b(r^{**})$.

It is possible to partition the values of r into those for which an interior break point exists and those for which a corner break point exists. Specifically, the sign of $\Omega'(0)$, at the level of ϕ which makes the CPS equilibrium just stable, ϕ^S, for a given level of r, determines whether trade liberalisation will lead to catastrophic or smooth relocation of firms. If $\Omega'(0)|_{\phi=\phi^S} > 0$, then $\phi^S < \phi_b(r)$, there is an interior break point and relocation of firms as trade is liberalised is catastrophic. If $\Omega'(0)|_{\phi=\phi^S} \leq 0$, then $\phi^S = \phi_b(r)$, there is a corner break point and relocation of firms as trade is liberalised is smooth. I refer to the knife-edge value of r at which $\Omega'(0)|_{\phi=\phi^S} = 0$ as r_h.

[74] $\phi_b(r)$ is approximately equal to 0.16 in this case and there is no stable diversified equilibrium possible for $\phi = 0.17$.

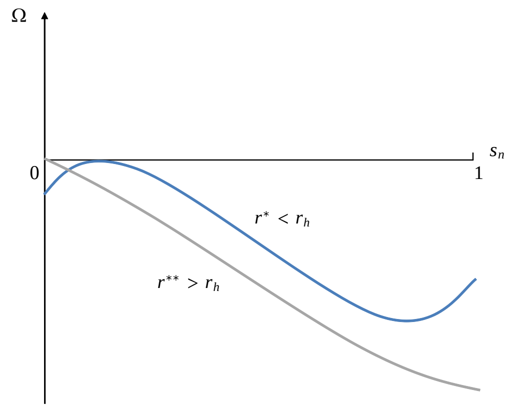

Figure 9: Wiggle diagram with catastrophic (blue) and non-catastrophic (grey) delocation as ϕ increases beyond $\phi_b(r)$

4.6.4 Graphical summary of the unharmonised tax case

The major results of Chapter 4 are summarised in Figures 10 and 11, which demonstrate how the set of stable equilibria changes in response to changes in the two parameters of interest r and ϕ.

Figure 10 illustrates the effect of trade liberalisation on the set of stable equilibria. This is the unharmonised tax version of the bifurcation diagram in Figure 4. 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 diversified 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 10 illustrates the nature of the pollution haven hypothesis (PHH) described in Chapter 1 in this model.[75] The model suggests that empirical studies which assume a simple monotonic relationship between firm location and trade costs may be incorrectly specified. In the model both trade liberalisation (above ϕ_b^N) and trade restriction (below ϕ_a^N) encourages firms to relocate from the more stringently regulated north to the less stringently regulated south.

[75] Recall the PHH predicts a positive relationship between trade freeness and the extent of relocation of polluting firms to the less stringently regulated region.

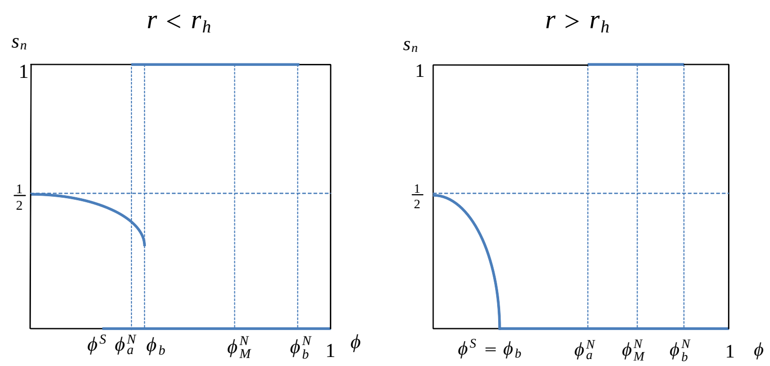

Figure 10: Asymmetric bifurcation diagram with catastrophic (left) and non-catastrophic (right) delocation

Two qualifications for Figure 10 are in order. First, as established, it is possible that $\phi_a^N > \phi_b(r)$ in the left hand pane.[76] Second, for r sufficiently large it is possible that the CPN equilibrium is not stable for any level of ϕ. I omit both scenarios in order to present a more parsimonious diagrammatic summary.

Figure 11 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 diversified to CPS equilibrium is smooth as r rises beginning from $r = 1$. The bottom left pane reflects a situation in which the relocation of firms is catastrophic as r rises from $r = 1$.

The top right pane illustrates the stable equilibria for ϕ greater than ϕ_s but less than the harmonised tax break point, ϕ_b. In this scenario, both the diversified and CP equilibria are stable for $r = 1$. As represented in the right hand pane, the CPN equilibrium becomes unstable for a value of r which is lower than that for which the diversified equilibrium becomes unstable. The opposite result is also possible, however, for simplicity, it is omitted.[77]

76 This occurs for a higher tax rate than that represented.

77 The opposite result is the only situation in which increasing the tax differential could possibly lead to an increase in the equilibrium level of s_n. In such a case, both CP equilibria are stable at the level of the tax differential at which the diversified equilibrium becomes unstable,r_b. To evaluate which CP equilibrium actually occurs for a small increase in r above r_b, one would need to consider the transition dynamics of the model. Such analysis is not undertaken in this thesis.

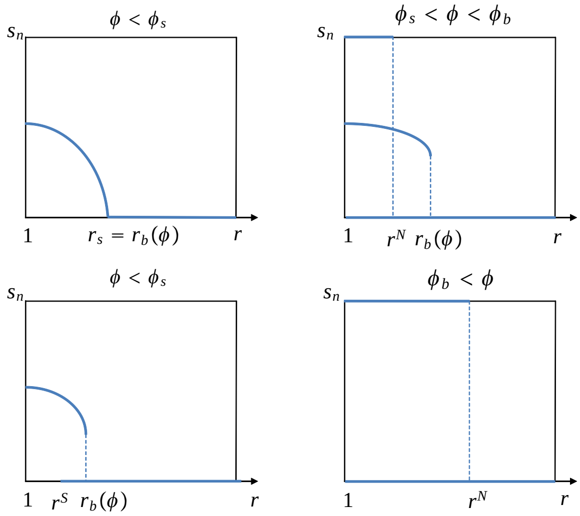

Figure 11: Stable equilibria as a function of r

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

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

4.7 Conclusion

In Chapter 1 I stated the first key question of this thesis: *How does the degree of differentiation of environmental policy influence the extent of firm relocation?*. In Chapter 4 I demonstrated that the answer crucially depends on the initial location of industry, trade costs and the tax rate differential. The response of agglomerated firms to differentiated taxation was shown to be different to the response of firms which are initially dispersed between regions. In addition, use of the FE model enabled important tipping points in the model, including the variables $r^N, r^S, \phi_M^N, \phi_a^N, \phi_b^N$ and ϕ^S to be determined analytically.

