ESSAYS IN INTERNATIONAL ECONOMICS AND THE ENVIRONMENT

A thesis

submitted in partial fulfillment

of the requirements for the degree of

D.PHIL. IN ECONOMICS

by

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MAGDALEN COLLEGE

UNIVERSITY OF OXFORD

HILARY TERM 2013

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Approximate number of words: 64,000

Abstract: Essays in International Economics and the Environment

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Chapter One

I consider the influence of foreign environmental policy on domestic manufacturing activity using theory and empirics. A tractable three-country spatial model yields a theory of locational comparative advantage in the production of pollution-intensive manufactured goods: greater market access to countries with stringent environmental policy encourages output in the polluting sector. Operationalizing the model empirically, I find robust evidence that high market access to countries with stringent environmental policy increases manufacturing value added. Both the theoretical and empirical analyses suggest that estimates of the Pollution Haven Effect that ignore third country environmental policy – yet make the stable unit treatment value assumption – can be misleading.

Chapter Two

We investigate the impact of short-term weather and long-term climate on self-reported life satisfaction using panel data. We find robust evidence that day-to-day weather variation impacts life satisfaction by a similar magnitude to acquiring a mild disability. Utilizing two sources of variation in the cognitive complexity of satisfaction questions, we present evidence that weather bias arises because of the cognitive challenge of reporting life satisfaction. Consistent with past studies, we detect a relationship between long-term climate and life satisfaction without individual fixed effects. This relationship is not robust to individual fixed effects, suggesting climate does not directly influence life satisfaction.

Chapter Three

This chapter 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 may make firms tolerant of regulatory disadvantage. Each region ratifies an international environmental agreement (IEA) requiring it to tax transboundary pollution created by local firms. In contrast to previous NEG studies, the model adopted is considerably more tractable, enabling comparative static analysis to be conducted 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. 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. Trade liberalization can actually make industry less likely to relocate in response to a regulatory disadvantage.

The model is further extended to consider the issue of carbon leakage, which arises in the regulation of greenhouse gas (GHG) emissions. 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. When industry is diversified between regions, firms respond to higher (lower) relative domestic taxes by increasing (decreasing) output and polluting more (less).

Acknowledgements

First and most importantly, I must express my gratitude to both of my supervisors, Peter Neary and Cameron Hepburn. Peter and Cameron have made significant contributions to both the content of this thesis and to my development as a researcher. It has been an enormous privilege to work with both of them.

Throughout this thesis – at the beginning of each chapter – I express my gratitude to those who assisted with that particular piece of research. Of those who contributed to the various chapters, I owe special thanks to Professors Beata Javorcik, Rick van der Ploeg and Tony Venables, who played important roles throughout my graduate studies, both on technical issues and to my development as a researcher. It is difficult to imagine a more supportive graduate research environment in international economics than the one provided at Oxford by Peter, Beata, Rick and Tony.

Ian Crawford, Julien Labonne and Simon Quinn also regularly set time aside – well above and beyond the call of duty – to speak about the minutiae of my econometric research. Russ Hillberry also generously provided council when needed on content and on the economics profession more broadly.

As friends and colleagues Sam Wills and Jacobus Cilliers are due special thanks. Over the past three years I have benefitted enormously from the council and advice offered by them.

I am grateful to my wife Katherine, who, in addition to being one of most meticulous proof readers I know, encouraged me to aspire to come to Oxford to study. Thanks also to my daughter Audrey, who has absolutely thrived over the past 16 months in spite of the many forms of neglect necessitated by her father's commitment to writing this thesis.

Thanks also to parents Fiona and Murray, and to my former classmates from Melbourne Ben, Cameron and James for their thoughtful comments.

I am also extremely grateful to the Rhodes Trust for its financial support. I would especially like to thank the former Warden, Don Markwell, and the 2008 Victorian selection panel, comprising David de Kretser, Patricia Faulkner, Simon McKeon, Diana Nicholson, Tim Orton, Ben Rimmer and Kate Vinot, for the faith they placed in me.

Of course, 'the usual caveat' applies, and I do not mean to implicate anyone else in the shortcomings of the present research. Nonetheless, it is no exaggeration that this research has only been made possible by the generous assistance of many people; I am extremely grateful for their help.

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Pollution Havens: Does Third Country Environmental Policy Matter?

John Feddersen[1]

Abstract

I consider the influence of foreign environmental policy on domestic manufacturing activity using theory and empirics. A tractable three-country spatial model yields a theory of locational comparative advantage in the production of pollution-intensive manufactured goods: greater market access to countries with stringent environmental policy encourages output in the polluting sector. Operationalizing the model empirically, I find robust evidence that high market access to countries with stringent environmental policy increases manufacturing value added. Both the theoretical and empirical analyses suggest that estimates of the Pollution Haven Effect that ignore third country environmental policy – yet make the stable unit treatment value assumption – can be misleading.

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1 Department of Economics, University of Oxford, Manor Road, Oxford, OX1 3UQ, United Kingdom (email: john.feddersen@economics.ox.ac.uk). I am grateful to my advisors Peter Neary and Cameron Hepburn for regular comments on this paper. Without implication, I also thank James Anderson, Richard Baldwin, Brian Copeland, Dieter Helm, Russell Hillberry, Beata Javorcik, Gianmarco Ottaviano, Rick van der Ploeg, John Romalis, Daniel Sturm, Karen Helene Ulltveit-Moe, Tony Venables, Eric Verhoogen, and seminar participants in Birmingham, London, Leuven, Mannheim and Oxford for comments that improved the paper.

1.1 Introduction

Q: Which non-EU countries would see the largest increase in production if the price of EU production were to rise?

A: The truck transport threshold of up to 1000km means that ... there is evidence of significant additional capacity due to be built just outside Europe ... in Belarus, Northern Africa, Russia and the Ukraine.

Response by The European Container Glass Federation to the 'public consultation on state aid in the context of the amended EU Emissions Trading Scheme (ETS)', 2011

Is location a source of comparative advantage in the production of polluting goods? Owing to its excellent market access, might Poland specialize in the production and export of polluting goods that are heavily regulated – and therefore expensive to produce – in Germany?[2] I answer these questions using theory and empirics. A tractable three-country spatial model yields a theory of locational comparative advantage in the production of pollution-intensive manufactured goods: greater market access to countries with stringent environmental policy encourages output in the polluting sector. Operationalizing the model empirically, I find robust evidence that high market access to countries with stringent environmental policy increases manufacturing value added.

Cross-border environmental policy effects have received surprisingly little attention in the empirical literature, given the increasing policy focus on transboundary pollutants. With transboundary pollutants, the simple calculus of marginal cost versus marginal benefit or 'jobs versus the environment' is more complicated. If more stringent domestic environmental policy increases foreign pollution (so-called 'leakage'), the effectiveness of environmental measures diminishes.

Recent literature focuses overwhelmingly on the effect of *domestic* environmental policy on *domestic* economic activity.[3] Papers by Eskeland and Harrison (2003) and Hanna (2010) are exceptions,

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2 For example, responding to Germany's decision to shut down all domestic nuclear power plants in May 2011, Polish Prime Minister Donald Tusk said: *From Poland's point of view this is a good thing not a bad one ... it means coal-based power will be back on the agenda.*

3 For example, Fredriksson et al. (2003), Greenstone (2002), Kellenberg (2009), and Wagner and Timmins (2009) consider the relationship between domestic policy and measures of economic activity, including FDI, employment and multinational affiliate value added. Another set of studies deploy multinomial choice models to estimate the effect of domestic environmental policy on plant location decisions. These include Becker and Henderson (2000), Ben Kheder and Zugravu (2012), Dean, Lovely and Wang (2009), Javorcik and Wei (2004), Keller and Levinson (2002), and List and Co (2000). Aldy and Pizer (2012), Ederington et al. (2005), Ederington and Minier (2003), and Levinson and Taylor (2008) estimate the effect of U.S. environmental policy on U.S. net trade flows and all find that more stringent U.S. environmental policy increases net imports. However, these studies do not consider how and where U.S. policy influences levels of foreign production or pollution.

which are closest in purpose to this chapter as they estimate the effect of U.S. environmental policy on foreign production. Eskeland and Harrison (2003) find little evidence that pollution abatement costs increase outbound U.S. FDI flows to developing countries. Hanna (2010) finds that U.S. multinational firms significantly increase foreign output in response to more stringent environmental policy. Neither of these studies identifies which foreign jurisdictions increase production most in response to U.S. environmental policy.

The paucity of empirical evidence on the international consequences of environmental policy is clearly not due to lack of interest in the subject. An enormous Computable General Equilibrium (CGE) literature on 'carbon leakage' has developed since the adoption of the Kyoto Protocol (1997) to stabilize greenhouse gas emissions, considering how domestic environmental policy influences foreign economic activity. Babiker (2005) provides a prominent example.

However, the shortcomings of CGE are well known. CGE complexity makes it difficult for anyone but the authors to understand what drives results. In comparison to empirical work, assumptions tend to drive conclusions. High sensitivity to parameter and functional form assumptions cause peer-reviewed CGE carbon leakage estimates to vary between less than 0 percent and over 100 percent when modelling identical international environmental agreements. In light of these challenges, empirical analysis is a necessary complement to existing CGE studies. If we plan to assume domestic environmental policy affects foreign production, then empirical evidence supporting this should exist.

The lack of internationally comparable data on environmental policy stringency is a major hurdle to empirical analysis.[4] A second challenge arises because estimating international effects, unlike domestic effects, requires a detailed theoretical structure if it is to plausibly account for the heterogeneous effects of domestic environmental policy across foreign countries. Without theory we cannot, for example, model the way stringent policy in Germany influences Polish and Peruvian production differently. This chapter directly addresses these two challenges, using theory to derive a measure of foreign environmental policy reflecting locational comparative advantage in polluting production for each country-industry-year triple, and estimating its importance with a recent and increasingly used cross-country data set measuring environmental policy stringency.

[4] Before making restrictive assumptions necessary to avoid the use of measures of foreign environmental policy, Aldy and Pizer (2012) state: *If our data allowed us to construct a proxy measure of foreign regulation, we could … estimate the coefficient on foreign regulation in a regression with domestic production as the regressand … unfortunately, such data are not available.*

Before any empirics, I present and solve a three-country model with environmental policy for the locus of manufacturing production. The use of a three-country model to derive analytic expressions for the location of polluting manufacturing activity differentiates this chapter from previous theoretical studies of the 'Pollution Haven Effect' (PHE)[5], which almost exclusively adopt two-country models.[6] A three-country model enables spatially heterogeneous effects of changes in environmental policy, rendering location a source of comparative advantage in pollution intensive production.[7] This motivates the empirical approach adopted.

A generalized version of the theoretical model is used for the empirical analysis. The structural estimating equation implies that polluting firms value environmental comparative advantage, locating where domestic environmental policy is lax and competitors in easily accessed foreign countries face high costs of complying with environmental policy. The estimating equation also makes explicit how failure to control for foreign environmental policy can introduce bias to studies of the effect of domestic environmental policy on domestic economic activity.

There is a growing empirical literature on 'third country' effects at the heart of which is the idea that location – in particular, the characteristics of nearby jurisdictions – matters.[8] Anderson and van Wincoop (2003) show – both theoretically and empirically – that third country transport costs are critical determinants of bilateral trade. Head and Mayer (2004) and Redding and Venables (2004) examine the influence of third country market size and output on inbound FDI and domestic income. Helpman et al. (2004) suggest that third country firm productivity is likely to influence FDI decisions.

Model in hand, using industry-level data on total value added for 49 countries – which together represent over 90 percent of world GDP – I show that locational comparative advantage in polluting production significantly influences manufacturing activity. More stringent foreign environmental policy, appropriately structurally weighted by market size and market access, increases domestic

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5 The PHE implies that tightening pollution policy affects plant location and trade flows (Copeland and Taylor 2004).

6 Two-country models include: Pethig (1976), Siebert (1979) and Neary (2006), who present models with constant returns to scale (CRS) and no transport costs; Markusen et al. (1993), Motta and Thisse (1994) and Ulph (1994), who present international oligopoly models; and Venables (1999) and Feddersen (2012), who put forward models with monopolistic competition and transport costs.

7 Deardorff (2004) makes a similar point, showing that 'local comparative advantage' (which is defined as arising from prices that are low in comparison to nearby countries rather than the world as a whole) drives trade in a world with transport costs.

8 In the present paper – as in Redding and Venables (2004) – the term 'third country' could be construed as slightly misleading. Conventional use of the term applies to situations where bilateral flows (typically FDI or trade) are influenced by the characteristics of a country that is neither origin nor destination. In the present paper, the term implies the characteristics of nearby jurisdicitons influence purely domestic variables, like manufacturing value added or profits. I therefore use the terms 'third country' and 'foreign country' interchangably.

manufacturing value added. This result survives instrumental variable (IV) estimation, extensive controls and fixed effects specifications.

To the best of my knowledge, this is the first study of the PHE to use total value added – rather than, for example, foreign affiliate value added, FDI or firm births – as a measure of economic activity. This more comprehensive activity variable arises from the theory and is of interest in light of Poelhekke and van der Ploeg's (2012) evidence that FDI faces 'corporate social responsibility' (CSR) motives, deterring investment in countries with lax environmental policy. Weak evidence of the PHE in past studies may be a result of using the wrong regressand.

My empirical results also suggest – as foreshadowed by theory – that past studies of the PHE that do not control for foreign-country environmental policy, can contain bias on the coefficient on domestic environmental policy. The estimated delocation elasticity – the negative influence of tighter domestic environmental policy on domestic manufacturing value added – typically decreases after accounting for third country environmental policy in the empirical model.

Finally, the chapter yields one key policy implication, suggesting that policy coordination with major trading partners is a powerful way to address the adverse competitiveness effects of unilateral environmental policy. With transport costs geographically segmenting markets, regional policy is extremely powerful. For example, the leakage levels of a global agreement on carbon dioxide emissions – which is widely considered to be a desirable goal in long-term greenhouse gas policy – may be very closely approximated by a series of more politically feasible regional agreements.

The remainder of this chapter proceeds as follows: Section 1.2 develops the model. Section 1.3 describes the empirical strategy and presents estimation results. Section 1.4 concludes the chapter.

1.2 A model of locational comparative advantage

The theoretical model serves two purposes. First, using a three-country structure I show that location alone – specifically, proximity to a country with stringent environmental policy – can lead a country with no comparative advantage induced by factor abundance or environmental policy to specialize in polluting production. This is the central empirical hypothesis of this chapter and it is a result that does not arise in a two-country model. I demonstrate the result in both a medium-run case where firm prices and quantities vary, but firm location is fixed, and a long-run case where firm location varies. Second, a more general many-country version of the theoretical model provides the structural measures of locational comparative advantage in polluting production, and transportation costs, used empirically in Section 1.3.

1.2.1 Setup

There are three countries labelled 1, 2 and 3. Country i hosts an exogenous number of consumers/workers L_i who each supply one unit of labor inelastically. Labor is the only factor of production and workers are internationally immobile.[9] Preferences of consumers are defined over horizontally differentiated manufacturing and a homogeneous non-manufactured good, with the utility of a representative consumer equal to:

$$U = C_M^{\mu} C_N^{1-\mu}, \quad C_M \equiv \left(\int_0^{n^w} D(v)^{\frac{\sigma-1}{\sigma}} dv \right)^{\frac{\sigma}{\sigma-1}}, \quad 0 < \mu < 1 < \sigma \tag{1.1}$$

Cobb-Douglas utility comprises consumption of the non-manufactured good (C_N) and a CES aggregate of all manufactured varieties (C_M). μ is the expenditure share for the manufactured good.

$D(v)$ denotes consumption of manufactured variety v. n^w is the mass of manufactured varieties produced globally. σ is the elasticity of substitution between manufactured goods. Maximizing (1.1) subject to the budget constraint yields the CES demand functions where E is the total expenditure on the manufactured good and G is the ideal manufacturing price index.

$$D(v) = \frac{p(v)^{-\sigma} E}{G^{1-\sigma}}, \quad G^{1-\sigma} \equiv \int_0^{n^w} p_j^{1-\sigma} dj \tag{1.2}$$

The non-manufactured good is produced with constant returns to scale (CRS) and is traded between countries without cost.[10] The cost of producing one unit of the non-manufactured good in country i is $w_i z_i$. w_i is the wage per worker in country i and z_i is the labor input per unit of

9 Assumptions regarding the location, mobility and utilization of the factor of production follow Krugman (1980) and are adopted for their analytical simplicity and their familiarity to international economists. These assumptions are not necessary. For example, the four results emphasized in this section can be derived in Martin and Rogers' (1995) Footloose Capital (FC) model and therefore, neither the absence of a second factor of production, say capital, nor the inter-country immobility of labor, is critical.

10 These assumptions yield substantial analytical tractability, but do not drive the paper's main results. As Deardorff (2004) shows, the two key assumptions giving rise to locational comparative advantage are first, transport costs and second, Ricardian comparative advantage (i.e. different levels of pollution intensity by sector).

output in both sectors in country i. With perfect competition, the price of the non-manufactured good in country i is $p_N^i = w_i z_i$, and with free trade $p_N \equiv p_N^1 = p_N^2 = p_N^3$. Assuming that all countries produce some of the non-manufactured good, unit labor cost equalization occurs: $w_1 z_1 = w_2 z_2 = w_3 z_3$.

The manufactured good is produced with increasing returns to scale (IRS) and is subject to iceberg transport costs, τ_{ij}, when transporting goods from country i for sale in country j. I assume that all countries host some manufacturing firms. A fixed quantity of labor, fz_i, is required per manufacturing firm, and z_i units of labor are required for each unit of the manufactured good produced in country i. Government environmental policy, t_i, adds to firm costs such that total costs in country i are:

$$TC_i = w_i z_i \left(f + t_i x_i\right), \qquad t_i > 1 \tag{1.3}$$

In the theoretical literature numerous methods have been adopted to model firms' cost of government environmental policy. Environmental policy in equation (1.3) can most naturally be thought of as requiring firms to hire workers to abate $t_i - 1$ units of pollution per unit of output.[11] This assumption is both highly analytically tractable and plausible in a number of applications. The four results emphasized in this section apply to more general forms of environmental policy and appendices with two plausible alternative specifications are available from the author.[12]

Because the theoretical model is introduced to show how location alone can drive comparative advantage in polluting, I assume that environmental policy is identical in countries 2 and 3 ($t_1 \neq t_2 = t_3$). Transport costs between any two countries are equal in both directions (i.e. $\tau_{ij} = \tau_{ji}$) and I adopt a hub-and-spoke trade arrangement with country 1 as the hub and $\tau_{23} = \infty$. This is the simplest trade structure that allows location choice for delocating production.[13] With-

[11] Units of pollution are selected such that abatement of each requires z_i units of labor.