4.8 Appendix 1: Derivation of price index ratio with unharmonised taxation

The true cost of living indices are:

$$\begin{array}{c} P = \left[s_n p_N^{1-\sigma} + \phi \left(1 - s_n\right) p_S^{*^{1-\sigma}} \right]^{\frac{\mu}{1-\sigma}} = \left(s_n p_N^{1-\sigma} + \phi \left(1 - s_n\right) p_S^{*^{1-\sigma}} \right)^a, a = \frac{\mu}{1-\sigma} \\ P^* = \left[\phi s_n p_N^{1-\sigma} + \left(1 - s_n\right) p_S^{*^{1-\sigma}} \right]^{\frac{\mu}{1-\sigma}} = \left(\phi s_n p_N^{1-\sigma} + \left(1 - s_n\right) p_S^{*^{1-\sigma}} \right)^a \end{array} \tag{56}$$

The ratio of the true cost of living indices is:

$$\frac{P}{P^*} = \left[\frac{\left(s_n + \phi \left(1 - s_n\right) \left[\frac{p_S^*}{p_N} \right]^{1-\sigma} \right)}{\left(\phi s_n + \left(1 - s_n\right) \left[\frac{p_S^*}{p_N} \right]^{1-\sigma} \right)} \right]^a \tag{57}$$

$$= \left[\frac{\left(s_n + \phi \left(1 - s_n\right) r \right)}{\left(\phi s_n + \left(1 - s_n\right) r \right)} \right]^a \tag{58}$$

$$= \left[\frac{\theta}{\theta^*} \right]^a \tag{59}$$

4.9 Appendix 2: Derivation of r^N

Solve $f_{CPN}\left(\phi\right) = 0$ for r.

$$\begin{array}{c} f_{CPN}\left(\phi\right) = \phi^a \left[\phi \frac{1+b}{2} + \frac{1-b}{2\phi} \right] - \frac{1}{r} \\ \therefore r = \frac{2\phi^{1-a}}{2-(1+b)(1-\phi^2)} \end{array} \tag{60}$$

4.10 Appendix 3: Derivation of r^S

Solve $f_{CPS}\left(\phi\right) = 0$ for r.

$$
\begin{aligned}
f_{CPS}(\phi) &= \phi^a \left[\phi \tfrac{1+b}{2} + \tfrac{1-b}{2\phi}\right] - r \\
\therefore r &= \tfrac{2-(1+b)\left(1-\phi^2\right)}{2\phi^{1-a}}
\end{aligned}
\tag{61}
$$

4.11 Appendix 4: Proof that for a given level of s_n, $\frac{\partial \Omega}{\partial r} < 0$

Expand the log real wage ratio:

$$
\Omega = \log\left(\theta^* s_E + \phi\theta\left(1 - s_E\right)\right) - \log\left(\phi\theta^* s_E + \theta\left(1 - s_E\right)\right) - \log\left(r\right) + a\log\left(\tfrac{\theta}{\theta^*}\right)
$$

I proceed by first demonstrating that the final term of this equation is decreasing in r for all possible parameter values and second demonstrating that the first three terms are decreasing in r for all possible parameter values.

Consider the last term. The following manipulations show that this is less than or equal to zero:

$$
\begin{aligned}
\tfrac{\partial\left(a\log\left(\frac{\theta}{\theta^*}\right)\right)}{\partial r} &= a\tfrac{\theta^*}{\theta}\left(\tfrac{\phi(1-s_n)\theta^* - (1-s_n)\theta}{\theta^{*2}}\right) \\
\tfrac{\partial\left(a\log\left(\frac{\theta}{\theta^*}\right)\right)}{\partial r} &= a\tfrac{\theta}{\theta^*}\left(1 - s_n\right)\left(\tfrac{\phi[(1-s_n)r+\phi s_n] - [s_n+\phi(1-s_n)r]}{\theta^{*2}}\right) \\
\tfrac{\partial\left(a\log\left(\frac{\theta}{\theta^*}\right)\right)}{\partial r} &= a\tfrac{\theta}{\theta^*}\tfrac{(1-s_n)}{\theta^{*2}}\left(\phi\left(1 - s_n\right)r + \phi^2 s_n - s_n - \phi\left(1 - s_n\right)r\right) \\
\tfrac{\partial\left(a\log\left(\frac{\theta}{\theta^*}\right)\right)}{\partial r} &= a\tfrac{\theta^*}{\theta}\tfrac{(1-s_n)}{\theta^{*2}}s_n\left(\phi^2 - 1\right) \leq 0
\end{aligned}
$$

The sign of this term is determined by the sign of $\left(\phi^2 - 1\right)$, which is less than or equal to zero.

Next I consider the first three terms:

$$
\frac{\partial\begin{pmatrix} \log\left(\theta^* s_E + \phi\theta\left(1 - s_E\right)\right) \\ -\log\left(\phi\theta^* s_E + \theta\left(1 - s_E\right)\right) \\ -\log\left(r\right)\end{pmatrix}}{\partial r} =
\begin{matrix}
\frac{1}{(\theta^* s_E + \phi\theta(1-s_E))}\begin{bmatrix} \frac{\partial s_E}{\partial r}\left[\theta^* - \phi\theta\right] \\ +\left[\left(1 - s_n\right) - \phi^2\left(1 - s_n\right)\right]s_E \\ +\phi^2\left(1 - s_n\right)\end{bmatrix} \\
-\frac{1}{(\phi\theta^* s_E + \theta(1-s_E))}\begin{bmatrix} \frac{\partial s_E}{\partial r}\left(\phi\theta^* - \theta\right) \\ +\left(\phi\left(1 - s_n\right) - \phi\left(1 - s_n\right)\right)s_E \\ +\phi\left(1 - s_n\right)\end{bmatrix} \\
-\frac{1}{r}
\end{matrix}
\tag{62}
$$