[12] One case considered is if regulation adds to fixed costs – such that $TC_i = w_i z_i \left(t_i f + x_i\right)$ or $TC_i = w_i z_i \left(f + x_i\right) + t_i$. In this case, the model is far simpler to solve and yields the four results emphasized in this section. A caveat applies when taking this approach to data because the assumptions of CES utility and a large number of firms ensure fixed mark-up pricing over variable costs (see equation (1.4)). Therefore, competitiveness impacts of environmental policy affecting only fixed costs are unlikely to be observed in annual data because they only affect the location of firms and have no price effect. The second case considered is environmental policy in the form of a flat tax per unit of output (such that $TC_i = w_i z_i \left(f + x_i\right) + x_i t_i$). This might be appropriate in the case of a tax on pollution that increases linearly with output and is therefore unaffected by labor costs. The model is solvable for the location of firms, however, comparative statics are analytically unwieldy. Simulation provides a high degree of confidence that the four results emphasized in this section apply in a model with a flat per unit tax.

[13] Ossa (2011) adopts the same trade arrangement in the Krugman (1980) model for its simplicity. Citing the *Braess paradox* (Braess 1968), Behrens et al. (2009) show how complexity increases dramatically in the Krugman (1980) model with trade between country 2 and country 3.

	1	**2**	**3**
1	1	τ_{12}	τ_{13}
2	τ_{21}	1	∞
3	τ_{31}	∞	1

TABLE 1.1: Summary of transport costs

out loss of generality I assume $\tau_{12} < \tau_{13}$. Table 1.1 summarizes the structure of transport costs between the locus of production (rows) and the locus of consumption (columns).

1.2.2 Equilibrium location of firms

The combination of CES monopolistic competition and iceberg transport costs ensures mill pricing: a given firm receives the same revenue per unit sold after accounting for transport costs in all markets. Firms charge a constant mark-up equal to $\tau_{ij}\sigma/(\sigma-1)$ over their environmental policy inclusive variable cost of production $(w_i z_i t_i)$. Selecting the non-manufactured good as numeraire ensures $w_i z_i = 1$ for all i. The price of a manufactured variety made in country i and sold in country j is therefore:

$$p_{ij} = \tau_{ij}\frac{\sigma}{\sigma-1}t_i \tag{1.4}$$

Equation (1.4) establishes the relationship between environmental policy and prices and therefore the competitiveness of firms. Without intermediate inputs, firm revenue equals value added:

$$\mathrm{VA}_i = \mu t_i^{1-\sigma}\sum_{j=1}^{3}\frac{\tau_{ij}^{1-\sigma}Y_j}{\sum_{k=1}^{3}\tau_{jk}^{1-\sigma}n_k t_k^{1-\sigma}}, \qquad Y_j = w_j L_j \tag{1.5}$$

Equation (1.5) represents a medium-run equilibrium with fixed firm location, appropriate for empirical estimation with annual data (the focus of Section 1.3). Clearly, with some trade between regions ($\tau_{ij} < \infty$, for some j) firm value added in country i declines in t_i and increases in any t_j. Because the influence of t_j is augmented by greater market access to country i, equation (1.5) trivially exhibits locational comparative advantage: all else equal, value added is larger if nearby jurisdictions possess stricter environmental policy.

Equation (1.5) provides a bridge to the empirical section of the chapter. In the medium-run changes in firm output and prices drive changes in value-added, yet a key question at the heart of existing pollution haven literature is whether stricter environmental policy causes dirty industries to migrate, rather than increase or decrease firm output. Therefore, prior to empirical estimation of equation (1.5), I prove that locational comparative advantage – with firms locating near markets with stringent environmental policy – arises in the long run.

Designating q_1 (q_2) to be the break-even output level of firms in country 1 (countries 2 and 3), in equilibrium $q_i = f(\sigma - 1)/t_i$. Using this expression for firm output, I solve market clearing conditions for manufacturing firms in countries 1, 2 and 3 for their corresponding equilibrium price indexes as a function of model parameters. Details are in Appendix 1.A.1. Setting the definition of G_i from equation (1.2) equal to these expressions – equations (1.16), (1.17) and (1.18) in Appendix 1.A.1 – I solve the price indexes for the main variable of interest, the equilibrium location of firms:

$$n_1 = \frac{\mu}{f\sigma} r^{\sigma-1} \left[\frac{Y_1}{\Omega} - \frac{Y_2\phi_{21}}{\Theta - \phi_{12}\Omega} - \frac{Y_3\phi_{31}}{\Theta - \phi_{13}\Omega} \right] \tag{1.6}$$

$$n_2 = \frac{\mu}{f\sigma} \left[\frac{Y_2\left(1 - \phi_{13}^2\right)}{\Theta - \phi_{12}\Omega} + \frac{Y_3\phi_{12}\phi_{31}}{\Theta - \phi_{13}\Omega} - \frac{Y_1\phi_{12}}{\Omega} \right] \tag{1.7}$$

$$n_3 = \frac{\mu}{f\sigma} \left[\frac{Y_3\left(1 - \phi_{12}^2\right)}{\Theta - \phi_{13}\Omega} + \frac{Y_2\phi_{21}\phi_{13}}{\Theta - \phi_{12}\Omega} - \frac{Y_1\phi_{13}}{\Omega} \right] \tag{1.8}$$

$$\Omega \equiv r^{\sigma} - \phi_{12} - \phi_{13}, \qquad \Theta \equiv 1 - \phi_{12}^2 - \phi_{13}^2, \qquad \phi_{ij} = \tau_{ij}^{1-\sigma}$$

ϕ_{ij}, which is a measure of trade 'freeness' between countries, equals one when trade has no cost and equals zero for infinitely costly trade. I denote the ratio of the environmental policy parameter in country 1 to country 2 (or country 3) $r \equiv t_1/t_2 (= t_1/t_3)$.

1.2.3 Comparative statics

Equations (1.6), (1.7) and (1.8) enable comparative static analysis of the long-run relationship between the location of firms and the model's key parameters: environmental policy (t); transport costs (ϕ); and market size (Y). First, by differentiating equations (1.6), (1.7) and (1.8) with respect to t_1, note that more stringent environmental policy in country 1 decreases the number of firms and the level of output in country 1 (i.e. $\partial n_1/\partial t_1 < 0$). This is the aspect of the PHE that has been the focus of most empirical analysis.

Taking the cross-partial derivatives with respect to domestic environmental policy and, respectively, industry transport costs and foreign environmental policy yields two testable predictions:

Lemma 1.1 *The delocation elasticity increases with trade freeness* $\left(i.e.\ \frac{\partial^2 n_1}{\partial t_1 \partial \phi_{12}} < 0, \frac{\partial^2 n_1}{\partial t_1 \partial \phi_{13}} < 0\right)$

Proof. See Appendix 1.A.2 ■

Lemma 1.2 *The delocation elasticity decreases with neighborhood environmental policy stringency* $\left(i.e.\ \frac{\partial^2 n_1}{\partial t_1 \partial t_2} > 0\right)$

Proof. See Appendix 1.A.2 ■

Lemmas 1.1 and 1.2 apply in a simpler two-country model and the real value of the three-country model arises from the stricter spatial definition of a pollution haven that it enables. Only in a model with three or more countries can the more successful pollution haven – the market favored by delocating polluting production – be identified as a function of model parameters. Proposition 1.1 establishes the location preferences of delocating production from country 1 as a function of country sizes and transport costs.

Proposition 1.1 $\frac{\partial n_2}{\partial t_1} > \frac{\partial n_3}{\partial t_1}$ *iff*

$$\overbrace{\frac{Y_2\left(1-\phi_{13}^2-\phi_{12}\phi_{13}\right)\phi_{12}}{\left(\Theta-\phi_{12}\Omega\right)^2}}^{Term\ 1}+\overbrace{\frac{Y_1\phi_{12}}{\Omega^2}}^{Term\ 2}$$
$$>$$
$$\underbrace{\frac{Y_3\left(1-\phi_{12}^2-\phi_{12}\phi_{13}\right)\phi_{13}}{\left(\Theta-\phi_{13}\Omega\right)^2}}_{Term\ 3}+\underbrace{\frac{Y_1\phi_{13}}{\Omega^2}}_{Term\ 4}$$

Proof. See Appendix 1.A.3 ■

Inspection of Proposition 1.1 reveals that delocating production favors both the larger market – a 'market size' effect – and the more accessible market – a 'market access' effect. The market size effect arises because firm profits decline by less in larger markets for each additional firm that opens. This effect can be switched off in the model by setting $Y_2 = Y_3$.

The market access effect can be split into two components. The first component – which is a third country version of the market size effect – can be given intuition by comparing terms 2 and 4 in

Proposition 1.1. Because varieties exported from country 2 incur lower transport costs than those exported from country 3, country 1 consumes a higher quantity of each country 2 variety. Country 2 is therefore better able to absorb new firms – in spite of the increased competition and decreased firm profits they cause – because the output of each additional firm is spread over the market in country 2 and the relatively high demand from country 1. This component can be switched off by setting $Y_1 = 0$ in the model.

The second component of the market access effect is similar to the export-platform motive for FDI; a comparison of terms 1 and 3 in Proposition 1.1 provides intuition. Tightening environmental policy in country 1 decreases domestic firm profits and firm numbers decline. This decline in firm numbers reduces competition for firms in countries 2 and 3 and increases their profits. Because the less competitive market in country 1 is more accessible to country 2 than to country 3, the reduction in competition enhances the profitability of country 2 firms more. Country 2 is the better export platform to country 1, avoiding stringent environmental policy while minimizing transport costs to the now less competitive market in country 1. This component can be switched off by setting $\phi_{12} = \phi_{13}$.

Finally, to illustrate the pure market access effect, consider a special case of Proposition 1.1 with $Y_2 = Y_3$ and asymmetric transport costs. In this case, with no advantage in market size or environmental policy, location is the only force creating comparative advantage for Country 2 in attracting polluting firms.

Corollary 1.1 $\frac{\partial n_2}{\partial r} > \frac{\partial n_3}{\partial r} \quad if \quad Y_2 = Y_3$

Proof. See Appendix 1.A.4. ■

The market access effect demonstrates how locational comparative advantage arises simply as a consequence of positive transport costs. In Section 1.3 I use the model to construct a measure of locational comparative advantage in environmental policy and estimate its effect on manufacturing output.

1.3 Empirical evaluation of the model

1.3.1 Econometric strategy

1.3.1.1 Functional forms for foreign environmental policy

The main empirical goal is to evaluate the importance of locational comparative advantage in polluting production. In doing so, I rely on guidance from the model to construct measures of foreign environmental policy that are appropriately adjusted for foreign market size and bilateral market access.

Equations (1.6), (1.7) and (1.8) present an intuitive and theoretically grounded functional form for estimating the long-run effect of foreign environmental policy on domestic manufacturing production. However, these functions are discontinuous and non-linear as well as analytically unwieldy in the many-country versions necessary for empirical estimation. Furthermore, and probably more importantly, such precise functional forms are unlikely to hold empirically in annual data, both because of measurement error and because they assume a time frame over which firm relocation yields zero profits.

I therefore do not estimate equations like (1.6), (1.7) and (1.8) in a many-country setting. Instead, I operationalize the medium-run version of the theory, estimating the relationship between environmental policy, both domestic and foreign, and firm value added when firm location is fixed.[14]

Profits can be non-zero and I allow for m countries, positive transport costs between all countries and a generalization of equation (1.1) with many CES manufacturing industries nested within a Cobb-Douglas utility function. μ_l is the Cobb-Douglas budget share for industry l and $w_i z_i t_i$ is the marginal cost of production in country i. Fixing firm location, firm value added is a generalized version of equation (1.5):

$$\mathrm{VA}_{ilt} = \mu_l \left(w_{it} z_{it} t_{it}\right)^{1-\sigma_l} \sum_{j=1}^{m} \frac{\phi_{ijl} Y_{jt}}{\sum_{k=1}^{m} \phi_{jkl} n_{klt} \left(w_{kt} z_{kt} t_{kt}\right)^{1-\sigma_l}} \tag{1.9}$$

Value added in country i is equal to the sum of domestic market value added and the value added from exporting to each foreign country. The value added from exporting to country j – which

[14] This is a common approach in the empirical literature on firm location. For examples, see Head and Mayer(2004) and Dean and Lovely (2009).

equals $\mu_l \left(w_{it} z_{it} t_{it}\right)^{1-\sigma_l} \phi_{ijl} Y_{jt} / \left(\sum_{k=1}^{m} \phi_{jkl} n_{klt} \left(w_{kt} z_{kt} t_{kt}\right)^{1-\sigma_l}\right)$ – is, according to the numerator, increasing in the market size and the freeness of trade between country j and country i and decreasing in country i's (environmental policy inclusive) marginal cost of production. According to the denominator, value added is also decreasing in the competitiveness of the market in country j.

Clearly, as in equation (1.5), more stringent foreign environmental policy increases domestic value added and the effect on domestic value added is increasing in the market access of the foreign country. Importantly for empirical specification, the model yields a simple linear expression in logs for value added:

$$\ln \mathrm{VA}_{ilt} = \ln \mu_l - (\sigma_l - 1) \ln t_{it} - (\sigma_l - 1) \ln w_{it} z_{it} + \ln \left(\sum_{j=1}^{m} \frac{\phi_{ijl} Y_{jt}}{\sum_{k=1}^{m} \phi_{jkl} n_{klt} \left(w_{kt} z_{kt} t_{kt}\right)^{1-\sigma_l}} \right) \tag{1.10}$$

Apart from the final term, equation (1.10) makes intuitive sense. Value added (and therefore profit) is increasing in the share of income spent on manufacturing industry l (μ_l), and decreasing in the environmental policy variable (t_{it}) and unit labor costs ($w_{it} z_{it}$). Following standard terminology, I call the exponent of the final term Krugman Market Potential (KMP) and its existence implies that profits from exporting to market j are increasing in GDP (Y_{jt}) and trade freeness from i to j (ϕ_{ijl}) and decreasing in the competitiveness of market j as measured by $\sum_{k=1}^{m} \phi_{jkl} n_{klt} \left(w_{kt} z_{kt} t_{kt}\right)^{1-\sigma}$. This denominator reflects the level of competition in market j from all foreign and domestic firms, giving rise to a 'market crowding' force that decreases profits of firms located where there are already many firms with a low cost of production. The market crowding force is increasing in the number of foreign firms (n_{klt}) and the trade freeness with which foreign firms access market j (ϕ_{jkl}), and decreasing in the environmental and non-environmental costs of production of those firms, $w_{kt} z_{kt} t_{kt}$.

The presence of the third term makes explicit a potentially important omitted variable from past studies of the PHE considering only domestic environmental policy. If environmental policy is correlated across space – as Fredriksson and Millimet (2002) find, and as suggested by the existence of several regional environmental agreements including the EU Emissions Trading Scheme and NAFTA – changes in t_{it} are correlated with changes in KMP. Because an increase in t_{it} decreases profitability while an increase in market potential increases profitability, past estimates of the effect of domestic environmental policy on measures of economic activity violate the 'non-interference' component of the Stable Unit Treatment Value Assumption (SUTVA) and may exhibit bias.[15]

KMP is typically structurally estimated using the importer fixed effects in an OLS regression with bilateral trade flows as regressand and with the inclusion of terms to control for bilateral transport costs.[16] However, in addition to correcting for potential omitted variable bias, my goal is to estimate the significance and magnitude of the effect of foreign environmental policy on domestic production. As environmental policy is only one source of variation in the third term of equation (1.10), I cannot estimate the third term as an importer fixed effect and interpret its effect on value added as evidence that locational comparative advantage in polluting production matters.

Instead, I follow Head and Mayer (2002), constructing the third term from its constituent parts, while ensuring that any variation is only a function of changes in environmental policy and transport costs to foreign countries, rather than Y, n, w or z. The constructed measure of locational comparative advantage in polluting production, which I distinguish from market potential by naming 'multilateral environmental competition' (MEC), is:

$$MEC^1_{ilt} = \ln\left(\sum_{j=1}^{m} \frac{\widehat{\phi_{ijl}} Y_j}{\sum_{k\neq 1}^{m} \frac{\widehat{\phi_{jkl}} Y_k}{\widehat{t_{kt}}}}\right)$$

I describe data sources, including derivation of a proxy for environmental policy, $\widehat{t_{kt}}$, in Section 1.3.1.2. To isolate the effect of foreign environmental policy, I have made four amendments to the structural measure of KMP from equation (1.10). First, Y_j is estimated as the average GDP of country j over the seven-year period considered from 1999 - 2005. This removes time variation in MEC caused by changes in GDP and avoids endogeneity arising from using domestic GDP as a regressor with industry value added as regressand. To control for time-variation in foreign GDP lost by this simplification, in econometric specifications I include either country-time fixed effects or a measure of 'foreign market potential' from Head and Mayer (2011) to control for time variation in foreign market characteristics.

15 Without reference to a particular theoretical model, Karp (2011) outlines the practical challenge posed in estimating the effect of domestic policy on domestic polluting activity when third country environmental policy matters. Morgan and Winship (2007) provide a popular explanation of the SUTVA assumption.

16 See Redding and Venables (2004).

Second, to account for the stylized fact that firm size varies substantially within each country, I use GDP rather than firm numbers to reflect the competitiveness of each country-industry. This amendment is based on the assumption that GDP is approximately proportional to manufacturing industry output.