$$= \frac{1}{(\theta^* s_E+\phi\theta(1-s_E))}\left[\frac{\partial s_E}{\partial r}\left[\theta^*-\phi\theta\right]+\left[(1-s_n)-\phi^2(1-s_n)\right]s_E+\phi^2(1-s_n)\right] - \frac{1}{(\phi\theta^* s_E+\theta(1-s_E))}\left[\frac{\partial s_E}{\partial r}(\phi\theta^*-\theta)+\phi(1-s_n)\right]-\frac{1}{r} \tag{63}$$

$$= \overbrace{\frac{\partial s_E}{\partial r}\left[\frac{[\theta^*-\phi\theta]}{(\theta^* s_E+\phi\theta(1-s_E))}-\frac{(\phi\theta^*-\theta)}{(\phi\theta^* s_E+\theta(1-s_E))}\right]}^{\text{1st term}}+\overbrace{\left[\frac{(1-s_n)\left(1-\phi^2\right)s_E}{(\theta^* s_E+\phi\theta(1-s_E))}-\frac{1}{r}\right]}^{\text{2nd term}} \underbrace{+\phi(1-s_n)\left[\frac{\phi}{(\theta^* s_E+\phi\theta(1-s_E))}-\frac{1}{(\phi\theta^* s_E+\theta(1-s_E))}\right]}_{\text{3rd term}} \tag{64}$$

I now consider the three components of the above derivative, demonstrating for each that its value must be less than or equal to zero.

To establish that the first term is less than or equal to zero, I note that both denominators inside the brackets are positive and that:[78]

$$\begin{gathered}[\theta^*-\phi\theta]=\left[r(1-s_n)+\phi s_n-\phi s_n-\phi^2 r(1-s_n)\right]=r(1-s_n)\left[1-\phi^2\right]\geq 0,\\ (\phi\theta^*-\theta)=\left[\phi r(1-s_n)+\phi^2 s_n-s_n-\phi r(1-s_n)\right]=s_n\left[\phi^2-1\right]\leq 0,\\ \frac{\partial s_E}{\partial r}\leq 0 \text{ for } s_n \text{ fixed}\end{gathered} \tag{65}$$

It follows that:

$$\frac{\partial s_E}{\partial r}\left[\frac{[\theta^*-\phi\theta]}{(\theta^* s_E+\phi\theta(1-s_E))}-\frac{(\phi\theta^*-\theta)}{(\phi\theta^* s_E+\theta(1-s_E))}\right]\leq 0 \tag{66}$$

To establish that the second term is less than or equal to zero I note that:[79]

$$\frac{(1-s_n)\left(1-\phi^2\right)s_E}{(\theta^* s_E+\phi\theta(1-s_E))}-\frac{1}{r}=\frac{\frac{1}{r}\left(1-\phi^2\right)}{1-\phi^2\left(1-\frac{1}{s_E}\right)+\frac{s_n}{(1-s_n)}\frac{\phi}{s_E}\frac{1}{r}}-\frac{1}{r}\leq 0 \tag{67}$$

[78] The third property is proven in Proposition 1.
[79] Manipulations are excluded but can be provided upon request.

The numerator of the left hand term is less than or equal to $\frac{1}{r}$.[80] The denominator of the left hand term is greater than one.[81] The result follows.

To establish that the third term is less than or equal to zero divide the numerator and denominator of the left hand term by ϕ. This yields:

$$\phi\left(1-s_n\right)\left[\begin{array}{c}\frac{\phi}{\left(\theta^* s_E+\phi\theta\left(1-s_E\right)\right)} \\ -\frac{1}{\left(\phi\theta^* s_E+\theta\left(1-s_E\right)\right)}\end{array}\right]=\phi\left(1-s_n\right)\left[\begin{array}{c}\frac{1}{\left(\frac{\theta^* s_E}{\phi}+\theta\left(1-s_E\right)\right)} \\ -\frac{1}{\left(\phi\theta^* s_E+\theta\left(1-s_E\right)\right)}\end{array}\right] \tag{68}$$

In this form, given that $\phi \leq 1$, it is obvious that $\frac{1}{\left(\frac{\theta^* s_E}{\phi}+\theta(1-s_E)\right)}$ is less than or equal to $\frac{1}{(\phi\theta^* s_E+\theta(1-s_E))}$. It follows that the third term is less than or equal to zero.

Having established that all terms in $\frac{\partial\Omega}{\partial r}$ are less than or equal to zero for a given level of s_n, the result follows.

Note also, that these derivations demonstrate that $\frac{\partial\Omega}{\partial r}=-\frac{1}{r}$ when $\phi=1$. The derivative is no longer a function of the distribution of firms.

4.12 Appendix 5: Conditions for catastrophic relocation for the diversified equilibrium

Refer to Figure 12 for an illustration of conditions under which relocation of firms will be catastrophic and non-catastrophic as r increases above r_b.

In the left hand pane, $\Omega'(0)>0$ when r is equal to r^S and Ω has a hump. A stable diversified equilibrium is therefore possible when r is equal to r^S (recall that $\Omega(s_n)$ changes convexity only once).[82] In this case, r_b is clearly greater than r^S. If r increases above r^S the number of northern firms in the stable diversified equilibrium declines until it is equal to s_n^* when $r=r_b$. For $r>r_b$, the diversified equilibrium is unstable and catastrophic relocation (in this case to the CPS equilibrium as the CPN is not stable) occurs.

In the right hand pane, $\Omega'(0)<0$ when r is equal to r^S and there is no hump. By the concavity

[80] As $\left(1-\phi^2\right) \leq 1$.

[81] As $\left(1-\frac{1}{s_E}\right) \leq 0$.

[82] Recall that r is equal to r^S and the CPS equalibrium is only marginally stable when $\Omega(0)$ is equal to 0.