Third, I remove non-environmental variation in production costs by assuming that the remaining component of costs, $w_{it}z_{it}$, does not vary by country. Time and industry variation in production costs is permitted by the specification, as these can be brought outside the summations in the third term of equation (1.10) where they are captured by time, industry or time-industry fixed effects.[17] This simplification retains the key features of the theory, namely that stricter foreign environmental policy increases domestic value added and that this influence is increasing in trade freeness and the level of foreign production, while remaining estimable with available data. Fourth, I remove domestic environmental policy from the summation, enabling interpretation of MEC^1_{ilt} as a measure of the environmental policy in foreign countries.[18]

$\widehat{\phi_{ijl}}$ is estimated structurally from the model using data on industry-level bilateral trade flows. The approach used is common in the empirical international economics literature and I relegate the specific details to Appendix 1.B.1. Estimating bilateral transport costs by industry enables construction of MEC^1_{ilt} and MEC^2_{ilt} to follow the theory presented here closely.

I consider several variants of the basic specification in order to raise the level of confidence in the results. Because MEC^1_{ilt} is dependant on the specific functional forms adopted, as an additional robustness check, I also construct a simpler MEC variable, derived from the theoretical measure of the effect of foreign environmental policy on value added from selling in the domestic market only. Theory suggests this is an important determinant of value added. From equation (1.9), the natural log of value added from selling in the domestic market only is:

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17 Head and Mayer (2002) take a slightly different approach, assuming that marginal costs are proportional to wages. I believe my approach to approximating wage differentials is more realistic: unit labor costs are better approximated as being equal across countries than being proportional to wages. Using the data from Mayer and Zignago (2005), I find that unit labor costs (in USD) for a given industry, are typically 3-4 times higher in the country representing the 90th percentile than in the 10th percentile country, while wages are 15 times higher in the 90th percentile than in the 10th. I do not use unit labor costs in constructing MEC^1_{ilt}, although this would be my preferred approach, because the data are not available for sufficient country-industry-time observations.

18 A previous version of this paper kept the domestic policy component in the summation. This approach fits the data better (higher R-squared and more significant coefficents on MEC and the environmental index), yields similar conclusions, but coefficient estimates are far less straightforward to interpret. These domestic-inclusive versions of MEC are available in the data set accompanying this paper.

$$\ln \mathrm{VA}_{il}^{D} = \ln \mu_l - (\sigma_l - 1)\ln(t_{it}) - (\sigma_l - 1)\ln(w_{it} z_{it}) + \ln Y_i + \ln \phi_{ii} - \ln\left(\sum_{j=1}^{m} \frac{\phi_{jil} n_{jl}}{(t_j z_{jl} w_{jl})^{\sigma-1}}\right) \quad (1.11)$$

Following the same four amendments to the theory used in constructing MEC^1_{ilt}, the alternative MEC variable is:

$$MEC^2_{ilt} = -\ln\left(\sum_{j\neq 1}^{m} \frac{\widehat{\phi_{ijl}} Y_j}{\widehat{t_{jt}}}\right)$$

While grounded in theory, this second measure is a simple GDP and transport cost weighted aggregate of foreign environmental taxes. It is closely related to the ad-hoc market potential measure of Harris (1954), sharing the same empirical virtue of simplicity.

1.3.1.2 Estimating equation and data sources

I estimate a model that controls for the factors in equation (1.10). The basic estimating equation is:

$$\ln \mathrm{VA}_{ilt} = \alpha_i + \alpha_l + \alpha_t + \beta_1 \ln \widehat{t_{it}} + \beta_2 MEC_{ilt} + \sum_o \gamma_o \ln X_{it} + \varepsilon_{ilt} \quad (1.12)$$

β_2 is the main parameter of interest. It measures the elasticity of value added with respect to MEC and the theory presented suggests it should be positive. β_1 is the elasticity of value added with respect to domestic environmental policy and theory predicts a negative value.

Descriptive statistics for variables used and their sources are presented in Appendix 1.C. VA_{ilt} is the value added in USD of ISIC revision two three-digit level industry l in country i at time t. VA_{ilt} comprises World Bank data supplemented by additional sources described in de Sousa et al. (2012). Two alternative left-hand-side variables were considered, total value of production in USD and US foreign affiliate value added. Value added is superior to production as a measure of economic activity because it excludes the cost of inputs, which are typically not subject to environmental regulation when purchased. US foreign affiliate value added, which is freely available from the US Bureau of Economic Analysis (BEA) may not respond to changes in foreign environmental policy the same way that total industry value added does. For example, Poelhekke and van der Ploeg

(2012) suggest that Dutch FDI in certain industries avoids countries with lax environment policy on CSR grounds. Domestically owned firms – which typically contribute significantly more to industry value added than foreign owned firms – are of greater policy interest and are also unlikely to be as motivated by CSR considerations.

Two further benefits of using value added data from de Sousa et al. (2005) are: first, it is disaggregated into 26 manufacturing industries, yielding significantly more observations than the US Bureau of Economic Analysis' multinational affiliate value added data, which is disaggregated into 7 manufacturing industries; second, previous studies tend to focus on FDI, plant births or U.S. affiliate value added and, to my knowledge, this is the first study of the PHE to analyze industry total value added.

On the right hand side of equation (1.12) α_i, α_l and α_t are country, industry and year fixed effects. The environmental index, $\widehat{t_{it}}$, is a proxy for environmental policy costs. It is drawn from the World Economic Forum (WEF) Global Competitiveness Report (GCR). To produce the GCR, the WEF conducts surveys of corporate executives in a large number of countries annually. In the construction of MEC^1_{ilt} and MEC^2_{ilt} I include only the 59 countries for which data are available every year from 1999 to 2004 (150 are available in 2004).[19] According to the Penn World Tables (Heston et al. 2012), these countries generated approximately 92 percent of global GDP in 1999. This restriction ensures that time variation in MEC^1_{ilt} and MEC^2_{ilt} is due only to changes in environmental policy and not new countries entering the summation.

I focus on two environmental measures from the GCR, reported in each edition from 2000 until 2006 - 2007.[20] The first measure reflects the stringency of environmental policy and the second measure reflects the consistency with which environmental policy is enforced.[21] Both measures are reported on a scale from one to seven of increasing stringency/consistency. These measures are multiplied together to yield a composite environmental index of the stringency of environmental policy and consistency of its enforcement for a given country in a given year, $\widehat{t_{it}}$. The environmental index is constructed in this way to incorporate regulation and enforcement, both of which probably influence

19 Because value added data is not available for 10 of these countries between 1999 and 2005, having constructed MEC measures with 59 countries, I include 49 countries in the empirical analysis.

20 Following the convention when using the GCR data, figures from the 2000 GCR are matched to non-GCR data from 1999. Because most surveys are completed at the beginning of the period to which the report applies (i.e. early 2000 for the 2000 edition of the GCR) respondents are likely to reflect on conditions in the previous year in providing their responses.

21 The stringency question is: 'The stringency of overall environmental regulation in your country is (1=lax compared with most other countries, 7=among the world's most stringent).' The enforcement question is: 'Environmental regulation in your country is (1=not enforced or enforced erratically, 7=enforced consistently and fairly).'

firms' marginal environmental costs, into a single measure, and to enable direct comparison with Kellenberg (2009) and Poelhekke and van der Ploeg (2012).

The GCR measure of environmental policy stringency provides three key advantages over the most obvious alternative, industry-level pollution abatement and control expenditure (PACE). A clear advantage is geographic coverage. I am interested in the influence of foreign environmental policy on domestic economic activity in a setting in which inter-jurisdictional collaboration is difficult, therefore cross-country data are desirable. PACE data are typically only collected in developed countries. Second, where it is available, the collection and construction of PACE data is subject to important cross-country methodological differences, making it less useful for international comparison of environmental policy stringency globally.[22]

The third benefit arises because the GCR's measures of environmental policy stringency and enforcement probably incorporate broader cost impacts of environmental policy than pollution abatement cost measures do. List and Co (2000) and Levinson (1996) argue that the regulation process is multidimensional, advocating the use of many measures of policy stringency to analyze the PHE. By surveying executives on the general stringency and enforcement of environmental policy, the GCR measures capture more dimensions of the regulatory process.

The standard criticisms of survey-based metrics apply to the GCR data, although this appears to be less problematic with the GCR data than many other cross-country surveys. The data are widely used in the international trade literature and have repeatedly demonstrated *construct validity* as GCR metrics behave the way they are expected to.[23] In addition, the GCR metrics demonstrate *convergent validity*, being correlated with objective measures of similar phenomena.[24] The seven versions of the World Economic Forum Global Competitiveness Report cited in this chapter provide details of validity checks performed on GCR metrics.

X_{it} contains a set of additional controls not captured by the fixed effects. To remove omitted variable bias I choose controls that are correlated with the environmental variables $\widehat{t_{it}}$, MEC^1_{ilt}

[22] For example, a common caveat in OECD PACE data is: 'definitions and methodologies remain diverse across member countries. International comparisons should therefore be limited to orders of magnitude.'

[23] For example Carr et al. (2001) find a negative impact on FDI of an index created by aggregating survey responses on restrictions on the ability to acquire control in a domestic company, limitations on the ability to employ foreign skilled labor, restraints on negotiating joint ventures, strict controls on hiring and firing practices, market dominance by a small number of enterprises, an absence of fair administration of justice, difficulties in acquiring local bank credit, restrictions on access to local and foreign capital markets, and inadequate protection of intellectual property. Markusen and Maskus (2002), Blonigen. et al. (2003) and Ekholm et al. (2007) also support the construct validity of GCR survey measures.

[24] For example, survey responses on the ease of doing business across countries correlates positively with the actual number of days required to start a business.

and MEC_{ilt}^2 and influence firm profits. As discussed above, I include non-industry-specific foreign market potential from Head and Mayer (2011) to control for non-environmental foreign country effects. I also include GDP per capita, which, according to Grossman and Krueger (1995), is strongly related to environmental policy stringency. I also include government's share of GDP, which captures within country changes in a wide range of government policy variables. Population and the domestic-USD exchange rate should both affect incentives to manufacture domestically and are controlled for. As a final set of control variables, I use indexes of voice and accountability, political stability, government effectiveness, regulatory quality, rule of law and control of corruption from the World Bank's Worldwide Governance Indicators.

1.3.1.3 Addressing potential endogeneity

Recent studies highlight the need to address potential endogeneity arising from the inclusion of a measure of domestic environmental policy in a regression with a measure of economic activity as the regressand (Karp 2011). Kellenberg (2009) finds a two-step procedure with instrumental variables (IVs) dramatically changes the estimated effect of domestic environmental policy on U.S. multinational affiliate value added, and Levinson and Taylor (2008) find a similar improvement when considering net imports. In contrast, Poelhekke and Van der Ploeg (2012) find little effect of instrumentation using the GCR data.

I address the econometric challenge posed by endogenous environmental policy in three main ways. First, I reduce the potential for simultaneity bias by considering a large number of manufacturing industries and an environmental policy variable for the entire country. For the available 6,765 country-industry-year observations, the mean industry value added is approximately 0.6 percent of GDP. As a consequence, value added in a given industry is unlikely to noticeably influence the environmental index in a given year. Second, to reduce the likelihood of omitted variable bias, I introduce country, industry and year fixed effects to all regressions. To control for omitted variables that are not country, industry or time invariant, first I include a number of potentially important controls through the vector X_{it} and second, I introduce more comprehensive fixed effects – pair-wise interacting country, industry, and year dummy variables.

The third means of addressing potential endogeneity involves adopting a generalized method of moments specification to estimate the model using IVs as a source of exogenous variation in environmental policy. A number of candidate IVs for environmental policy have been proposed. I follow Copeland and Taylor (2003), using measures of the demand for environmental protection as IVs. Specifically, I use the UN World Development Indicators' measures of marine protected areas as a percentage of territorial waters and terrestrial protected areas as a percentage of total land area. In selecting these instruments, I assume that in designating land or territorial water protected, countries trade potential consumption from use in the agriculture or fisheries industry for an environmental benefit. Time variation in these two measures therefore reflects changing preferences over environmental goods. Because the available quantity of neither land nor territorial water influences manufacturing profitability, these variables do not affect the level of value added in manufacturing industries directly.

1.3.2 Estimation results

1.3.2.1 Baseline estimates

The main purpose of this section is to demonstrate that the theory of locational comparative advantage in polluting production explains the global distribution of manufacturing activity. The main evidence presented for this is a robustly positive and significant value of $\widehat{\beta_2}$ – the coefficient on the two proposed structural MEC measures – estimated across a broad range of model specifications.

As a preliminary step, to motivate subsequent results, I simply use GDP-weighted average foreign environmental policy in concentric circles around each observation as a reduced-form measure of MEC. This type of reduced form measure has been used previously in the spatial econometric literature (Harrigan 2010). Although this concentric circle variable doesn't exploit industry transport cost variation like the measures MEC^1_{ilt} and MEC^2_{ilt} do, its simplicity and transparency are valuable as a starting point for empirical analysis.

Table 1.6 presents estimation results. Models 1-4 consider all countries and Models 1 and 2 use GDP-weighted average foreign environmental policy by distance[25] tertile and Models 3 and 4 considering foreign environmental policy by distance quartile.[26] Models 2 and 4 include Head and Mayer's (2011) foreign market potential measures to control for non-environmental foreign country effects. Models 1-4 yield significant positive coefficients on foreign environmental policy. In all

[25] The bilateral distance measure used throughout the paper is a population-weighted measure, described in detail at http://mpra.ub.uni-muenchen.de/26469/1/noticedist_en.pdf.

[26] Tertile and quantile cutoffs are used to avoid the perception that cutoffs could have been chosen in order to drive the results. The 25th distance percentile (first quartile) is calculated as the country-country bilateral distance for which 25% of country-country distance pairs in the sample are shorter. Countries with a population centroid less than 5,330km (greater than 9,436km) from the observation country belong to the first (third) tertile. Countries belonging to each quartile are delineated at distances of 4,315km, 7,616km and 10,474km.

models the coefficient on the first quantile – which theory suggests influences domestic economic activity most – is not significant.

This absence of first-quantile significance probably arises because distance to close neighbors varies substantially by country, meaning that for many countries there are very few observations in this quantile. For example, in Europe a 4000km concentric circle captures a large number of foreign countries. In almost all directions, locations 4000km around the population centroid of the USA capture only one country (Canada or Mexico). Harrigan (2010) use a simple approach to address this: consider only one country or region. Models 5-8 therefore restrict the sample to European countries, provided striking evidence of the importance of the environmental policy of nearby neighbors in determining domestic value added: The influence of GDP-weighted foreign environmental policy declines monotonically by distance quantile.

Table 1.7 presents results exploiting the structural measures of MEC: MEC^1_{ilt} and MEC^2_{ilt}. In Models 9 - 16 the coefficient on MEC^1_{ilt} lies between 0.26. and 0.30, implying that more stringent foreign environmental policy increases domestic manufacturing value added. Consistent with the theory on locational comparative advantage, all four estimated coefficients are significant at least at the five percent level. Because the equation is linear in logs, coefficients can be interpreted as elasticities: a one percent increase in MEC^1_{ilt} is associated with an increase of approximately 0.28 percent in manufacturing value added. The coefficient on $\ln \widehat{t_{it}}$ is negative as implied by the theory. Estimates of the impact of a one percent increase in $\widehat{t_{it}}$ on industry value added range from -0.195 percent to -0.30 percent.

Model 9 only includes the domestic and foreign environmental policy terms in addition to country, industry and year fixed effects. In Model 10 the six governance measures are introduced. The inclusion of these variables reduces the magnitude of the coefficient on $\ln \widehat{t_{it}}$. Only two of the six subjective measures are significant at the ten percent level, with positive coefficients on the regressors reflecting control of corruption and regulatory quality.

Model 11 controls for important non-environmental domestic market factors that have been shown to influence economic activity. The inclusion of GDP per capita, government share of GDP, population and exchange rate make little difference to the environmental regressors' coefficients. I find that high GDP per capita countries have higher value added and that higher domestic-USD exchange rates and tariffs decrease manufacturing value added.

Model 12 introduces the country-time specific foreign market potential term from Head and Mayer (2011). The inclusion of foreign market potential as a control ensures that MEC^1_{ilt} is not confounded with non-environmental foreign country effects. For example, taking the theory at face value, foreign market potential reflects all of the benefits of foreign market size and the costs of foreign competition. Unlike in the Models 1 - 8, the inclusion of the foreign market potential term reduces the coefficient on MEC^1_{ilt}, but it remains significantly greater than zero.

Models 13 - 16 paint a very similar picture, with a positive coefficient on MEC^2_{ilt} consistent with the theory. Estimated coefficients on all regressors in Models 9 - 12 match those in Models 13 - 16 very closely, suggesting that the functional form of MEC^1_{ilt} is not driving the results.

1.3.2.2 Robustness checks

In Table 1.8, Models 17 - 18 present the IV estimates obtained by two-stage generalized method of moments (GMM) estimation using the two instruments for $\widehat{t_{it}}$ described in Section 1.3.1.3. Included control variables correspond respectively to the two full models (Models 12 and 16). Table 1.9 presents first stage regression results. Three diagnostic tests are conducted for the IV specifications. In both cases, the Hansen J-statistic rejects the joint null hypothesis that the instruments are invalid and the Anderson likelihood ratio test rejects the null hypothesis that the equation is under-identified. The Cragg-Donald F-statistic rejects the null hypothesis of weak instruments at a five percent significance level for maximal bias levels of 0.1 of the IV estimator relative to OLS. Table 1.9 presents first stage regression results for Models 17 and 18.

The estimated coefficients are similar to those in Table 1.7, an observation supported by highly insignificant Durbin-Wu-Hausman test p-values, which fail to reject the assumed exogeneity of the environmental index. By comparison with Kellenberg's (2009) finding of endogenous environmental policy when using the GCR data, the insignificant Durbin-Wu-Hausman test statistic suggests that endogeneity bias can be addressed through the use of country-level fixed effects and disaggregated data by manufacturing industry. Instrumentation reduces efficiency relative to OLS, yielding larger standard errors. These IV results provide little reason to forego the efficiency of OLS estimation in favor of a GMM-IV approach.

Table 1.10 evaluates the robustness of the results presented in Table 1.7 to the inclusion of extensive fixed effects. Because MEC is country, industry and time varying, I expect to be able to identify an effect through variation in any of these dimensions. Models 19 - 21 include MEC^1_{ilt}, and Models 22 - 24 include MEC^2_{ilt}. I omit non-environmental control variables from the table for convenience.

Models 19 and 22 include country-year fixed effects. The coefficient on environmental policy is no longer estimable and the effect of these added regressors on MEC^1_{ilt} and MEC^2_{ilt} is small and positive, with both coefficients significant at the one percent level and equal to approximately 0.3. Potentially omitted country and time invariant factors from prior specifications do not appear problematic. This provides further reassurance that the MEC variables are not capturing non-environmental foreign country variables.

Models 20 and 23 include industry-year fixed effects with very little impact on the coefficients on the environmental policy variables. This suggests that omitted industry-time specific factors, such as innovation or global demand and supply shocks are not causing any bias in the estimated environmental policy coefficients.

Models 21 and 24 introduce country-industry fixed effects, relying on time variation in MEC^1_{ilt} to identify an effect of foreign environmental policy. The inclusion of over 1,000 country-industry dummy variables reduces the magnitude of the coefficient on the environmental policy variables and renders coefficients insignificant. The R-squared of 0.98 implies that fixed effects absorb most of the variation in value added.

Identification of environmental policy effects using only time variation in the data presents a very high hurdle.[27] With at most seven observations per country-industry pair, there is insufficient variation in MEC^1_{ilt} to establish a significant relationship with value added.

Perhaps the most plausible omitted country-industry specific variable that MEC could be capturing is industry transport cost adjusted foreign market size. For example, the foreign markets that benefit domestic firms the most vary depending on industry transport costs. Even this seems unlikely , as it would require environmental policy to be correlated with market size (a relationship that is not strong in the data). Also, results in Table 1.6 – which show that a non-industry-varying measure of foreign environmental policy influences domestic manufacturing activity – suggest that industry variation in MEC is not necessary to identify a significant positive effect.

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[27] This is especially the case in the WEF data. Kellenberg (2009) is unable to detect a significant effect of domestic environmental policy on domestic U.S. foreign affiliate value added with country fixed effects, and the main specification therefore uses only 'region' fixed effects. This may arise because the WEF data has little time variation when compared to other measures of environmental policy. Indeed, there should be no time trend because respondents are asked to rate environmental policy relative to the current global average.

As a further robustness check, I adopt the approach of Kellenberg (2009), taking a long-difference with a five year span between the years with the least and most stringent average environmental policy across all countries, 2001 and 2005. Results from estimating eight different models with country-industry fixed effects are presented in Table 1.11. Models incorporate increasingly stringent control variables from left to right, with the right-most models (28 and 32) including country-year fixed effects in addition to country-industry fixed effects. The coefficients on the environmental policy variables over this time frame are substantially larger, perhaps reflecting the fact that in the long-run environmental policy is a more potent determinant of the location of polluting activity. The MEC coefficients are significant and positive, indicating that it is possible to identify a significant effect of MEC using only its time-variation.

As a final robustness test, specifications in Table 1.12 control for industry pollution intensity. If the value added in pollution intensive industries responds more to environmental policy, this increases confidence that the GCR environmental policy metrics accurately reflect environmental policy stringency.

As a measure of industry pollution intensity, I use 2005 U.S. industry Pollution Abatement Operating Costs (PAOC) divided by 2005 U.S. industry value added ($\text{PAOC}_{l,US}/\text{VA}_{l,US}$).[28] The use of operating (rather than total) expenditure is standard and follows Levinson and Taylor (2008) among others. The industry pollution intensity measures are presented in Table 1.4, along with the concordance used between NAICS and ISIC three-digit manufacturing industries.[29]

For each of the four columns from left to right, the controls included are identical to Table 1.11. Model 33 includes only country, industry and time fixed effects. Model 34 adds governance controls, Model 35 adds macroeconomic controls, and finally model 36 incorporates country-time fixed effects. Across all specifications, the coefficient estimates on the three environmental policy variables change little. Clearly, the value added of more pollution intensive industries is more responsive to domestic environmental policy. Interpreting the coefficients from Model 35, a one percent increase in the level of the domestic environmental index decreases domestic manufacturing value added in the manufacturing industry with average pollution intensity[30] by 0.28 percent. The same one percent change is estimated to decreases value added by 0.75 percent in the heavily-polluting iron and steel industry and increases it by 0.37 percent in the largely pollution-free 'machinery, except

[28] Both PAOC and value added are expressed in 2005 USD and are freely available from the U.S. Census Bureau.
[29] For empirical analysis, prior to taking the log, I rescale $PAOC_{l,US}/VA_{US}$ relative to its mean so that industries with above (below) average pollution intensity have $\ln\left(PAOC_{l,US}/VA_{l,US}\right) > 0$ (< 0).
[30] The average value for industry PAOC divided by industry value added is 1.37 percent.

electrical' industry. The positive coefficient on the least polluting manufacturing industry is not surprising, arising quite naturally in a general equilibrium model like that in Section 1.2, but with a continuum of polluting manufacturing industries with increasing – rather than equal – pollution intensity.

1.3.2.3 Policy analysis

Foreign environmental policy is of statistical significance, but is it of practical significance? To consider this question, I simulate regional environmental policy coordination scenarios assuming the structural relationship and coefficient estimates from the empirics above. The simple simulation process is as follows. First, I select three reasonably representative country-industry-year triples. I consider only the food products industry, which exhibits approximately average trade freeness and pollution intensity. As a consequence, the food products industry behaves much like the entire manufacturing industry would. I select Indonesia, Mexico and Poland as countries because they belonging to different regions, are of similar economic size and possess similar environmental indexes. The year 2000 is the latest in which value added data for the food products industry is available for all three countries.

Second, I select three policy experiments, one for each country-industry-year triple. For the Indonesian simulation, I assume that environmental indexes for all east Asian countries must at least increase to the level of Malaysia (17.63).[31] For the Mexican simulation, I assume that environmental indexes for Canada (32.45) and USA (34.16) reach Germany's level (38.19). For the Polish simulation, European countries[32] lower their environmental index to the level of Poland (17.64).

Third, I choose the coefficient estimates from Model 32 to use in the simulation. Model 32 benefits from the inclusion of a large set of controls and the measure of MEC^2_{ilt} is easier to construct and more intuitive to interpret than MEC^1_{ilt}. Model selection impacts the coefficient on MEC very little provided country-industry fixed effects are not included, and simulation using the coefficient estimates from Model 29, which includes MEC^1_{ilt}, yields almost identical results. .

31 East Asian countries in the sample with environmental indexes below Malaysia in 2000 were Bangladesh (6.96), China (12.95), Philippines (7.84), Thailand (14.06) and Vietnam (8.28).

32 These are Austria (37.62), Belgium (31.11), Switzerland (39.00), Czech Republic (18.36), Germany (38.19), Denmark (37.52), Spain (20.58), Estonia (19.27), Finland (41.6), France (34.1), United KIngdom (32.48), Hungary (19.78), Ireland (24.96), Iceland (35.34), Italy (23.94), Lativa (18.92), Neatherlands (39.53), Norway (33.48), Slovak Republic (19.2), Slovenia (20.16), Sweden (36.4).

Country	Scenario	Percentage change in exp(-MEC^2)	Percentage change in value added
Indonesia	East Asian countries increase environmental index at least to Malaysian level	-8.3%	2.6%
Mexico	USA and Canada increase environmental index to German level	-8.3%	2.5%
Poland	European countries reduce environmental index at least to Polish level	75.0%	-15.0%

Notes: Simulations apply to the food products industry (ISIC 311) for the year 2000.

TABLE 1.2: The practical significance of three simulated policy changes

Table 1.2 presents simulation results. The third column shows the effect of each policy change on the measure $\sum_{j\neq 1}^{m} \widehat{\phi_{ijl}} Y_j / \widehat{t_{jt}}$.[33] This provides a sense of how policy changes in a few nearby countries can influence MEC.[34] The fourth column shows the simulated effect on value added in the food products industry.

Two key messages arise from the simulation exercise. First, foreign environmental policy influences domestic manufacturing value added materially. A 2.5% change in the size of the manufacturing industry for a substantial – but not implausible – environmental policy change clearly matters. Second, regional cooperation is a powerful way to offset the negative competitiveness effects of domestic environmental policy changes. For example, as $\widehat{\beta_1} \approx$0.2 across Models 9 - 16, the negative impact of, say, a 10% increase in the domestic environmental policy index on value added is more than offset by the simulated policy proposals for Mexico and Indonesia.

1.3.2.4 Omitted variable bias

Is the estimated delocation elasticity $\widehat{\beta_1}$ biased if a measure of multilateral environmental competition is omitted from the estimating equation? The preceding results suggest a clear breach of the Stable Unit Treatment Value Assumption (SUTVA) assumption typically made in PHE studies considering the effect of domestic environmental policy on domestic polluting economic activity: I

[33] If all foreign countries double their environmental index this measure declines by fifty percent. If all foreign countries halve their environmental index, this measures increases by one hundred percent.

[34] Because policy scenarios are regional, the same scenario would influence value added more in industries with lower trade freeness than food products.

have shown that the treatment status of any unit *does* affect the outcomes of other units. However, this effect may be of little practical concern.

Table 1.13 provides mixed evidence of the practical importance of breaching the SUTVA assumption. Consider first the upper-half of the table, which analyzes the full sample. The specification in left hand column includes the standard governance and macroeconomic controls as well as country, industry and year fixed effects, the second column adds industry-year fixed effects and the third column adds country-industry fixed effects.[35] Within each column, I compare $\widehat{\beta_1}$ when estimated without controls for MEC, with estimates obtained when controlling for MEC^1_{ilt} and MEC^2_{ilt}. In all three columns, estimates of β_1 with MEC controls differ by less than three percent from $\widehat{\beta_1}$ when estimate without a MEC control. This suggests that omitted MEC does not pose a bias problem in practice.

Because environmental policy in neighboring jurisdictions is correlated through time (Fredriksson and Millimet, 2002), one might be concerned that omitting MEC is problematic if $\widehat{\beta_1}$ is estimated using only time variation in environmental policy. This hypothesis receives stronger support. In the lower-half of Table 1.13, I consider observations only for 2001 and 2005 – recall these are the years with the lowest and highest average level of environmental policy across countries in the sample – because time variation in environmental policy has a significant impact on value added in this sub-sample. When β_1 is estimated without country-industry fixed effects, omission of MEC from the specification causes a small change in $\widehat{\beta_1}$ (< seven percent). However, with country-industry fixed effects $\widehat{\beta}_1$ declines by over 20 percent. Table 1.13, in its entirety, suggests exercise of some caution in applying the SUTVA to empirical studies of the PHE.

1.4 Conclusion

This chapter considers the influence of locational comparative advantage in polluting production on the level of domestic manufacturing activity using theory and empirics. Deploying a spatial model with increasing returns to scale and transport costs, I show how comparative advantage in the production of pollution intensive goods can arise purely from location. The theory suggests that high market access to jurisdictions with stringent environmental policy increases the size of the domestic polluting industry.

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[35] β_1 cannot be estimated with country-time fixed effects.

Operationalizing the model empirically, I find robust evidence that stricter foreign environmental policy increases domestic manufacturing value added and that stricter domestic environmental policy reduces it. Both the theoretical and empirical analyses suggest that estimates of the Pollution Haven Effect that ignore third country environmental policy – yet make the stable unit treatment value assumption – can be misleading.

The present chapter suggests several directions for future research. The use of a multilateral policy term like MEC to consider the spatial effects of non-environmental policies like labor laws or intellectual property rights may provide similar empirical insights in those areas. Empirical results also suggest that the long-term response to environmental policy may be very different to the short-term response. Clearly future work should also ensure that estimates of the PHE are not biased because of a failure to allow for foreign country effects.

This chapter provides an important and novel policy implication, suggesting that policy coordination with major trading partners is a powerful way to address the adverse competitiveness effects of unilateral environmental policy. With transport costs geographically segmenting markets, regional policy is extremely powerful. Based on Table 1.2, the additional benefits of global coordination over, say, European or North American coordination are likely to be small for most manufacturing industries. A global agreement on carbon dioxide emissions – which is widely considered to be a desirable goal in long-term greenhouse gas policy – may be very closely approximated by a series of more politically feasible regional agreements.

1.A Appendix to Section 1.2

1.A.1 Definition of market clearing conditions and derivation of price indexes

Market clearing conditions for manufacturing firms in countries 1, 2 and 3 allow me to solve for the location of manufacturing firms. These conditions are:

$$q_1 = p_1^{-\sigma} G_1^{\sigma-1} \mu Y_1 + p_1^{-\sigma} \phi_{12} G_2^{\sigma-1} \mu Y_2 + p_1^{-\sigma} \phi_{13} G_3^{\sigma-1} \mu Y_3 \tag{1.13}$$

$$q_2 = p_2^{-\sigma} \phi_{12} G_1^{\sigma-1} \mu Y_1 + p_2^{-\sigma} G_2^{\sigma-1} \mu Y_2 \tag{1.14}$$

$$q_2 = p_2^{-\sigma} \phi_{13} G_1^{\sigma-1} \mu Y_1 + p_2^{-\sigma} G_3^{\sigma-1} \mu Y_3 \tag{1.15}$$

$\phi_{ij} = \tau_{ij}^{1-\sigma}$ is a measure of trade 'freeness' between countries. $\phi_{ij} = 1$ implies zero transport costs while $\phi_{ij} = 0$ implies infinite transport costs. Country i expenditure, denoted Y_i, equals $L_i w_i \, (= L_i/z_i)$. Equations (1.13), (1.14) and (1.15) can be solved for the price indexes as a function of model parameters. Note that q_i and p_i have already been determined as functions of model parameters:

$$G_1 = \left[\frac{r q_1 p_1^{\sigma} \left(1 - r^{-\sigma}\phi_{12} - r^{-\sigma}\phi_{13}\right)}{\mu Y_1 \left(1 - \phi_{12}^2 - \phi_{13}^2\right)} \right]^{\frac{1}{\sigma-1}} \tag{1.16}$$

$$G_2 = \frac{q_1 p_1^{\sigma} r}{\mu Y_2} \left[\frac{r^{-\sigma}\left(1 - \phi_{12}^2 - \phi_{13}^2\right) - \phi_{12}\left(1 - r^{-\sigma}\phi_{12} - r^{-\sigma}\phi_{13}\right)}{\left(1 - \phi_{12}^2 - \phi_{13}^2\right)} \right]^{\frac{1}{\sigma-1}} \tag{1.17}$$

$$G_3 = \frac{q_1 p_1^{\sigma} r}{\mu Y_3} \left[\frac{r^{-\sigma}\left(1 - \phi_{12}^2 - \phi_{13}^2\right) - \phi_{13}\left(1 - r^{-\sigma}\phi_{12} - r^{-\sigma}\phi_{13}\right)}{\left(1 - \phi_{12}^2 - \phi_{13}^2\right)} \right]^{\frac{1}{\sigma-1}} \tag{1.18}$$

The ratio of the environmental policy parameter in country 1 to country 2 (or country 3) is denoted $r \equiv t_1/t_2 (= t_1/t_3)$.

1.A.2 Derivation of Lemmas 1.1 and 1.2

It is useful to define bounds on the parameter space. By the assumption that all countries produce both goods I have restricted the parameter space such that:

$$\phi_{13} + \phi_{12} < r^{\sigma}$$

$$r^{\sigma} < \left(1 - \phi_{13}^2 + \phi_{13}\phi_{12}\right) / \phi_{12}$$

$$r^{\sigma} < \left(1 - \phi_{12}^2 + \phi_{12}\phi_{13}\right) / \phi_{13}.$$

To see this, note from Equation (1.6) that when these inequalities are satisfied with equality, the number of firms in country 1 is infinitely positive or negative.