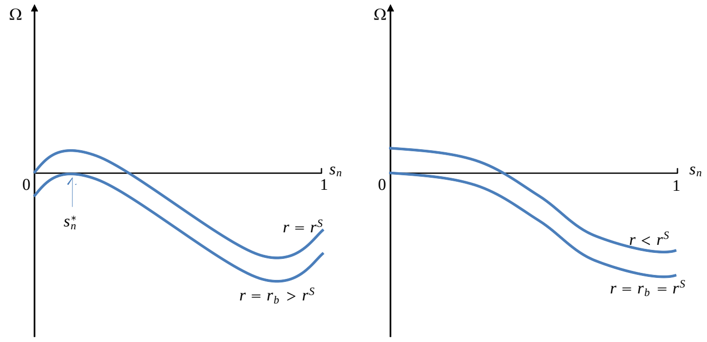

Figure 12: Wiggle diagram with catastrophic (left) and non-catastrophic (right) delocation

properties of $\Omega(s_n)$ there can be no diversified equilibrium in this case. As r increases from $r < r^S$, the number of northern firms in the diversified equilibrium declines continuously until all firms are located in the south when $r = r_b = r^S$. There is therefore no catastrophic delocation.

Therefore, for a given level of ϕ at which the diversified equilibrium is stable when $r = 1$, if $\Omega'(0) > 0$ ($\Omega'(0) \leq 0$) when evaluated at the level of r at which the CPS equilibrium is marginally stable, r^S, the transition from diversified to CP equilibrium is catastrophic (smooth). In the catastrophic case $r_b > r^S$, while in the smooth case $r_b = r^S$.

5 ENVIRONMENTAL POLICY AND CARBON LEAKAGE

If we decide as a nation to regulate greenhouse gas emissions—and I hope we won't—then the result will be carbon leakage. That's a fancy term that means manufacturing jobs and emissions will move overseas to countries that don't regulate emissions. By sending our jobs and basic industries to China and India, America will be weaker, and our strategic competitors will be stronger.

Senator James M. Inhofe

U.S. Senate Committee on Environment and Public Works,

Hearing on Climate Change and National Security, 30 July, 2009

5.1 Introduction

In this chapter I extend the model of Chapters 3 and 4 and consider the issue of carbon leakage as a consequence of differentiated GHG regulation. The second question introduced in Chapter 1 is addressed: *How does the degree of differentiation in environmental policy influence the extent of carbon leakage?*

To answer this question, I evaluate the change in the level of global emissions brought about by the ratification of an IEA which fixes the levels of t and t^* in the long-run. The remainder of this chapter proceeds as follows. In section 5.2 expressions are derived for the level of emissions per firm and per region as a function of model parameters. In section 5.3 I consider carbon leakage when taxes are harmonised. This provides a base case with which to compare an unharmonised taxation scenario. In section 5.4 unharmonised taxation is considered. In section 5.5 the chapter is concluded with a summary of its main results.

5.2 Expressions for emission levels

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 (or scale) of each firm. The total emissions in the north and south, Γ and Γ^* respectively are therefore given by:

$$\Gamma = s_n \gamma x \tag{69}$$

$$\Gamma^* = (1 - s_n)\,\gamma x^* \tag{70}$$

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). I digress briefly to consider both of these effects.

Expansion of equations (69) and (70) makes the two effects more explicit:[83]

$$\begin{aligned} \Gamma &= s_n b \left[\left(\frac{s_E}{s_n + \phi(1-s_n)\left[\frac{1+t}{1+t^*}\right]^{\sigma-1}} \right) + \phi \left(\frac{1-s_E}{(1-s_n)\left[\frac{1+t}{1+t^*}\right]^{\sigma-1} + s_n\phi} \right) \right] \frac{\sigma-1}{1+t} \\ \Gamma^* &= (1-s_n)\, b \left[\phi \left(\frac{s_E}{s_n\left[\frac{1+t^*}{1+t}\right]^{\sigma-1} + \phi(1-s_n)} \right) + \left(\frac{1-s_E}{(1-s_n) + \phi s_n\left[\frac{1+t^*}{1+t}\right]^{\sigma-1}} \right) \right] \frac{\sigma-1}{1+t^*} \end{aligned} \tag{71}$$

Firm scale effect Firm size is equal to the ratio of fixed costs (bB and brB^*) to variable input costs ($1+t$ and $1+t^*$), multiplied by $\sigma - 1$. For every distribution of firms except the two CP equilibria, changes in the tax rate alter firm size through both types of costs.

Fixed costs (which are reflected by the terms inside the square brackets in equation (71)) are influenced by the tax differential, $r = \left(\frac{1+t}{1+t^*}\right)^{\sigma-1}$, rather than by the absolute level of either region's tax rate.[84] As r affects skilled wages in both regions, a change in one tax rate alters the fixed costs in both regions through the market access and market crowding effects identified in Chapter 4. However, in a CP equilibrium the effect of r on firm fixed costs disappears and the skilled wage is constant for any tax differential which does not result in relocation of the core (this is equivalent to any tax differential such that $r \leq r^N$).

The effect of t on variable costs is purely local; that is, changes in t affect the local variable cost directly by altering the price of polluting. Variable costs respond to changes in the domestic tax rate at both CP and diversified equilibria.

83 The inability to solve for s_n at the diversified equilibrium in the FE model means s_n cannot be expressed analytically as a function of exogenous model parameters. Note also that s_E is a function of s_n which (as a consequence of Proposition 1) is declining in r for a given level of s_n.

84 In this chapter, the assumption that the north is the higher taxing region after ratification of the IEA is maintained.

Firm relocation effect In Chapter 4 the critical tax parameter for determining firm location was shown to be the tax differential, r. If the core is in the north (south), provided the condition that $r \leq r^N$ ($r \geq r^S$) holds after ratification of the agreement, no relocation is induced and the firm relocation effect does not cause carbon leakage. If firms are at the diversified equilibrium prior to ratifying the agreement, the increase in the parameter r causes firms to relocate from the north to the south, causing carbon leakage through the firm relocation effect.

5.3 Case 1: Harmonised taxation

As carbon leakage can only occur when taxes are unharmonised, the harmonised tax case provides a maximum efficiency benchmark with which to compare the unharmonised tax case which is considered in the section 5.4. I denote the global level of emissions as χ, which is simply the sum of Γ and Γ^*. The harmonised tax rate is denoted by $\bar{t}$ in both regions. As $r = 1$ when taxes are harmonised there is no firm relocation effect, only a firm scale effect.