Equation (1.6) can be rearranged as:

$$n_1 = \frac{\mu}{f\sigma}\left(\frac{Y_1}{r - \frac{\phi_{12}+\phi_{13}}{r^{\sigma-1}}} - \frac{Y_2\phi_{21}}{\frac{1-\phi_{13}^2+\phi_{12}\phi_{13}}{r^{\sigma-1}} - \phi_{12}r} - \frac{Y_3\phi_{31}}{\frac{1-\phi_{12}^2+\phi_{13}\phi_{12}}{r^{\sigma-1}} - \phi_{13}r}\right)$$

r now only occurs in the denominator terms. Clearly, the derivatives of the first, second and third denominator terms are:

$$1 + (\phi_{12} + \phi_{13})(\sigma - 1)/r^{\sigma} > 0 \tag{1.19}$$

$$-\phi_{12} - (\sigma - 1)\left(1 - \phi_{13}^2 + \phi_{12}\phi_{13}\right)/r^{\sigma} < 0 \tag{1.20}$$

$$-\phi_{13} - (\sigma - 1)\left(1 - \phi_{12}^2 + \phi_{13}\phi_{12}\right)/r^{\sigma} < 0 \tag{1.21}$$

By the signs on these three terms $\partial n_1/\partial r < 0$. Given the parameter bounds established above, differentiating inequalities (1.19), (1.20) and (1.21) with respect to ϕ_{12} or ϕ_{13} confirms Lemma

1.1. Similarly, Lemma 1.2, is obtained by differentiating inequalities (1.19), (1.20) and (1.21) with respect to t_2.

1.A.3 Proof of Proposition 1.1

From equations (1.7) and (1.8):

$$\begin{aligned} n_2 - n_3 &= \frac{\mu}{q_1 p_1}\left[\frac{L_2\left(1-\phi_{13}^2\right)}{1-\phi_{13}^2-\phi_{12}r^\sigma+\phi_{12}\phi_{13}} + \frac{L_3\phi_{12}\phi_{31}}{1-\phi_{12}^2-\phi_{13}r^\sigma+\phi_{12}\phi_{13}} - \frac{L_1\phi_{12}}{r^\sigma-\phi_{12}-\phi_{13}}\right] \\ &\quad -\frac{\mu}{q_1 p_1}\left[\frac{L_3\left(1-\phi_{12}^2\right)}{1-\phi_{12}^2-\phi_{13}r^\sigma+\phi_{12}\phi_{13}} + \frac{L_2\phi_{21}\phi_{13}}{1-\phi_{13}^2-\phi_{12}r^\sigma+\phi_{12}\phi_{13}} - \frac{L_1\phi_{13}}{r^\sigma-\phi_{12}-\phi_{13}}\right] \end{aligned}$$

Therefore:

$\frac{\partial n_2-n_3}{\partial r} > 0$ if $\frac{\partial f}{\partial r} > 0$ where $f \equiv \frac{L_2\left(1-\phi_{13}^2-\phi_{21}\phi_{13}\right)}{1-\phi_{13}^2-\phi_{12}r^\sigma+\phi_{12}\phi_{13}} - \frac{L_3\left(1-\phi_{12}^2-\phi_{12}\phi_{31}\right)}{1-\phi_{12}^2-\phi_{13}r^\sigma+\phi_{12}\phi_{13}} - \frac{L_1(\phi_{12}-\phi_{13})}{r^\sigma-\phi_{12}-\phi_{13}}$

Note that:

$\frac{\partial f}{\partial r} = \frac{L_2\left(1-\phi_{13}^2-\phi_{21}\phi_{13}\right)}{\left(1-\phi_{13}^2-\phi_{12}r^\sigma+\phi_{12}\phi_{13}\right)^2}\sigma\phi_{12}r^{\sigma-1} - \frac{L_3\left(1-\phi_{12}^2-\phi_{12}\phi_{31}\right)}{\left(1-\phi_{12}^2-\phi_{13}r^\sigma+\phi_{12}\phi_{13}\right)^2}\sigma\phi_{13}r^{\sigma-1} + \frac{L_1(\phi_{12}-\phi_{13})}{(r^\sigma-\phi_{12}-\phi_{13})^2}\sigma t^{\sigma-1}$

Therefore:

$\frac{\partial f}{\partial r} > 0$ if $\sigma r^{\sigma-1}\left[\frac{L_2\left(1-\phi_{13}^2-\phi_{21}\phi_{13}\right)\phi_{12}}{\left(1-\phi_{13}^2-\phi_{12}r^\sigma+\phi_{12}\phi_{13}\right)^2} - \frac{L_3\left(1-\phi_{12}^2-\phi_{12}\phi_{31}\right)\phi_{13}}{\left(1-\phi_{12}^2-\phi_{13}r^\sigma+\phi_{12}\phi_{13}\right)^2} + \frac{L_1(\phi_{12}-\phi_{13})}{(r^\sigma-\phi_{12}-\phi_{13})^2}\right] > 0$

This condition can be rewritten as:

$$\frac{L_2\left(1-\phi_{13}^2-\phi_{21}\phi_{13}\right)\phi_{12}}{\left(\Theta-\phi_{12}\Omega\right)^2} > \frac{L_3\left(1-\phi_{12}^2-\phi_{12}\phi_{31}\right)\phi_{13}}{\left(\Theta-\phi_{13}\Omega\right)^2} - \frac{L_1\left(\phi_{12}-\phi_{13}\right)}{\Omega^2}$$

1.A.4 Proof of Corollary 1.1

From Proposition 1.1, the proof requires that the following inequality holds:

$$\frac{\left(1-\phi_{13}^2-\phi_{21}\phi_{13}\right)\phi_{12}}{\left(\Theta-\phi_{12}\Omega\right)^2} > \frac{\left(1-\phi_{12}^2-\phi_{12}\phi_{31}\right)\phi_{13}}{\left(\Theta-\phi_{13}\Omega\right)^2} - \frac{\left(\phi_{12}-\phi_{13}\right)}{\Omega^2}$$

The second RHS term is clearly positive as $\phi_{12} > \phi_{13}$. Because $\phi_{12} > \phi_{13}$ it is also true that $\left(1-\phi_{13}^2-\phi_{21}\phi_{13}\right)\phi_{12} > \left(1-\phi_{12}^2-\phi_{12}\phi_{31}\right)\phi_{13}$. Therefore, the proposition holds if $\left(\Theta-\phi_{12}\Omega\right)^2 <$

$(\Theta - \phi_{13}\Omega)^2$. This condition is equivalent to $\phi_{13} + \phi_{12} < r^{\sigma}$. Therefore, the assumption of the existence of some manufacturing firms in all regions implies that this inequality holds.

1.B Appendix to Section 1.3

1.B.1 Derivation of industry transport costs

Trade freeness in industry l, between countries i and j, ϕ_{ijl}, is estimated from data on bilateral trade flows within each industry. Designating the variable cost of production in industry l in country i as c_{il}, bilateral trade flows between country i and country j in industry l can be expressed as:

$$M_{ijl} = p_{ijl}q_{ijl}n_{il} = \left[\frac{\mu_l Y_j}{\sum_{k=1}^{m} n_{kl}\phi_{kjl}c_{kl}^{1-\sigma}}\right]\left[n_{il}\phi_{ijl}c_{il}^{1-\sigma}\right] \tag{1.22}$$

Taking logs of both sides of equation (1.22) yields:

$$\ln M_{ijl} = \ln\left(\frac{n_{il}}{c_{il}^{\sigma-1}}\right) + \ln\left(\frac{\mu_l Y_j}{\sum_{k=1}^{m} n_{kt}\phi_{kj}c_{kl}^{1-\sigma}}\right) + \ln\phi_{ijl} \tag{1.23}$$

The first and second right-hand terms can be estimated using exporter and importer fixed effects. The third term is estimated using three typical components of bilateral trade freeness identical to those used in Head and Mayer (2004): (population-weighted) distance; contiguity; and common language. This yields the following estimating equation:

$$\ln M_{ijl} = \exp_i + imp_j + B_{1l}\ln d_{ij} + B_{2l}contiguous_{ij} + B_{3l}commonlanguage_{ij} \tag{1.24}$$

I estimate this equation using import data from a compilation of trade flows used by Head et al. (2010). Their data is taken from the IMF's Direction of Trade Statistics (DOTS) database. Geographic data on distances, contiguity and language are obtained from CEPII's GeoDist database. With the estimates $\widehat{B_{1l}}$, $\widehat{B_{2l}}$ and $\widehat{B}_{3l}$, I adopt Redding and Venables (2004) preferred adjustment for internal trade, constructing trade freeness measures between countries i and j in industry l as:

$$\begin{aligned}\widehat{\phi}_{ijl} &= \left(distw_{ij}^{\widehat{B_{1l}}} \exp^{\widehat{B_{2l}}contiguous_{ij}+\widehat{B_{3l}}commonlanguage_{ij}}\right) \text{ if } i \neq j \\ \widehat{\phi}_{iil} &= \left(distw_{ij}^{\widehat{B_{1l}}/2}\right)\end{aligned}$$

The costs of transport by industry, as measured by $\widehat{B_{1l}}$, are presented in Table 1.3. For industries in which $\widehat{B_{1l}}$ is more negative, bilateral export value drops more quickly with distance.

Industry	B_1	**Industry**	B_1
Professional and scientific equipment	-1.143	Wearing apparel, except footwear	-1.441
Tobacco	-1.178	Wood products, except furniture	-1.493
Footwear, except rubber or plastic	-1.178	Non-ferrous metals	-1.523
Pottery, china, earthenware	-1.195	Industrial chemicals	-1.533
Leather products	-1.255	Printing and publishing	-1.54
Transport equipment	-1.301	Glass and products	-1.541
Beverages	-1.325	Fabricated metal products	-1.555
Rubber products	-1.345	Iron and steel	-1.566
Machinery, electric	-1.385	Plastic products	-1.582
Machinery, except electrical	-1.397	Other chemicals	-1.597
Food products	-1.403	Other non-metallic mineral products	-1.604
Furniture, except metal	-1.435	Petroleum refineries	-1.658
Textiles	-1.436	Paper and products	-1.817

TABLE 1.3: Industry trade freeness measures

1.B.2 Industry pollution intensity and ISIC-NAICS concordance

ISIC Industry	**NAICS Industry**	**Pollution Abatement Operating Costs (2005) divided by VA VA (2005)**
Machinery, except electrical	Machinery	0.29%
Wearing apparel, except footwear	Textile product mills	0.32%
Professional and scientific equipment	Computer & electronic product	0.34%
Furniture, except metal	Furniture & related product	0.39%
Machinery, electric	Electrical equipment, appliance, & component	0.48%
Fabricated metal products	Fabricated metal product	0.63%
Printing and publishing	Printing & related support activities	0.64%
Transport equipment	Transportation equipment	0.70%
Rubber products	Plastics & rubber products	0.77%
Plastic products	Plastics & rubber products	0.77%
Beverages	Beverage & tobacco product	0.86%
Tobacco	Beverage & tobacco product	0.86%
Textiles	Textile mills	1.05%
Food products	Food	1.13%
Pottery, china, earthenware	Non-metallic mineral product	1.54%
Glass and products	Non-metallic mineral product	1.54%
Other non-metallic mineral products	Non-metallic mineral product	1.54%
Wood products, except furniture	Wood product	1.71%
Leather products	Leather & allied product	2.50%
Footwear, except rubber or plastic	Leather & allied product	2.50%
Petroleum refineries	Petroleum & coal products	2.69%
Industrial chemicals	Chemical	2.85%
Other chemicals	Chemical	2.85%
Paper and products	Paper	3.33%
Iron and steel	Primary metal	4.26%
Non-ferrous metals	Primary metal	4.26%

TABLE 1.4: Industry Pollution Abatement and Control Operating Experditure (PAOC) for 2005 divided by Industry Value Added (VA) for 2005

1.C Data description

[TABLE BEGINS OVERLEAF]

Variable	Obs.	Mean	Std.Dev	Min	Max	Source
Value added ($US at current prices)	6765	5,422,854.00	19,200,000.00	- 1,141.12	279,000,000.00	Sousa et al. (2012)
MEC^2_{-i}	6765	42.47	71.85	0.08	1,008.39	See Section 3
MEC^1_{-i}	6765	1,052.99	3,279.77	4.82	58,840.27	See Section 3
MEC^2	6765	466.33	642.92	6.45	5,478.73	See Section 3
MEC^1	6765	20.55	9.55	3.74	42.78	See Section 3
Environmental Index (0-49)	6765	22.11	10.11	5.28	42.24	World Economic Forum
Voice and Accountability (0-100)	6765	64.00	15.73	18.51	86.51	World Bank
Political Stability (0-100)	6765	56.50	19.43	1.75	83.26	World Bank
Gov't Effectiveness (0-100)	6765	68.82	18.07	31.71	96.23	World Bank
Regulatory Quality (0-100)	6765	67.59	15.17	31.43	91.70	World Bank
Rule of Law (0-100)	6765	65.38	18.52	28.58	89.89	World Bank
Control of Corruption (0-100)	6765	67.66	21.42	27.21	101.52	World Bank
GDP per capita (PPP) at current prices (international $)	6765	18,294.08	12,048.75	1,487.55	43,111.42	Penn World Tables
Government Consumption Share of GDP	6765	8.96	3.05	3.21	18.17	Penn World Tables
Domestic-USD Exchange Rate	6765	380.21	1,679.04	0.42	14,167.75	Penn World Tables
Population (000s)	6765	91,430.56	225,303.50	277.28	1,284,303.00	Penn World Tables
Foreign Market Potential	5133	4,203,812.00	5,449,816.00	314,661.60	31,100,000.00	Head and Mayer (2011)
Marine Protected Areas (percentage of territorial waters)	6006	9.71	14.57	0.14	74.87	United Nations
Terrestrial Protected Areas (percentage of land area)	6765	13.77	8.72	0.95	41.95	United Nations

Countries: Argentina, Australia, Austria, Bolivia, Brazil, Bulgaria, Canada, Chile, China, Colombia, Costa Rica, Czech Republic, Denmark, Ecuador, Finland, France, Germany, Greece, Hong Kong, Hungary, Iceland, India, Indonesia, Ireland, Israel, Italy, Japan, Jordan, Malaysia, Mauritius, Mexico, Netherlands, New Zealand, Norway, Peru, Philippines, Poland, Portugal, Russian Federation, Singapore, South Africa, Spain, Sweden, Switzerland, Thailand, Turkey, United Kingdom, United States, Vietnam

Years: 1999 - 2005

Industries: See Table 1.3 for industries included

Notes: Only observations with recorded value added are included in this table. Six observations of value added are less than zero. These are omitted prior to taking the natural log. Data used to construct the measures of MEC is included in the data files accompanying this paper.

TABLE 1.5: Summary of data used

1.D Estimation results

[TABLES BEGIN OVERLEAF]

Model	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Dependent variable: ln(value added)								
ln(Environmental Index - Tertile 1)	-0.0609	-0.246			2.977**	3.358***		
	(0.145)	(0.170)			(1.256)	(1.195)		
ln(Environmental Index - Tertile 2)	1.117***	1.129**			1.543*	1.301		
	(0.350)	(0.443)			(0.831)	(1.085)		
ln(Environmental Index - Tertile 3)	0.811***	0.733**			0.311	0.289		
	(0.302)	(0.316)			(0.327)	(0.297)		
ln(Environmental Index - Quartile 1)			0.245	0.221			1.477	2.680**
			(0.154)	(0.209)			(1.417)	(1.247)
ln(Environmental Index - Quartile 2)			0.265	0.433***			0.0238	0.0810
			(0.167)	(0.161)			(0.162)	(0.198)
ln(Environmental Index - Quartile 3)			0.196	0.402*			0.0672	-0.149
			(0.241)	(0.239)			(0.228)	(0.179)
ln(Environmental Index - Quartile 4)			0.144	0.403*			-0.298	-0.301
			(0.225)	(0.217)			(0.208)	(0.196)
Environmental Index	Y	Y	Y	Y	Y	Y	Y	Y
Governance controls	Y	Y	Y	Y	Y	Y	Y	Y
Macroeconomic controls	Y	Y	Y	Y	Y	Y	Y	Y
Market potential	N	Y	N	Y	N	Y	N	Y
Country fixed effects	Y	Y	Y	Y	Y	Y	Y	Y
Industry fixed effects	Y	Y	Y	Y	Y	Y	Y	Y
Year fixed effects	Y	Y	Y	Y	Y	Y	Y	Y
Observations considered	All	All	All	All	EU only	EU only	EU only	EU only
R-squared	0.822	0.823	0.822	0.823	0.855	0.855	0.855	0.855
Observations	6763	5131	6725	5105	2697	1947	2697	1947

Notes: Year-country clustered standard errors of mean in parentheses. Dependent variable is log of industry value added in current USD for the 26 ISIC revision two three-digit manufacturing industries and for 49 countries from 1999 - 2005. *10% level, **5% level, ***1% level. See Appendix C for more detailed variable descriptions.

TABLE 1.6: Naive estimates of the effect of foreign environmental policy

Model	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)
Dependent variable: ln(value added)								
ln(MEC^1)	0.293***	0.296***	0.293***	0.261**				
	(0.0974)	(0.0977)	(0.0977)	(0.109)				
ln(MEC^2)					0.273***	0.275***	0.270***	0.248**
					(0.0982)	(0.0988)	(0.0989)	(0.110)
ln(Environmental Index)	-0.298**	-0.223*	-0.193**	-0.195*	-0.295**	-0.221*	-0.192**	-0.194*
	(0.119)	(0.114)	(0.0889)	(0.101)	(0.119)	(0.114)	(0.0889)	(0.101)
ln(Voice and Accountability)		-0.146	-0.0637	0.0151		-0.148	-0.0655	0.0145
		(0.164)	(0.119)	(0.115)		(0.164)	(0.119)	(0.115)
ln(Political Stability)		0.0686	0.0332	0.0210		0.0690	0.0334	0.0207
		(0.0427)	(0.0392)	(0.0431)		(0.0425)	(0.0392)	(0.0432)
ln(Gov't Effectiveness)		0.158	0.226	0.732		0.161	0.229	0.735
		(0.486)	(0.395)	(0.455)		(0.486)	(0.394)	(0.454)
ln(Regulatory Quality)		0.661*	0.0302	0.117		0.655*	0.0273	0.119
		(0.339)	(0.253)	(0.365)		(0.340)	(0.253)	(0.365)
ln(Rule of Law)		-0.0959	-0.343	-0.762		-0.0975	-0.347	-0.771
		(0.492)	(0.369)	(0.521)		(0.493)	(0.370)	(0.522)
ln(Control of Corruption)		0.849***	0.464*	0.435		0.849***	0.463*	0.434
		(0.320)	(0.239)	(0.318)		(0.320)	(0.239)	(0.318)
ln(GDP per capita)			1.614***	1.658***			1.616***	1.662***
			(0.283)	(0.405)			(0.285)	(0.407)
ln(Gov't share of GDP)			-0.169	-0.00601			-0.166	-0.0000513
			(0.261)	(0.322)			(0.261)	(0.323)
ln(Exchange Rate)			-0.397***	-0.509***			-0.396***	-0.509***
			(0.0943)	(0.0935)			(0.0944)	(0.0935)
ln(Population)			-0.327	1.055			-0.309	1.072
			(0.747)	(1.002)			(0.751)	(1.007)
ln(Market Potential)				0.147				0.146
				(0.136)				(0.137)
Country fixed effects	Y	Y	Y	Y	Y	Y	Y	Y
Industry fixed effects	Y	Y	Y	Y	Y	Y	Y	Y
Year fixed effects	Y	Y	Y	Y	Y	Y	Y	Y
R-squared	0.820	0.821	0.822	0.823	0.820	0.821	0.822	0.823
Observations	6763	6763	6763	5131	6763	6763	6763	5131

Notes: Year-country clustered standard errors of mean in parentheses. Dependent variable is log of industry value added in current USD for the 26 ISIC revision two three-digit manufacturing industries and for 49 countries from 1999 - 2005. *10% level, **5% level, ***1% level. See Appendix C for more detailed variable descriptions

TABLE 1.7: Structural estimates of the effect of foreign environmental policy on value added with domestic policy omitted from MEC

Model	(17)	(18)
Dependent variable: ln(value added)		
ln(MEC^1)	0.283**	
ln(MEC^2)		0.243**
		(0.119)
ln(Environmental Index)	-0.0599	-0.0532
	(0.258)	(0.258)
ln(Voice and Accountability)	0.0616	0.0675
	(0.149)	(0.151)
ln(Political Stability)	0.0637*	0.0637*
	(0.0379)	(0.0381)
ln(Gov't Effectiveness)	1.023**	1.011**
	(0.453)	(0.456)
ln(Regulatory Quality)	-0.446	-0.435
	(0.369)	(0.369)
ln(Rule of Law)	0.272	0.273
	(0.490)	(0.490)
ln(Control of Corruption)	0.760**	0.759**
	(0.359)	(0.360)
ln(GDP per capita)	1.112***	1.107***
	(0.352)	(0.351)
ln(Gov't share of GDP)	-0.270	-0.279
	(0.309)	(0.309)
ln(Exchange Rate)	-0.505***	-0.504***
	(0.0948)	(0.0948)
ln(Population)	0.531	0.507
	(1.355)	(1.354)
ln(Market Potential)	0.359***	0.361***
	(0.129)	(0.130)
Country fixed effects	Y	Y
Industry fixed effects	Y	Y
Year fixed effects	Y	Y
Durbin-Wu-Hausman statistic	0.193	0.215
Durbin-Wu-Hausman p-value	0.660	0.643
Hansen J-statistic	0.886	0.893
Hansen J-statistic p-value	0.347	0.345
Anderson L-R statistic	135.4***	135.4***
Anderson L-R statistic p-value	4.06e-30	4.01e-30
Cragg-Donald F-statistic	68.04	68.06
R-squared	0.0112	0.0106
Observations	4510	4510

Notes: Year-country clustered standard errors of mean in parentheses. Dependent variable is log of industry value added in current USD for the 26 ISIC revision two three-digit manufacturing industries and for 49 countries from 1999 - 2005. *10% level, **5% level, ***1% level. See Appendix C for more detailed variable descriptions. Marine and terrestrial protected area as a percentage of total territorial waters and land are instruments for ln(environmental index). Table 1.9 presents first stage regression results.

TABLE 1.8: Instrumental variable estimation

First Stage of Model	(17)	(18)
Dependent variable: ln(value added)		
ln(MEC^1)	0.0075	
	(0.0106)	
ln(MEC^2)		0.0065
		(0.0107)
ln(Voice and Accountability)	0.4286***	0.4286***
	(0.1629)	(0.1629)
ln(Political Stability)	-0.0596	-0.0596
	(0.0463)	(0.0463)
ln(Gov't Effectiveness)	-0.0513	-0.0509
	(0.3989)	(0.3989)
ln(Regulatory Quality)	0.8946**	0.8945**
	(0.3531)	(0.3532)
ln(Rule of Law)	-1.4327***	-1.433***
	(0.4348)	(0.4349)
ln(Control of Corruption)	-0.3077	-0.3077
	(0.3037)	(0.3037)
ln(GDP per capita)	0.2197	0.2198
	(0.3339)	(0.3339)
ln(Gov't share of GDP)	0.2639	0.2642
	(0.3626)	(0.3626)
ln(Exchange Rate)	0.0192	0.0191
	(0.1316)	(0.1316)
ln(Population)	3.3323***	3.3335***
	(0.7603)	(0.7605)
ln(Market Potential)	0.2535**	0.2535**
	(0.1113)	(0.1113)
Marine Protected Area (% of territorial waters)	-0.0104***	-0.0104***
	(0.0038)	(0.0038)
Terrestrial Protected Area (% of land area)	-0.0024	-0.0024
	(0.0116)	(0.0116)
Observations	4510	4510

Notes: Year-country clustered standard errors of mean in parentheses. *10% level, **5% level, ***1% level. See Appendix C for more detailed variable descriptions.

TABLE 1.9: First stage regression results

Model	(19)	(20)	(21)	(22)	(23)	(24)
Dependent variable: ln(value added)						
ln(MEC^1)	0.311***	0.298***	0.00269			
	(0.104)	(0.0979)	(0.185)			
ln(MEC^2)				0.291***	0.275***	0.00527
				(0.106)	(0.0986)	(0.185)
ln(Environmental Index)		-0.196**	-0.134		-0.195**	-0.134
		(0.0897)	(0.0932)		(0.0897)	(0.0932)
Governance controls	N	Y	Y	N	Y	Y
Macroeconomic controls	N	Y	Y	N	Y	Y
Country fixed effects	N	Y	N	N	Y	N
Industry fixed effects	Y	N	N	Y	N	N
Year fixed effects	N	N	Y	N	N	Y
Country-Year fixed effects	Y	N	N	Y	N	N
Industry -Year fixed effects	N	Y	N	N	Y	N
Country-Industry fixed effects	N	N	Y	N	N	Y
R-squared	0.825	0.824	0.980	0.825	0.824	0.980
Observations	6763	6763	6763	6763	6763	6763

Notes: Year-country clustered standard errors of mean in parentheses. Dependent variable is log of industry value added in current USD for the 26 ISIC revision two three-digit manufacturing industries and for 49 countries from 2001 and 2005. *10% level, **5% level, ***1% level. See Appendix C for more detailed variable descriptions.

TABLE 1.10: Estimated effects of MEC with two-way fixed effects

Model	(25)	(26)	(27)	(28)
Dependent variable: ln(value added)				
ln(MEC^1)	1.364**	1.302**	1.110	5.647**
	(0.538)	(0.554)	(0.739)	(2.577)
ln(Environmental Index)	-0.649*	-0.874***	-0.630**	
	(0.331)	(0.227)	(0.252)	
R-squared	0.986	0.987	0.987	0.988
Observations	1833	1833	1833	1833
Model	(29)	(30)	(31)	(32)
Dependent variable: ln(value added)				
ln(MEC^2)	1.375**	1.309**	1.119	5.834**
	(0.537)	(0.552)	(0.741)	(2.608)
ln(Environmental Index)	-0.647*	-0.872***	-0.628**	
	(0.331)	(0.227)	(0.252)	
R-squared	0.986	0.987	0.987	0.988
Observations	1833	1833	1833	1833
Governance controls	N	Y	Y	N
Macroeconomic controls	N	N	Y	N
Country fixed effects	N	N	N	N
Industry fixed effects	N	N	N	N
Year fixed effects	Y	Y	Y	Y
Country-Year fixed effects	N	N	N	Y
Country-Industry fixed effects	Y	Y	Y	Y

Notes: Year-country clustered standard errors of mean in parentheses. Dependent variable is log of industry value added in current USD for the 26 ISIC revision two three-digit manufacturing industries and for 49 countries from 2001 and 2005. *10% level, **5% level, ***1% level. See Appendix C for more detailed variable descriptions

TABLE 1.11: Country-Industry fixed effects with observations for years with lowest and highest environmental index

Model	(33)	(34)	(35)	(36)
Dependent variable: ln(value added)				
$\ln(MEC^1)$	0.215**	0.218**	0.213**	0.227**
	(0.0960)	(0.0965)	(0.0966)	(0.102)
ln(Environmental Index)	-0.379***	-0.304***	-0.278***	
	(0.120)	(0.114)	(0.0885)	
ln(Environmental Index)*ln(Pollution Intensity)	-0.413***	-0.413***	-0.413***	-0.411***
	(0.0297)	(0.0297)	(0.0297)	(0.0302)
Governance controls	N	Y	Y	N
Macroeconomic controls	N	N	Y	N
Country fixed effects	Y	Y	Y	N
Industry fixed effects	Y	Y	Y	Y
Year fixed effects	Y	Y	Y	N
Country-Year fixed effects	N	N	N	Y
R-squared	0.826	0.826	0.828	0.830
Observations	6763	6763	6763	6763

Notes: Year-country clustered standard errors of mean in parentheses. Dependent variable is log of industry value added in current USD for the 26 ISIC revision two three-digit manufacturing industries and for 49 countries from 1999 - 2005. *10% level, **5% level, ***1% level. See Appendix C for more detailed variable descriptions

TABLE 1.12: Accounting for industry pollution intensity

Full sample			
Dependent variable: ln(value added)			
ln(Environmental Index) - No MEC control	-0.188**	-0.191**	-0.134
ln(Environmental Index) - MEC^1 control	-0.193**	-0.195**	-0.134
Relative to estimate without MEC control	97.4%	97.9%	100.0%
ln(Environmental Index) - MEC^2 control	-0.192**	-0.196**	-0.134
Relative to estimate without MEC control	97.9%	97.4%	100.0%
Observations	6763	6763	6763
Years 2001 and 2005			
Dependent variable: ln(value added)			
ln(Environmental Index) - No MEC control	-0.781***	-0.795***	-0.761***
ln(Environmental Index) - MEC^1 control	-0.733***	-0.746***	-0.630**
Relative to estimate without MEC control	106.5%	106.6%	120.8%
ln(Environmental Index) - MEC^2 control	-0.731***	-0.743***	-0.628**
Relative to estimate without MEC control	106.8%	107.0%	121.2%
Observations	1833	1833	1833
Governance controls	Y	Y	Y
Macroeconomic controls	Y	Y	Y
Country fixed effects	Y	Y	N
Industry fixed effects	Y	N	N
Year fixed effects	Y	N	Y
Industry-Year fixed effects	N	Y	N
Country-Industry fixed effects	N	N	Y

Notes: Year-country clustered standard errors of mean in parentheses. Dependent variable is log of industry value added in current USD for the 26 ISIC revision two three-digit manufacturing industries and for 49 countries from 1999 - 2005. *10% level, **5% level, ***1% level. See Appendix C for more detailed variable descriptions.

TABLE 1.13: Estimating bias with omitted MEC

2

Subjective Well-Being: Weather Matters; Climate Doesn't

John Feddersen, Rob Metcalfe and Mark Wooden[1]

Abstract

We investigate the impact of short-term weather and long-term climate on self-reported life satisfaction using panel data. We find robust evidence that day-to-day weather variation impacts life satisfaction by a similar magnitude to acquiring a mild disability. Utilizing two sources of variation in the cognitive complexity of satisfaction questions, we present evidence that weather bias arises because of the cognitive challenge of reporting life satisfaction. Consistent with past studies, we detect a relationship between long-term climate and life satisfaction without individual fixed effects. This relationship is not robust to individual fixed effects, suggesting climate does not directly influence life satisfaction.

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2.1 Introduction

Social scientists increasingly turn to measures of subjective well-being (SWB) in addition to traditional 'objective' measures of welfare such as GDP, crime levels and health statistics. Recent analysis uses SWB measures to evaluate social progress[2], value non-market goods (Welsch 2006; Rehdanz and Maddison 2008; Carroll et al. 2009; Frey, Luechinger, and Stutzer 2009; Luechinger 2009; Levinson 2012) and assess government policy (Diener et al. 2009; Dolan et al. 2011; Boarini et al. 2012; Dolan and Metcalfe 2012).

A key reason that social scientists feel more confident using SWB measures is that several major causes of skepticism toward them have been addressed. Two of the most critical challenges are ensuring the *validity* and the *consistency* of SWB measures. Put simply: *do SWB measures reflect actual well-being, and do they reflect it consistently through time?*

There is a large and growing body of evidence supporting the validity of SWB as a measure. Several studies show a strong association between SWB and objective measures that could conceivably proxy for well-being (i.e. 'convergent validity' studies).[3] Another literature has identified associations between SWB and measures one might think it should be related to (i.e. 'construct validity' studies).[4] SWB measures are also fairly consistent through time.[5]

While this recent work may be enough to placate a skeptical economist, the validity and consistency of SWB measures is not perfect, as they reflect a variety of factors that are of little empirical interest. SWB measures may be sensitive to question order (Strack et al. 1988; Deaton 2012) and the way the survey is introduced (Ubel et al. 2001). Recent pleasant experiences, such as finding a dime on a photocopier immediately prior to the survey (Schwarz 1987) or receiving a chocolate bar (Münkel et al. 1987), increase SWB by magnitudes that cannot be explained by the income effect.

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2 For examples of the use of SWB as a measure of social progress see reports by the Governments of Australia (Measures of Australia's Progress), Finland (Findicator - Set of Indicators for Social Progress), Germany (Sustainable Development Report), and New Zealand (Measuring New Zealand's Progress Using a Sustainable Development Approach). Also see Stiglitz, Sen, and Fitoussi (2009).

3 Kahneman & Krueger (2006) find a positive correlation between self-appraisal of SWB and appraisal by both friends and strangers; Oswald & Wu (2010) find that amenities with higher hedonic value increase life satisfaction; and Konow & Earley (2008) report correlations between SWB and the duration of genuine 'duchene' smiles, heart rate and blood pressure.

4 SWB is a useful predictor of suicide, sociability, extroversion and quality of sleep (Boarini et al. 2012). There is also a large literature documenting the sensitivity of SWB to changes in circumstances, such as losing a job or becoming disabled, which are objectively positive or negative (Frijters, Haisken-DeNew, and Shields 2004).

5 When asked the same SWB question twice on the same day, Krueger & Schkade (2008) find a correlation ranging from 0.6 to 0.7 between a person's answers. Schimmack, Diener, and Oishi (2002) show that people tend to reflect on the same information to make SWB judgments at different times, which may explain this consistency.

Similarly, Schwarz et al. (1987) report a significant increase in life satisfaction when respondents are in a more comfortable room.

Campbell (1981, p. 23) argues that for reports of SWB to be accurate people must be able to 'describe [well-being] with candor and accuracy.' Diener et al. (2009) agree, suggesting (p. 19): 'the only link that creates potential problems for the measurement of well-being is between the evaluation itself and a person's judgment of the evaluation'. In this chapter we investigate Campbell's condition, considering the influence of contemporaneous transient weather[6] on SWB in a large nationally representative Australian panel survey.

In many cases a disconnect between well-being and a person's judgment of well-being is of theoretical interest but of practical irrelevance. For example, judgment biases may be so small, and their causes sufficiently random, that in large representative samples they are of no practical consequence (Boarini et al. 2012). In addition, for non-transient factors like question order, once the bias is identified it may be nullified by appropriate study design. This solution relies on potential sources of bias being identified in the first place.

Weather bias – which arises when transient weather influences long-run measures of SWB such as life satisfaction – may not be avoided in large samples and is difficult to overcome through study design. The first main challenge arises because weather may drive underlying variables of interest. One prominent example is the way wind speed and direction causes variation in local air pollution levels (Levinson 2012). If wind affects SWB then estimates of the influence of pollution on SWB may be biased. Second, within a given location weather is highly temporally correlated and could influence inference based on time-variation in treatment. Studies of the impact of, for example, sporting events, natural disasters or terrorist attacks should mitigate the risk that variation in weather before and after the event influences inference. A better understanding of the influence of weather on SWB is therefore of practical, as well as purely theoretical, interest.

In this study, we evaluate the theoretical and practical relevance of weather on self-reported life satisfaction. This study is not the first to consider this question. Schwarz & Clore (1983) analyzed a sample of 84 respondents to a telephone survey and is the most widely cited study on this topic. Considering the effects of 'sunny' and 'rainy' days, the authors detect large and significant impacts on self-reported life satisfaction with subjects not primed to attribute their mood to the

[6] We follow convention and refer to weather as a short-term phenomenon and climate as a long-term phenomenon. We operationalize these defintions in our data by using meteorologic observations for a particular location at a particular hour or on a particular day to measure the weather. Climate is calculated as an annual average over the decade from Jan 1, 2000 to Dec 31, 2009.

weather.[7] The authors speculate that weather affects mood, which is one of several transient factors respondents reflect on in expressing their own life satisfaction.

Weather effects of the magnitude of Schwarz & Clore (1983) have, to the best of our knowledge, never been replicated. Recent studies use larger cross-sectional data sets and provide conflicting punch lines. Connolly (forthcoming) finds a significant negative effect of more precipitation and higher temperature, while Levinson (2012) finds no effect of precipitation and a positive (though declining) effect of temperature on life satisfaction. Barrington-Leigh (2008) reports that life satisfaction varies significantly with the amount of recent cloud cover. Finally, Lucas & Lawless (2012) find little evidence of a relationship between any of a large number of weather variables and life satisfaction.[8]

Despite uncertainty over the relationship between life satisfaction and weather, there is evidence that weather influences mood (Watson 2000; Denissen et al. 2008) and risk-taking behavior (Simonsohn 2009). It has even been found that morning sunshine in the city of a country's leading stock exchange is strongly correlated with stockmarket returns (Hirschleifer and Shumway 2003).

Our estimated weather effects are novel for four reasons. First, ours is the first study to include individual fixed effects while estimating the effect of weather on life satisfaction. Recent psychology and economics literature has found that fixed person-specific traits are enormously important predictors of general satisfaction (Argyle 1999; Diener and Lucas 1999; Ferrer-i-Carbonell and Frijters 2004). As a consequence, a failure to control for this large source of cross-person variation in life satisfaction has substantial potential to create omitted variable bias in estimates of the effect of weather on life satisfaction.[9] Our results show that this is an important innovation.

Second, Barrington-Leigh (2008), Connolly (forthcoming), Levinson (2012) and Lucas & Lawless (2012) use weather variables for the day of – rather than at the precise time of – collection of life satisfaction data. Using a time marker for the start of the survey in which life satisfaction data are collected, we are able to use weather data at almost precisely the time of interview. Previous

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[7] On a scale from one to ten, respondents on a sunny day reported mean life satisfaction of 6.57. Those surveyed on a rainy day reported 4.86.

[8] Connolly (forthcoming) includes location (State) and seasonal (month) fixed effects in her largest model. Levinson (2012) includes year, month and county fixed effects. Barrington-Leigh (2008) includes location and month fixed effects. Lucas & Lawless (2012) do not include fixed effects. Instead, the authors specifically control for month and location by including monthly and annual average values of their weather variables in each specification.