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

CP equilibria In order to evaluate the CPN and CPS equilibria I set $s_n = 1$ and $s_n = 0$ respectively in (71). This yields a total level of emissions in the core (and therefore globally) of $b\frac{\sigma-1}{1+\bar{t}}$ for both equilibria. Trade freeness, ϕ, plays no role in determining the level of emissions at either the firm, region or global level.[85] Global emissions are thus monotonically decreasing in the harmonised tax rate, $\bar{t}$.

Diversified equilibrium Recall from Chapter 4 that the diversified equilibrium is always symmetric when taxes are harmonised. The global level of emissions is thus determined by setting $s_n = \frac{1}{2}$ in (71). This yields, $\Gamma = \Gamma^* = \frac{1}{2}b\frac{\sigma-1}{1+\bar{t}}$ and therefore $\chi = b\frac{\sigma-1}{1+\bar{t}}$.

As was the case for the CP equilibrium, ϕ plays no role in the determination of the level of global emissions. From a diversified 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.[86]

[85] This occurs because nominal expenditure on manufactures in the periphery is a constant fraction of the 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 for export in the core.

[86] This a weak result, however, in the sense that it depends critically upon the collective assumptions of constant

Two obvious consequences of this are stated in Proposition 8.

Proposition 8 *When taxation is harmonised, the diversified and CP equilibria yield identical levels of global emissions and the level of global emissions is independent of trade freeness.*[87]

Proof. Note that $\chi = b\frac{\sigma-1}{1+\bar{t}}$ in both the CP and the diversified equilibria. ■

Taking the derivative of the global level of emissions with respect to $\bar{t}$ demonstrates that global emissions are declining in $\bar{t}$ at rate $b\frac{\sigma-1}{(1+\bar{t})^2}$.

The relationship between the level of global emissions χ and the parameters ϕ and $\bar{t}$ under harmonised taxation are illustrated in Figure 13. Increasing trade freeness from $\phi = 0$ to $\phi = 1$ alters the location of firms from a diversified equilibrium to either of the CP equilibria but it does not change the level of global emissions. Increasing the harmonised tax rate $\bar{t}$, leaves the location of firms unchanged (this result was established in Chapter 4) and decreases the global level of emissions, χ, monotonically.

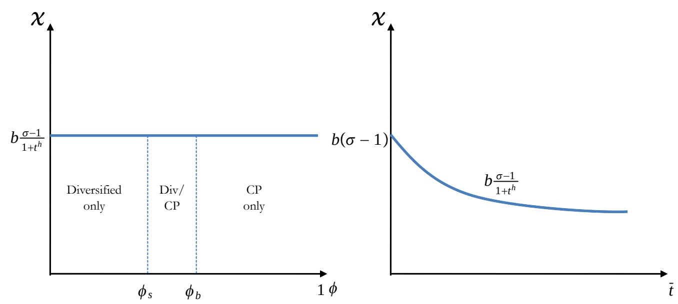

Figure 13: Global emissions with harmonised taxation

The harmonised tax case provides a baseline of maximum efficiency for a given increase in the tax rate in one region. However, as the existence of unequal levels of regulation is a precondition

elasticity of substitution (CES) sub-utility, iceberg trade costs and the symmetry implied by harmonised taxation. Altering any of these will invalidate the result.

87 This Proposition is almost identical to Proposition 1 in Ishikawa and Okubo (2009). In contrast, however, it applies for all trade costs, not just those at which full agglomeration occurs.

for carbon leakage, the harmonised tax case features no carbon leakage and yields little insight into its nature. To consider carbon leakage I evaluate the unharmonised tax case.

5.4 Case 2: Unharmonised taxation

In this section I consider the global level of emissions when taxes are unharmonised. As demonstrated in Chapter 4, the tax differential, r, and trade freeness ϕ, are both important determinants of the location of firms.

Unlike in Chapter 4 (in which the values of t and t^* only affected the extent of firm relocation through their effect on the tax differential r), I cannot ignore the absolute level of each tax rate and focus only on r in undertaking comparative static analysis of the global level of emissions. This problem arises because the absolute levels of both t and t^* alter local variable costs and therefore firm size through the firm scale effect.

To abstract from complications arising from the need to consider both the absolute values of t and t^* and the resulting value of r, while retaining the full generality of the model I assume that the environmental agreement leaves t^* fixed at its pre-agreement level and only increases t. This assumption does not reduce the generality of the results but ensures that r and t have a one-to-one mapping.

As the relocation response of firms to environmental regulation differs significantly between the CP and diversified equilibria, I consider each in turn, beginning with the CP equilibria.

5.4.1 The CP equilibria

In this section I assume that the core is initially in the north in order to ease exposition.[88]

I begin by establishing the level of global emissions in the CPN and CPS equilibria. Substituting $s_n = 1$ and $s_n = 0$ into equation (71), the global level of emissions for the CPN and CPS equilibria are:

$$\chi = \Gamma + \Gamma^* = b\frac{\sigma - 1}{1 + t} + 0, \text{ for the CPN equilibrium} \tag{72}$$

[88] Some generality is lost through this assumption as I no longer consider the case in which the core is initially in the south prior to the IEA. 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.

$$\chi = \Gamma + \Gamma^* = 0 + b\frac{(\sigma - 1)}{1 + t^*}, \text{ for the CPS equilibrium} \tag{73}$$

I consider the effects of t and ϕ on χ separately.

The effect of t on χ Equations (72) and (73) suggest three useful conclusions.

Conclusion 3 *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.*

Conclusion 4 *The global level of emissions is decreasing in the core's tax rate provided no relocation of firms occurs. Specifically, increasing t decreases the level of global emissions at rate $b\frac{\sigma-1}{(1+t)^2}$ 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 from $b\frac{\sigma-1}{1+t}$ to $b\frac{(\sigma-1)}{1+t^*}$.*

Conclusion 5 *The tax rate in the periphery, t^*, has no effect on the global level of emissions provided the IEA is such that $r < r^N = \frac{2\phi^{1-a}}{2-(1+b)(1-\phi^2)}$.*

An IEA which sets unharmonised taxes can be as effective at reducing global emissions as a harmonised IEA which has the same northern tax rate provided the tax rates are not too differentiated. χ declines in the northern tax rate until the tax differential is such that $r = r^N$, beyond this level of differentiation χ catastrophically increases as all firms relocate to the south. The southern tax rate can now influence χ. When such a relocation of firms occurs the leakage rate is greater than unity and can be as large as $\frac{1+t}{1+t^*}$.[89]

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

The effect of ϕ on χ The level of ϕ can also influence χ if it precipitates catastrophic relocation of firms. Both liberalisation (such that $\phi > \phi_b^N$) and restriction (such that $\phi < \phi_a^N$) of trade

[89] 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 delocation occurs.

can lead to 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 15 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 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 $b\frac{\sigma-1}{1+t}$) 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 the equivalent northern tax rate 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, $b\frac{(\sigma-1)}{1+t^*}$. Points D, E and F in Figure 15 demonstrate the effect of first increasing the tax differential (D to E) and then decreasing it (E to F). This simple illustrates how the environmental consequences of changes in the tax differential may be difficult to reverse.