[9] As one example of a source of omitted variable bias consider 'active' people, who tend to be both more satisfied than average and busier than average when the sun is shining, and therefore tend not to be available to answer the HILDA survey in sunny conditions. These satisfied active people are likely to be overrepresented in cloudy and rainy weather conditions.

studies that find small and insignificant weather effects may simply have too much noise in the regressors and more specific measurement of weather conditions at the time of the interview will improve efficiency and remove downward bias.

Third, previous studies have typically focused on a small set of weather variables. Connolly (forthcoming) and Levinson (2012) consider precipitation and temperature variables and Barrington-Leigh (2008) includes cloud cover in addition. We consider these variables in addition to barometric pressure, wind speed and relative humidity, which have all been shown to influence mood or behavior (Keller et al. 2005; Frijters and van Praag 1998; and Denissen et al. 2008). These six weather variables are described by biometeorologists San-Gil, González de Rivera, and González (1991, p. 402) as 'the complete weather picture'. Lucas & Lawless (2012) consider similar weather variables to this chapter.

Because weather variables tend to be correlated, considering all weather variables together is important when evaluating which ones actually matter. For example, because cloud cover and temperature are negatively correlated, Barrington-Leigh's (2008) combination of significant cloud cover and insignificant temperature may actually reconcile with Levinson's (2012) significant temperature effects in the absence of a control for cloud cover.

Fourth, our weather data are very spatially detailed, removing another potential source of noise in the regressors when compared to previous studies. Almost all weather variables are collected from within 20km of the survey location.[10]

With these enhancements, the first main contribution of the chapter is the significant weather effects we estimate. Using OLS regression with individual fixed effects, we find a positive and statistically significant effect of global solar exposure, which provides a precise and spatially detailed measure of cloudiness. Additionally, we find negative and significant effects of barometric pressure and wind speed. Wind direction is also found to affect life satisfaction. If total daily solar exposure is one standard deviation (6.43 MJ/m^2) above its average, life satisfaction increases by 0.012 on an eleven-point scale from zero to ten. A one standard deviation decrease in mean sea level pressure (7.08 hPa) increases life satisfaction by 0.016. The estimated effect of mean daily wind speed is larger, especially for females, where a one standard deviation decrease in wind speed (1.91 m/s) increases life satisfaction by 0.026.

[10] The mean distance from the location of collection of life satisfaction data to the nearest weather station is 8.9 kilometers (km). The values for the 10th, 50th and 90th percentiles of this distance are 2.45km, 6.76km and 17.26km respectively.

To place these magnitudes into context, first note that there is a substantial component of SWB that is stable over time, due in part to personality traits and other factors that are inherited (Lykken and Tellegen, 1996). As a result, even very large changes in circumstances tend not to change life satisfaction by even one unit. Our weather effects are small relative to being unemployed rather than employed (-0.203), acquiring a severe disability (-0.460) or being separated from a partner rather than being single (-0.398). However, typical day-to-day changes in weather affect life satisfaction by similar orders of magnitude to acquiring a mild disability – one which does not affect ability to work – (-0.0553) and not being in the labour force rather than employed (-0.0362). Considering income, we find to a first-order approximation that a ten percent increase in household nominal equivalized income is associated with an increase in life satisfaction of 0.0024. This small income effect implies that day-to-day weather variation has effects of similar magnitude to doubling income.

In comparison to the size of Schwarz and Clore's (1983) effects, these results are puny; even comparing the observations of daily global solar exposure, sea level pressure and daily wind speed that yield the lowest life satisfaction (0.22 MJ/m^2, 1039.15 hPa and 19.05 m/s respectively) with the observations yielding the highest satisfaction (35.29 MJ/m^2, 979.72 hPa and 1.91 m/s), the estimated change in life satisfaction is 0.32, only a small fraction of Schwarz and Clore's (1983) estimated difference of 1.71 between 'sunny' and 'cloudy' days on a very similar ten-point scale. Despite this difference in magnitude, we do confirm Schwarz and Clore's (1983) finding that cloudiness matters.

Solar exposure and mean sea level pressure significantly influence males while the speed and direction of the wind affect females. We find no significant interaction effects between the transient weather variables and their annual and monthly averages. This implies, for example, that higher solar exposure on the day of the interview increases life satisfaction regardless of the time of the year or the average annual solar exposure where the survey is administered. Similarly, wind and mean sea level air pressure appear to negatively influence life satisfaction regardless of the season or climate.

We also investigate the existence of non-linear associations between weather and life satisfaction. When we include squared weather terms in the specification we find no evidence of a non-linear relationship between daily wind speed and life satisfaction. As a final test of non-linearity, we include dummy variables for weather extremes (defined as being below the 5th percentile or above the 95th percentile for each variable) and find no significant effects.

To consider the effect of recent changes in weather, we estimate a version of the model with lagged weather variables from three and six hours before the survey. We find little evidence that recent weather conditions or recent changes in weather conditions influence life satisfaction. The only exception is the wind speed variable, for which we have evidence that the change in wind speed from six hours earlier influences life satisfaction.

The second main contribution of the chapter is evidence supporting the hypothesis that the cognitive complexity of reporting life satisfaction causes weather bias. To do this we make two assumptions – supported both theoretically and empirically – giving rise to variation in cognitive complexity of satisfaction questions. First, we consider the effect of weather on nine 'domain-specific' measures of well-being, which we assume are cognitively simpler to report than life satisfaction.[11] These measures cover satisfaction with: one's job, employment opportunities, personal financial situation, home life, local community, local neighborhood, safety, health and free time. We find almost no significant weather effects for all of these variables, suggesting that less cognitively complex questions suffer less from weather bias.

Second, based on evidence of 'panel conditioning' in the HILDA survey as well as other life satisfaction surveys, we assume that the cognitive complexity of the life satisfaction question declines with experience.[12] We show that weather bias declines with panel experience and therefore cognitive complexity.

The third main contribution comes from revisiting past studies of the effect of climate on life satisfaction while using panel data and individual fixed effects. Similar to past studies, without individual fixed effects we find significant effects of climate on life satisfaction (Frijters and van Praag 1998; Rehdanz and Maddison 2005; Brereton et al. 2008; Ambrey and Fleming 2011; Maddison and Rehdanz 2011). Once we allow for individual fixed effects, therefore estimating the climate effect using only within-person climate variation arising when people move their household location, we find no effect of climate on life satisfaction. This suggests that causation does not flow directly from climate to life satisfaction; rather that previously omitted time-invariant individual characteristics influence both location and life satisfaction.

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[11] General life satisfaction is what psychologists call a 'domain-free' measure of wellbeing. According to Strack, Argyle, and Schwarz (1991), compared to domain-specific measures, domain-free measures are more cognitively demanding to provide and are therefore potentially more influenced by transient factors.

[12] Several studies show experience effects in panel data surveys (Toepoel, Das, and van Soest 2009; Das, Toepoel, and van Soest 2011; van Landeghem 2012). Work in progress at the Melbourne Institute of Applied Economic and Social Research by Wooden and Li using the HILDA Survey data finds learning effects for males as both the dispersion and the level of life satisfaction decline with experience.

This new puzzle – that weather matters but climate doesn't – is consistent with the finding of Graham (2009) and Deaton (2012) that people's capacity to adapt to permanent changes tends to mediate well-being effects, while changes people cannot adapt to – such as uncertain weather – have a much stronger effect. From a policy perspective, this finding implies that climate does not provide amenity value (at least within the climatic ranges experienced in Australia), suggesting, for example, that greenhouse gas induced climatic change will not directly influence life satisfaction.[13]

The remainder of the chapter proceeds as follows. Section 2 describes the econometric framework used and construction of the data set. Section 3 presents results. Section 4 concludes the chapter.

2.2 Econometric framework and data

2.2.1 Econometric framework

There is no structural framework motivating the analysis and instead reduced form equations estimate the marginal effect of the variables of interest on SWB, a proxy for actual well-being. We estimate the following linear regression model:[14]

$$SWB_{ijt} = \alpha_i + \alpha_j + \alpha_m + \alpha_y + W'_{jt}\beta + X'_{it}\gamma + \varepsilon_{ijt} \tag{2.1}$$

SWB_{ijt} is the stated life satisfaction of respondent i in location j at time t, where time is expressed in terms of the year, month, day and hour of interview, and α_i, α_j, α_m and α_y are dummy variables for individual, location (measured by post code), month and year.

The use of individual fixed effects to control for omitted variable bias is a main contribution of this chapter. Because unmeasurable individual characteristics are important determinants of life satisfaction (Argyle 1999; Diener and Lucas 1999) the scope for omitted variable bias in their absence is large. Indeed, with our life satisfaction data the R-squared of an OLS regression fitting only individual dummy variables as independent variables is 0.6.

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[13] Climate change may influence life satisfaction through consequences not captured in our data, for example, through acute events, like flooding (Leuchinger and Raschky 2009), with temporally and spatially limited effects making them difficult to detect in national data collected over several months.

[14] Prior to estimating this we conducted a Hausman test of the appropriateness of a random effects specification, rejecting the hypothesis that unobserved individual traits are not correlated with the explanatory variables.

Year dummies are assigned according to the HILDA Survey year, which starts in August, in order to control for wave-specific factors from the HILDA Survey as well as other year-specific factors. Month fixed effects control for seasonal variation in life satisfaction, and their inclusion eliminates confounding of weather at the time of interview with seasonal factors. For example, in the absence of month fixed effects, a positive effect of temperature on life satisfaction could either be caused by summer-specific factors or by the daily weather itself. Location fixed effects address a similar confounding problem between daily weather variables and climate – which is calculated as an annual average over ten years – rather than season.

We include weather variables corresponding to the time and location of the interview denoted by W_{jt}. These are the main variables of interest and the selection and construction of these is explained in detail in Section 2.2.2. In Section 2.3.3, in order to estimate climate effects, we include climate variables in our specification and remove post code fixed effects.

We also include individual time-specific controls, X_{it}. These are age and its square, the number of household dependents aged between 0 and 24, and the natural log of nominal household disposable income for the previous financial year in Australian dollars. Dummy variables are also included for disability status, employment status, marital status and education. These controls are typically the most important determinants of life satisfaction (Frijters et al. 2004).

Finally, we investigate three other non-weather sources of potential bias. Based on Csikszentmihalyi & Hunter (2003) we include a dummy variable indicating if the interview was conducted on a weekend and a variable measuring the hour of day at which the interview is conducted. Controlling for hour of day serves a second purpose; because four weather variables are measured at the time of the interview, absence of the hour variable would cause weather variables like temperature, which changes predictably throughout the day, to be confounded with effects related to the time of day, such as tiredness. Finally, following Wooden et al. (2009), we include an indicator variable which is equal to one if another person is present during the interview.

2.2.2 Data

Two sources are used in the construction of the data set. All non-weather variables are obtained from the Household, Income and Labour Dynamics in Australia (HILDA) Survey, while weather variables are extracted from the Australian Bureau of Meteorology (BoM) database.

2.2.2.1 Household, Income and Labour Dynamics in Australia (HILDA) Survey

The well-being data used in this study are drawn from waves one to nine of the HILDA Survey. Described in more detail in Wooden & Watson (2007), the HILDA Survey is an unbalanced household panel survey with a focus on work, income and family. Its design is closely modelled on the British Household Panel Survey (BHPS) and the German Socio-Economic Panel (GSOEP).

The survey commenced in 2001 with a national probability sample of Australian households. Personal interviews were completed at 7,682 households in wave one and these generated a responding sample of 13,969 individuals. The characteristics of the sample match the broader adult population quite well.

The members of these participating households form the basis of the panel pursued in the subsequent waves of interviews, which are conducted approximately one year apart. Interviews are conducted with all adults (defined as persons aged 15 years or older on 30 June preceding the interview date) who are members of the original sample, as well as any other adults who, in later waves, are residing with an original sample member. Annual re-interview rates (the proportion of respondents from one wave who are successfully interviewed the next) are reasonably high, rising from 87 per cent in wave two to 96.3 per cent in wave nine.

The main outcome variable used in this analysis is a measure of overall life satisfaction. It is constructed from responses to a single item scored on an eleven-point scale ranging from zero to ten.[15] The question, delivered by interviewer, either in person or by telephone is:[16] 'All things considered, how satisfied are you with you life?' A score of zero is labelled and described as 'totally dissatisfied' and a score of ten labelled and described as 'totally satisfied'. This question is almost identical to a question included every year in the GSOEP and is similar to those in cross-country surveys, such as the World Values Survey and the Euro-Barometer Survey. It is also very similar to the question used in Schwarz and Clore's (1983) seminal work.[17]

We also consider the effect of weather variables on satisfaction with job, employment opportunities, financial situation, home, local community, neighborhood, safety, health and free time, which are similarly scaled from zero to ten. Finally, the HILDA Survey also provides the controls for age, number of household dependents, the natural log of nominal household equivalized disposable

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15 Single item life satisfaction questions are the most commonly used measure of SWB by economists (Dolan, Peasgood, and White 2008).

16 The proportion of interviews conducted by telephone in the HILDA Survey has ranged from 0.5 percent in wave one to 10.1 percent in wave eight (Watson and Wooden 2010).

17 Schwarz and Clore (1983) asked: 'How satisfied are you with your life as a whole these days?'

income[18], disability status, employment status, relationship status, highest level of education and gender. Summary statistics for all HILDA Survey variables used are presented in Table 2.10. Detailed descriptions of all variables are in Tables 2.12 and 2.13.

For our purposes, one advantage of using data from the HILDA Survey, rather than the BHPS and GSOEP, is the spread of weather conditions in Australia. We are able to consider weather and climate effects in many highly heterogeneous locations. Because interviews are conducted between August and February, we are also able to consider weather effects in different seasons. It seems plausible that life satisfaction would, for example, exhibit a positive weather influence of both warm temperatures in winter and cool temperatures in summer.

A second advantage over other sources of data on life satisfaction arises because the data set contains information on survey start time. This allows weather data to be matched very precisely to the time of interview.

2.2.2.2 Bureau of Meteorology

Weather data are obtained from the Australian Bureau of Meteorology (BoM) and to identify the relative contribution of similar weather types, we choose to include a broad selection of the available weather variables.[19] First, we incorporate similar measures to past studies: precipitation, temperature and cloud cover (Barrington-Leigh 2008; Connolly forthcoming; Levinson 2012; Lucas and Lawless 2012).[20] We approximate cloudiness with global solar exposure, which is measured by satellite and available for more locations than cloud coverage.[21] To those previously-used variables we add three additional variables, which past studies suggest are important. These are barometric pressure (Keller et al. 2005), relative humidity (Frijters and van Praag 1998) and wind speed (Denissen et al. 2008). Together, these are the six most commonly reported weather variables by a significant margin. Summary statistics are provided in Table 2.10, a correlation matrix for the weather variables is in Table 2.11 and a description of the weather variables is in Table 2.12.

Whenever possible, we use weather variables recorded at the time of the interview. There are four interview time-specific weather variables – mean sea level pressure, temperature, wind speed and

[18] 309 observations take the value zero so we add 1 to each value before taking the log. 440 observations report negative real household equivalized disposable income and these are dropped from the sample.

[19] For example, estimating the effect of temperature on life satisfaction in a model that does not control for solar exposure is likely to yield spurious results.

[20] Past studies have also considered snow, which is very rare in Australian population centers.

[21] Values of daily global solar exposure are highest in clear conditions and lowest on very cloudy days. BoM daily solar exposure gridded data sets cover Australia with a resolution of 0.05 degrees in latitude and longitude (roughly 5km^2).

relative humidity – which are recorded at three-hour intervals throughout the day (BoM provides weather variables at 3am, 6am, ... 9pm and 12am). Global solar exposure and precipitation are recorded on a daily basis and because wind speed and direction tend to be correlated, in all models we also include dummy variables indicating the direction of the wind (north, south, east or west). Finally, as wind speed changes rapidly throughout the day, we include daily mean wind speed in addition to wind speed at time of interview.

As a robustness check, and to consider the effects of season and climate on life satisfaction, we also consider monthly and annual averages of global solar exposure, wind speed, daily maximum temperature and precipitation in our analysis. Monthly and annual averages for mean sea level pressure and relative humidity are not readily available from the BoM.

Weather variables are obtained from each of the approximately 850 weather stations in operation from January 2001 until the completion of wave nine in 2010. Figure 2.1 plots the location of all stations operating at the end of HILDA Survey wave nine with longitude on the x-axis and latitude on the y-axis. Over 90 percent of observations are within 20km of the closest weather station.

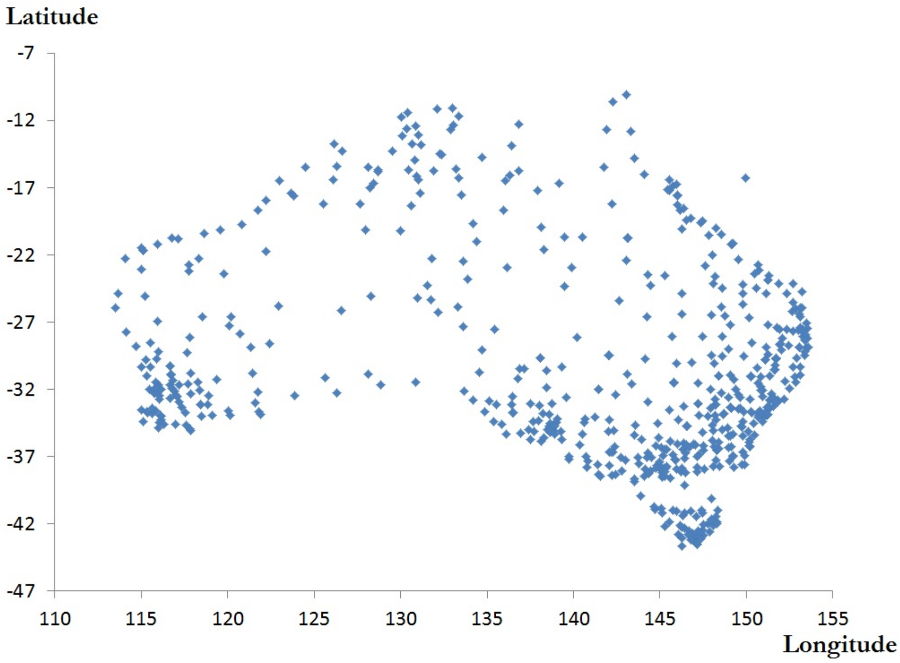

FIGURE 2.1: Map of weather stations

Reported longitude and latitude of census collection districts (CDs) in the HILDA Survey data and of weather stations in the BoM data enable HILDA Survey responses to be matched to weather variables on the survey day. With 850 stations and HILDA Survey sample members spread across roughly 9,000 CDs, each weather station may map to several CDs.[22]

We take two steps to match the data. First, we calculate the three closest weather stations to the CD of the household completing the HILDA Survey by great-circle distance. Second, we take a simple distance-weighted average of the weather at these three stations to use for analysis.[23] This method has the advantage of enabling interpolation between weather stations in order to better measure the weather at a particular location.