Interestingly, as firm relocation is entirely responsible for the increase in emissions, the time scale over which one considers the regulation matters. In the short-run, even if $r > r^N$ and catastrophic relocation of industry is induced, no carbon leakage occurs as no firms are able to relocate. Only in the long-run (after firms relocate) does the IEA cause any carbon leakage.[90]

[90] This result reconciles with the belief in policy circles that carbon leakage is predominantly a long-term phenomenon. A recent report on the EU-ETS (International Energy Agency (2008)) suggests that it is too early to evaluate the extent of carbon leakage induced. The report contends that long-term contracts and long-lived capital investments such as plant and machinery have made it undesirable for firms to relocate from the EU in the short term despite the relatively high cost of emitting GHGs.

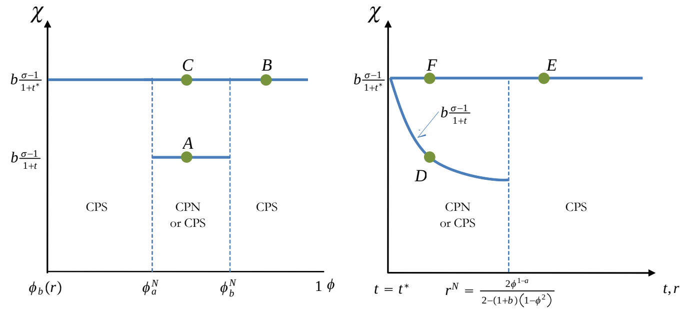

Figure 14: Global emissions at CP equilibria with unharmonised taxation

5.4.2 The diversified equilibrium

As was the case in Chapter 4 when considering firm relocation, the level of global emissions, χ, responds differently to increases in t from an initial diversified equilibrium than it does from a CP equilibrium. Propositions 9 and 10 reveal this.

Proposition 9 *Beginning from the harmonised tax diversified equilibrium (that is, if $t = t^*$ and $s_n = \frac{1}{2}$), $\frac{\partial \chi}{\partial t} < 0$.*

Proof. See Appendix 5.6. ■

Proposition 9 implies that beginning from a symmetric diversified equilibrium, as t increases, the total level of emissions initially declines.

There is, however, a level of t above which χ increases. Proposition 10 establishes this result.

Proposition 10 *Beginning from a diversified equilibrium, if the IEA sets t sufficiently large, all firms locate in the south and $\chi = b\frac{(\sigma-1)}{1+t^*}$.*

Proof. Complete relocation occurs if the tax differential is sufficiently large.[91] The result follows. ■

[91] This result was established in Chapter 4.

Propositions 9 and 10 imply that 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.

Figure 15 illustrates the effect of increasing t while holding t^* constant. The level of ϕ determines the number of firms which relocate in response to a given tax rate differential. High ϕ (that is, ϕ close to the harmonised tax break point, ϕ_b) induces a large number of firms to relocate for a given tax differential and can lead to a catastrophic relocation to the CPS equilibrium. This was demonstrated in Chapter 4. For lower values of ϕ, the same tax differential will yield smooth relocation to the south.

A level of r exists at which increasing t no longer reduces global emissions. This is reflected in Figure 15 at the minimum of each of the three curves. At this level of t, tighter environmental policy in the north cannot be justified on environmental grounds. Derivation of the exact point at which this occurs is not possible due to the presence of the s_n term in χ which implies that it cannot be analytically differentiated with respect to t.

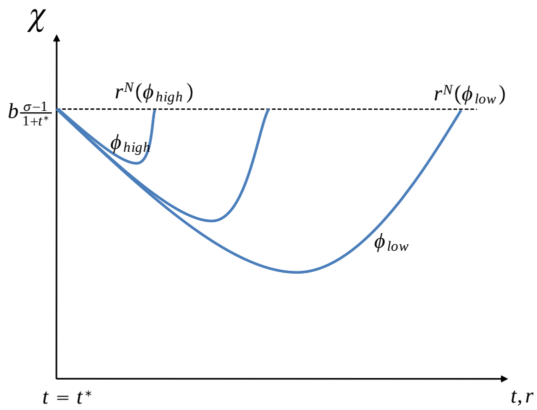

Figure 15: Global emissions at the diversified equilibrium

A final interesting (and somewhat counter-intuitive) result is that firms in the north, where environmental regulation is more stringent, are actually larger than those in the south as t increases. I state this as a proposition and prove it.

Proposition 11 *At the diversified equilibrium the higher taxing region has larger firms than the* *lower taxing region.*

Proof. See Appendix 5.7. ■

Skilled workers in the north face a higher cost of living index than they would if they relocated to the south. Therefore nominal skilled wages must be higher in the north in a diversified equilibrium. Higher skilled wages requires higher profits and therefore a larger firm size.[92] Therefore, somewhat counter-intuitively (and in contrast to Conclusion 3 for the CP equilibria), firm size is larger in the region with the higher tax rate. Yet again, the response of endogenous parameters to changes in the tax rate depends critically on the initial configuration of industry. The reduction in global emissions as t increases is brought about by a contraction in firm size in the south and the relocation of firms from north to south.

5.5 Conclusion

In Chapter 1 I stated the second key question of this thesis: *How does the degree of differentiation of environmental policy influence the extent of carbon leakage?*. In Chapter 5 I showed that the answer depends crucially on the initial location of industry, trade costs and relative tax rates.

The NEG approach adopted illustrates the important role agglomeration forces can play in determining the extent of carbon leakage. By introducing agglomeration forces this chapter has demonstrated several results which differ significantly from previous studies of carbon leakage. I showed that agglomeration forces may reduce the extent of carbon leakage if the tax differential is not too great. In addition, I showed how long-run leakage, which arises as a consequence of firm relocation, can be significantly higher than short-run leakage, which arises as a consequence of factor price or firm scale changes. Finally, I showed how the presence of agglomeration forces can make the effect of policy changes on global emissions difficult to reverse.

[92] Interestingly, this is a similar result to Proposition 2 of Lawrence and Spiller (1983). In their model, with monopolistic competition and immobile factors, plant size is smaller in the region which is abundant in the variable factor of production. In this thesis the lower carbon tax rate reflects this relative abundance in the south.

5.6 Appendix 1: Proving $\frac{\partial \chi}{\partial t}\Big|_{t=t^*=0} < 0$

Global emissions can be expressed as:

$$\chi = b\left(\sigma - 1\right)\left[s_E\left[\frac{1}{1+t} + \phi q\frac{1}{1+t^*}\right]\frac{1}{(1+\phi q)} + (1-s_E)\left[\phi\frac{1}{1+t} + q\frac{1}{(1+t^*)}\right]\frac{1}{(q+\phi)}\right], \frac{1-s_n}{s_n}r = q \tag{74}$$

Taking the derivative yields:

$$\frac{\partial \chi}{\partial t} = b\left(\sigma - 1\right)\left[\begin{array}{c} \frac{\partial s_E}{\partial t}\left[\frac{1}{1+t} + \phi q\frac{1}{1+t^*}\right]\frac{1}{(1+\phi q)} + s_E\left[\frac{\partial q}{\partial t}\frac{\phi}{1+t^*} - \frac{1}{(1+t)^2}\right]\frac{1}{1+\phi q} \\ -\frac{\phi\frac{\partial q}{\partial t}}{(1+\phi q)^2}s_E\left[\frac{1}{1+t} + \phi q\frac{1}{1+t^*}\right] + \frac{\partial(1-s_E)}{\partial t}\left[\left[\phi\frac{1}{1+t} + q\frac{1}{(1+t^*)}\right]\frac{1}{(q+\phi)}\right] \\ +\left(1-s_E\right)\left[\frac{\partial q}{\partial t}\frac{1}{1+t^*} - \frac{\phi}{(1+t)^2}\right]\frac{1}{(q+\phi)} - \left(1-s_E\right)\left[\phi\frac{1}{1+t} + q\frac{1}{(1+t^*)}\right]\frac{\frac{\partial q}{\partial t}}{(q+\phi)^2} \end{array}\right] \tag{75}$$

Substituting in $t = 0, t^* = 0, s_n = \frac{1}{2}$, yields:

$$\frac{\partial \chi}{\partial t} = b\left(\sigma - 1\right)\left[\frac{\partial s_E}{\partial t} + \frac{1}{2}\left[\frac{\partial q}{\partial t}\phi - 1\right]\frac{1}{1+\phi} - \frac{\phi\frac{\partial q}{\partial t}}{(1+\phi)}\frac{1}{2} + \frac{\partial\left(1-s_E\right)}{\partial t} + \frac{1}{2}\left[\frac{\partial q}{\partial t} - \phi\right]\frac{1}{(1+\phi)} - \frac{1}{2}\frac{\frac{\partial q}{\partial t}}{(1+\phi)}\right] \tag{76}$$

Cancelling terms yields:

$$\frac{\partial \chi}{\partial t} = -\frac{1}{2}b\left(\sigma - 1\right) < 0 \tag{77}$$

5.7 Appendix 2: Proof higher taxing region has larger firms in a diversified equilibrium

Recall expressions for the real wages in each region:

$$\begin{aligned}\omega = \eta \tfrac{w_H}{P}, P \equiv P_M^{\mu}, P_M \equiv \left(\int_0^{n^w} p_i^{1-\sigma} di\right)^{\frac{1}{1-\sigma}} = p_N \left[s_n + (1-s_n)\phi r\right]^{\frac{1}{1-\sigma}} \\ \omega^* = \eta \tfrac{w_H^*}{P^*}, P^* \equiv P_M^{*\mu}, P_M^* \equiv \left(\int_0^{n^w} p_i^{*1-\sigma} di\right)^{\frac{1}{1-\sigma}} = p_N \left[\phi s_n + (1-s_n) r\right]^{\frac{1}{1-\sigma}}\end{aligned} \quad (78)$$

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

$$P_M - P_M^* = p_n \left[[1-\phi]\left[s_n - [1-s_n] r\right]\right]^{\frac{1}{1-\sigma}} \quad (79)$$

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:

$$x = w_H \frac{(\sigma - 1)}{1 + t} \quad (80)$$

Therefore:

$$\frac{x}{x^*} = \left[r^{\mu} \frac{[s_n \phi + r[1-s_n]]}{[s_n + r\phi[1-s_n]]}\right]^{\frac{\mu}{\sigma-1}} \quad (81)$$

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

$$r[1-s_n] > s_n \quad (82)$$

Alternatively, this can be expressed as:

$$r\left[1-s_n\right]=s_n+\Delta \tag{83}$$

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

$$s_n\phi+s_n+\Delta \tag{84}$$

The denominator in the fraction inside the square brackets is:

$$s_n+\phi\left[s_n+\Delta\right]=\phi s_n+s_n+\phi\Delta \tag{85}$$

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

6 CONCLUSION

In the introduction to this thesis, I asked two key questions. First: *How does the degree of differentiation of environmental policy influence the extent of firm relocation? Second: How does the degree of differentiation of environmental policy influence the extent of carbon leakage?*

In Chapter 2 I surveyed the existing economic literature in order to demonstrate the relevance of these two questions and the importance of my proposed approach. In Chapter 3 I introduced and solved an NEG model capable of addressing both questions. In Chapter 4 I considered the former question and in Chapter 5, the latter. Throughout this thesis I have considered a variety of related questions and contributed to the theoretical literature. In concluding this thesis I summarise its main contributions, suggest three avenues for future research and finally draw out the most important policy implications arising from my analysis.

6.1 Summary of contributions

6.1.1 Contributions to the theory of the PHE: Chapter 4

Chapter 4 set out two main contributions to the theory of the PHE. First, where trade liberalisation increases the strength of the bonds between co-located firms, it may reduce the extent of firm relocation in response to a given environmental policy disadvantage. This result challenges the logic underlying the PHH, which has been previously supported by models which do not feature agglomeration forces.

Second, the effect of changes in environmental tax levels on the location of industry depends on whether industry is agglomerated in one region (i.e. all firms are located in the same region) or dispersed across both. Agglomerated industry does not relocate in response to a small tax disadvantage, while dispersed industry does.

6.1.2 Contributions to the theory of carbon leakage: Chapter 5

In Chapter 5 an FE model was applied to the issue of carbon leakage. The analysis suggested that agglomeration forces can both increase and decrease the extent of carbon leakage. If all industry is agglomerated in one region, firms simply decrease their scale (and therefore emissions) in response to moderate tax differentials. Under this condition, differentiated policies can be as effective as harmonised policies in reducing global emissions. If, however, the tax differential is large enough to encourage a firm to relocate ($r > r^N$), then all firms relocate and the carbon leakage rate can be greater than 100%.

When industry is dispersed between regions, it responds differently to differentiated taxation than when it is agglomerated in one region. I established that when industry is dispersed, carbon leakage will always occur when regulation is differentiated. In addition, a level of tax differentiation was shown to exist, beyond which more stringent regulation in the higher taxing region increases global emissions. At the dispersed equilibrium I showed that firms in the more stringently regulated region are larger than those in the less stringently regulated region. This provides an interesting testable hypothesis which could be considered in future empirical research.

6.2 Extensions

6.2.1 Border taxation and side payments

I have shown that the harmonisation of taxes can minimise the extent of carbon leakage and deindustrialisation caused by tightening environmental regulation. However, in international negotiations regulating GHG emissions almost all nations have agreed that responsibilities should be differentiated. This thesis therefore raises a further important question: *How can responsibilities be differentiated without differentiating regulations?*

This appears to be a critical question currently at the centre of international negotiations on the regulation of GHG emissions. For example, of the twelve paragraphs in the Copenhagen Accord (2010), seven paragraphs describe mechanisms for differentiating responsibility without differentiating regulation. These mechanisms generally take the form of lump sum payments for ‘technology transfer’, ‘capacity-building’ or financial compensation to developing countries for reducing their own emissions.

While such measures may have political merit, it is likely that more efficient policies exist which prevent the leakage and deindustrialisation that can arise from regulatory differentiation as demonstrated in this thesis. One such policy might be the imposition of border tariffs by more stringently regulated regions on carbon intensive goods produced in less regulated countries.[93]

[93] Hoel (2001) considers the optimal combination of border pollution taxation and side payments to reduce

Incorporating such measures into the model presented in this thesis may indicate the most efficient methods of differentiating responsibility between nations.

6.2.2 Competitive environmental policy

The analysis undertaken in this thesis has considered the response of firms to exogenous policy. I have simply assumed that both regions ratify the IEA. This is desirable for addressing the two key questions of this thesis. 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 would enable consideration of the trade-off between environmental and economic objectives in a model with agglomeration forces.

6.2.3 Computable general equilibrium modelling

Simple models such as that presented in this thesis are useful in demonstrating novel theoretical effects in an analytically tractable setting. This simplification comes at the cost of realism. I have shown that the core does not relocate in response to relatively small tax differentials and that carbon leakage can be very large for even very small changes in the tax differential. However, I cannot determine whether these are theoretical aberrations based on unrealistic parameter inputs and highly specific functional forms, or whether they are realistic possibilities in a multi-region, multi-industry setting which has been calibrated to observable parameters.

It may be possible to represent the FE model as a CRS model with external economies that create rents accruing (largely, and possibly completely) to the mobile factor. Markusen (1990) shows that monopolistically competitive trade models of the Dixit Stiglitz variety have an equivalent representation as CRS models with external economies. Such a representation may facilitate CGE modelling as well as future empirical work.

6.3 Policy implications

The findings of this research are relevant for policy makers seeking to design optimal environmental policies. I have touched on a number of the most relevant policy implication throughout

carbon leakage from differentiated regulation between industrialised and non-industrialised countries. He concludes that a combination of both measures is, in general, optimal.

this thesis, however, I expand upon the three most important policy implications below.

First, industry characteristics should determine the level of regulation imposed within a region. I have shown that both the cost (in terms of lost industry) and effectiveness of any given level of regulation is likely to differ drastically across sectors depending on trade costs and market structure. Simply assuming that lower transport costs make firms more likely to relocate abroad in response to a regulatory differential may be misleading if industries are agglomerated. This is due to the fact that higher transport costs may in fact weaken agglomeration forces, making relocation more attractive. In order to avoid industry relocation while implementing differentiated regulation, the price of emitting should be varied such that it is low (high) for those sectors which are (are not) relatively footloose.[94]

Second, in this model regulation can serve two purposes in environmental agreements (and as a consequence, it imposes two types of costs). Regulation can encourage firms to pollute less (by encouraging a contraction of firm size) and it can discourage firms from relocating to less regulated countries (this implies an opportunity cost for the potential recipient of industry). A region with no industry can minimise carbon leakage by committing to impose a tax on any firm which relocates to its shores, even if (in the absence of industry) the tax raises no revenue. Therefore, an absence of polluting industry need not be a reason (on its own) for a region not to adopt a pollution tax. However, there is also an opportunity cost to that region of such regulation (in the form of the loss of the establishment of industry).

The third policy implication comes in the form of a warning. This thesis suggests that carbon leakage is a phenomenon which is best evaluated in the long-run. In the model in this thesis, all leakage from a CP equilibrium is brought about by firm relocation rather than adjustments in the scale of firms. The diversified equilibrium features both relocation and scale adjustment. Empirical estimates based on relatively short periods of observation (such as those based on the EU-ETS) may not capture the potentially significant consequences of firm relocation for carbon leakage.

[94] Those industries which are not relatively footloose include industries for which agglomeration forces are strong (i.e. $\phi \approx \phi_M^N$) and those which are not tradable (i.e. $\phi \approx 0$). Relatively footloose industries include those for which $\phi \approx \phi_a^N$ and $\phi \approx \phi_b^N$.

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