2.3 Results

2.3.1 Weather effects

2.3.1.1 Main results

Table 2.1 presents results from our baseline attempts at estimating weather effects. Model 1 incorporates month and wave fixed effects only, while Model 2 also includes location fixed effects. These specifications are included to replicate the approach in a recent analysis by Connolly (forthcoming) and they help illustrate the importance of adopting individual and post code fixed effects (as in Model 4). Like Connolly (forthcoming), Models 1 and 2 detect a significant effect of temperature on life satisfaction; warmer weather reduces life satisfaction. We also find that higher sea level air pressure causes disutility and that the direction of the wind matters.

Time-invariant post code level heterogeneity is likely to be important in light of the literature on the relationship between climate variables (i.e. long-run weather averages) and life satisfaction.[24] In the absence of a control for this, short-term weather and long-term climate are confounded such that it is not possible to isolate the weather effect.[25] In Model 3 we include post code level fixed effects to address this empirical challenge and find that coefficients on solar exposure, temperature and humidity are no longer significant.

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22 Australia has approximately 37,000 CDs in total with roughly 225 dwellings in each.

23 To be precise, the weight placed on weather variables at the closest station is $(1/d_1)\,/\,(1/d_1 + 1/d_2 + 1/d_3)$.

24 See, for example, Frijters & Van Praag (1998), Rehdanz & Maddison (2005) and Brereton, Clinch, and Ferreira (2008).

25 For example, a positive coefficient on temperature may arise because people in warm places have higher life satisfaction, even if transient weather has no impact on life satisfaction.

Model 4, which is our preferred specification, also controls for time-invariant individual specific heterogeneity. The increase in the R-squared term from 0.14 to 0.62 with individual fixed effects supports previous literature showing that unobserved individual specific factors are among the most important predictors of life satisfaction and this suggests that the scope for omitted variable bias is significantly reduced in Model 4.

Total daily solar exposure, mean sea level air pressure and the direction of the wind have significant coefficients.[26] Specifically, higher solar exposure and lower air pressure, which is typically associated with clouds, rain and strong winds, increase life satisfaction. The positive and significant coefficient on the dummy for east-directed wind is less intuitive. It seems unlikely that this result will hold in all locations, and we speculate that this is a consequence of the significant population concentration on the east coast of Australia.[27] We interpret this result as suggesting that wind direction is a source of bias in life satisfaction measures, but that the strength and direction of the effect depends on local factors. Neither temperature nor precipitation coefficients are significant in Model 4, suggesting that our new variables, solar exposure and sea level pressure, are more important variables than those traditionally used to evaluate the impact of weather on life satisfaction. An F-statistic for the joint significance of the weather variables is reported in all tables in this chapter and for Models 1 to 4 the hypothesis that weather has no influence on self-reported life satisfaction is strongly rejected.

Considering the size of the effects in Model 4, if total daily solar exposure is one standard deviation (6.43 MJ/m^2) above average, we estimate that life satisfaction is 0.012 points higher. A one standard deviation decrease in mean sea level pressure (7.08 hPa) increases life satisfaction in our model by 0.016 and a one standard deviation decrease in wind speed (1.91 m/s) increases life satisfaction by 0.014.

How large are these effects? It is informative to compare these effects to non-weather coefficients in Model 4. These are presented in Model 6 from Table 2.2. Weather coefficients are small relative to becoming unemployed from employed (-0.203), acquiring a severely disability (-0.460) or separating from a partner (-0.398). However, common day–to-day changes in weather influence

[26] A minor caveat on the 'multiple comparisons problem' in statistics is in order. With seven weather variables of interest the probability that any one of the coefficients will be statistically significantly different from zero is higher than 5%. However, given our highly significant and robust results, we think this is unlikely to be a material problem. F-tests rejecting the joint insignificance of weather variables provide additional evidence that weather affects life satisfaction.

[27] Estimating model three with a sub-sample comprising only those observations for the two States with the greatest population living on the east coast (Queensland and New South Wales) yields a significant coefficient on east-directed wind, which does not arise when model three is estimated using responses from all other States.

life satisfaction by similar orders of magnitude to acquiring a mild disability (-0.0553) and leaving the labour force having been employed (-0.0362). To a first-order approximation, a ten percent increase in household nominal equivalized income is associated with an increase in life satisfaction of 0.0024, meaning that day-to-day weather variation has an effect of roughly similar magnitude to doubling income.

Three other coefficients are of note as potential sources of bias. Life satisfaction declines throughout the day, a ten hour difference in interview time resulting in a roughly 0.05 unit decrease in life satisfaction. The coefficient on the variable indicating whether another person was present during the interview increases life satisfaction by approximately 0.04 units. Finally, as in Csikszentmihalyi & Hunter (2003) and Kahneman & Deaton (2010), we initially find evidence (in Models 1, 2 and 3), that interviews on the weekend influence life satisfaction; however, the effect disappears with individual fixed effects.

The existence of significant coefficients is likely to be of theoretical interest; however, the practical importance of the bias deserves mention. In Table 2.2, we present three models: Model 5 contains only weather variables; Model 6 is identical to Model 4 in Table 2.1 and is presented with coefficients on the full set of controls; and Model 7 omits all weather variables. Most importantly, the inclusion of weather controls does not appear to alter the non-weather coefficients much. The 'widowed' coefficient is no longer significant once weather variables are included in the regression; however this is unusual and coefficients mostly change by less than ten percent. This suggests that controlling for weather does not appear to influence statistical inference on these recognized determinants of life satisfaction much.

Comparing Models 5 and 6, the significant coefficients are somewhat different (especially the coefficient on relative humidity), highlighting the importance of controlling for individual-specific influences on life satisfaction when estimating the effect of weather on life satisfaction.

While weather does not appear to be a concern in this study, given the rapidly expanding uses to which life satisfaction data are being put, it is relatively easy to consider situations in which weather bias will matter. For example, as Levinson (2012) notes, wind speed and air quality are correlated and any study attempting to estimate the effect of air pollution on life satisfaction must account for wind or risk capturing the weather effects in their estimation.[28] Alternatively, studies which consider the effect of once-off events on life satisfaction (Kavetsos and Szymanski

[28] This has typically not been the case in past studies of pollution effects.

2010; Metcalfe, Powdthavee, and Dolan 2011) should take measures to ensure that weather at that particular time and location is not driving results.

2.3.1.2 Sensitivity analysis and robustness checks

We next turn to the question of whether heterogeneous weather effects arise across genders, seasons, locations and lags of weather variables. Such effects have been identified by both Connolly (forthcoming) and Lucas & Lawless (2012). Connolly (forthcoming) finds that females are typically more responsive to weather variables, while Lucas & Lawless (2012) find a small heterogeneous effect depending on the season. The first two columns in Table 2.3 display results when Model 4 is estimated for male and female respondents separately. For males, the two key variables are total daily global solar exposure and mean sea level air pressure. Wind speed is not significant, either at the time of the interview or the daily average, and neither are relative humidity, temperature and the direction of the wind.

The results for females are all in the same direction as for males, but the significant variables are different. Female response to solar exposure and sea level air pressure are respectively roughly one-third and 70 percent that of males and neither is found to be significantly different from zero. Female life satisfaction is more responsive to wind speed than that of males and wind direction appears to play a similarly significant role across genders.

The coefficients on climate and season interactions – which are generated by multiplying the weather variables by their annual and monthly (during the month of the response) averages – are estimated in Models 10-12 of Table 2.4, and are less pronounced than expected.[29] Our prior had been that many weather variables would have opposite effects in warm and cold climates or months. We find that coefficients on those variables that are significant for the whole sample do not change sign across the seasons. In one respect these results are not surprising: while weather can be either too hot or too cold, those variables that we find to be significant – solar exposure and mean sea level pressure – do not have an obvious bliss point.

Table 2.5 presents results from the inclusion of non-linear effects both through inclusion of squared weather terms and additional dummy variables indicating if weather is 'extreme' (below the 5th percentile and above 95th percentile for all observations). In both cases we find no evidence of non-linear effects.

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[29] To remove zeros, coefficient estimates are multiplied by 100 in this table.

Finally, in Table 2.6, we consider the effect of lagged weather variables, both three hours and six hours before the survey commences. In Model 15, which does not interact three and six hour lagged weather variables with those at the time of the interview, none of the weather variables are significant. Once we allow for these interactions in Model 15 we find significant coefficients on six-hour lagged wind speed and its interaction with the wind speed at the time of interview. The change in wind speed matters, with high wind speed six hours prior to the interview and low wind speed at the time of interview increasing life satisfaction.

2.3.1.3 Interpretation

Our results are different to, yet not inconsistent with, the results of Barrington-Leigh (2008), Connolly (forthcoming), Levinson (2012) and Lucas & Lawless (2012). We believe this is mainly a consequence of four novel aspect of our study. First, we use panel data and Table 2.1 shows that the absence of individual fixed effects yields a significant temperature effect similar to Connolly (forthcoming). Second, by including more variables we are able to detect new relationships. For example, we detect a highly significant coefficient on air pressure, a variable past studies have not considered. These additional variables may also explain why we find no significant effects of precipitation, which may have been a proxy for air pressure in past studies. Finally, we believe that the temporal and spatial accuracy of our data removes downward bias in the coefficients on weather variables. This may explain why we find significant weather effects where Lucas and Lawless (2012) find none.

Coefficients on solar exposure and wind speed in Model 4 are consistent with most common theoretical priors. There is a well documented link between sunlight and levels of the mood regulating neurotransmitter serotonin. Sunniness and cloudiness were also the original weather variables hypothesized by Schwarz and Clore (1983) to influence life satisfaction. Less obvious is why sunshine matters for males and not females. Without speculating why, we note that gender differences in life satisfaction influences are extremely common. Wind speed, especially gusty conditions, may be unsettling to respondents and the fact that wind is more important for female life satisfaction appeals to gender stereotypes. Females may be more likely to dress or groom in a way that is more adversely affected by wind.

The strongly significant coefficient on air pressure is more difficult to reconcile with intuition. Low air pressure is associated with inclement weather and Table 2.11 indicates its strongest correlations are with wind speed and temperature. Internet search yields enormous anecdotal and quasiacademic literatures on the relationship between air pressure and pain without robust unifying conclusions.[30] The notion that changes in air pressure cause pain is among the most common and we have considered changes in pressure three and six hours prior to interview in Table 2.6 and found no significant effects. We refrain from speculating further on the causes, noting that it is amongst the most robust weather influences we find and that its mechanism deserves further empirical attention.

Finally, we put forward three potential explanations for the hour of day effect. First, those interviewed later in the day may be working longer hours (surveys are almost never conducted at the workplace) and we do not control for this in our specification. Second, those answering the question later in the day may exhibit 'grumpiness' at having to fill out a survey in the evening. Third, responses later in the day may reflect tiredness, which may be associated with a decrease in perceived life satisfaction.

2.3.2 Cognitive complexity and weather bias

2.3.2.1 Domain-specific satisfaction

Strack, Argyle & Schwarz (1991) are among the first to suggest that the complexity of the task of evaluating one's life satisfaction may lead respondents to use heuristics, such as one's mood at the time, when reporting life satisfaction. This can introduce effects of transient variables such as weather. They note (at p. 39) that:

> Evaluations of general life satisfaction pose an extremely complex task that requires a large number of comparisons along many dimensions with ill-defined criteria and the subsequent integration of the results of these comparisons into one composite judgment ... evaluations of specific domains, on the other hand, are often less complex. In contrast to judgments of general life satisfaction, comparison information is usually available for judgments of specific life domains and criteria for evaluation are well-defined.

For example, Schwarz et al. (1987) demonstrate an effect of the German national football team's performance on life satisfaction but not satisfaction with work or income. In this section we test

[30] One of the more reputable sources is the Swiss Department of Meteorology and Climatology, which finds no clear evidence on how pressure affects people (http://www.meteosuisse.admin.ch).

whether our weather variables influence a series of domain-specific measures of subjective well-being. First, we make explicit the assumption required to conduct this test:

Assumption 2.1 *Domain-specific satisfaction is cognitively less complex to report than domain-free satisfaction.*

Table 2.7 presents the results of estimating Model 4 with measures of satisfaction with job, employment opportunities, personal financial situation, the home, local community, local neighborhood, safety, health and free time. Strikingly, in light of the significant influence of weather variables, both individually and jointly, on life satisfaction, we find that in all nine domain-specific models the weather variables are never jointly significant, even at the ten percent level. Of the 90 weather coefficients estimated, three are significant at the 5 percent level and eight are significant at the ten percent level. This is slightly less significance than one would expect randomly, further suggesting that weather has no impact on these domain-specific measures. The three instances of weather variables significant at the 5 percent confidence level occur for three different weather variables. Temperature is significant at the 5 percent level in Model 19, which considers satisfaction with one's financial situation, while solar exposure is significant in Model 20 and wind speed at the time of the survey is significant in Model 25. On the whole, Table 2.7 presents strong evidence that weather has practically no effect on responses to domain-specific SWB measures like these.

2.3.2.2 Panel-conditioning and weather bias

Differences in weather bias in the HILDA survey's domain-free and domain-specific variables may arise for reasons other than differences in cognitive complexity.[31] As a robustness check, our second approach uses variation in the complexity of the same life satisfaction question arising from experience.[32] Stating life satisfaction for the first time requires the respondent to translate their internal scale into the scale offered in the interview and this challenge can cause the level and accuracy of responses to a given life satisfaction question to change with experience. Toepoel, Das, and van Soest (2009), Das, Toepoel, and van Soest (2011) and Van Landeghem (2012) find evidence of experience effects in European panel studies, including declining life satisfaction.

[31] One likely alternative candidate is question order. For example, Schwarz and Clore (1983) find that priming to attribute mood to the weather removes this influence on life satisfaction.

[32] We are grarteful to Alois Stutzer for suggesting this approach.

Current work in progress by Wooden and Li finds that male life satisfaction and its dispersion decline with the number of times interviewed as part of the HILDA Survey. Using this source of exogenous variation in question complexity for males, we revisit our cognitive complexity hypothesis. Again, we explicitly state the assumption prior to conducting this test:

Assumption 2.2 *For men, the cognitive complexity of reporting the HILDA Survey measure of life satisfaction declines with experience.*

Table 2.8 presents coefficient estimates from our preferred model (Model 4) with the inclusion of interaction terms for each weather variable multiplied by the number of times the respondent has completed the HILDA survey. Model 26 considers the whole sample and Model 27 considers only males.

In the sample with only males we find evidence that weather bias declines with experience. As in Model 8, air pressure and solar exposure significantly influence male life satisfaction. This flexible specification identifies temperature bias in the early panel waves, which is not present in Model 4.

More interesting are the experience interaction terms. All ten weather variable coefficients – of which those on pressure and temperature are significant at the 5% level – have signs indicating that weather bias declines with panel experience. This is strong evidence of the cognitive complexity hypothesis. An important corollary, especially for those studying life satisfaction with panel data, is that weather bias declines with successive survey waves.

Support for the cognitive complexity hypothesis for the entire sample is less pronounced. This is expected as females do not exhibit the pronounced experience effect males do in the HILDA survey. We cannot conclude that any coefficients on the interaction terms are significantly different from zero at the five percent level, however, we see the same striking pattern with the signs on all interaction terms implying that weather bias declines with panel experience.

2.3.3 Climate effects

Studies such as Frijters & Van Praag (1998), Rehdanz & Maddison (2005), Brereton et al. (2008) and Maddison & Rehdanz (2011) find significant effects of climate on life satisfaction. These results should not, however, be interpreted as a direct effect of climate on peoples' feelings of well-being. First, it is difficult to know whether changes in climate directly enhance life satisfaction or whether more satisfied people live in certain climates. Second, a number of indirect mechanisms may be responsible. For example, Rehdanz and Maddison (2005, p. 111) hypothesize that climate's influence on life satisfaction may arise through effects on 'heating and cooling requirements, health, clothing and nutritional needs and recreational activities'.

In this section we use our panel data to show that climate does not appear to provide amenity value (as measured by life satisfaction). Table 2.9 presents four models, all of which include climate variables. Fixed effects in each model are described at the bottom of the table. Note that in order to identify climate effects we use state rather than post code fixed effects.[33] Also, when individual fixed effects are included in the specification, any climate effect is identified through by individuals moving location (and therefore climate) during the nine waves.

Pair-wise comparison of Models 28 and 29 or Models 30 and 31 shows that the inclusion of state dummies does not make much difference to estimated climate coefficients. However, the inclusion of individual fixed effects when estimating coefficients on the climate variables matters a great deal. In the absence of individual fixed effects we find significant effects on both wind speed and average daily solar exposure. For example, in model 29, a one standard deviation (2.02 MJ/m^2) increase in the annual average of average daily solar exposure yields a 0.038 unit increase in life satisfaction. F-statistics for the climate variables indicate strong joint significance.

However, we find no climate effects – either individually or jointly – when we use only the variation within individuals to identify them. This result, together with the other cross-sectional studies finding climate effects, suggests that rather than climate providing amenity value and actually making people more satisfied, certain climates attract, or are already home to, more satisfied people. For example, higher life satisfaction on the Mediterranean Sea or the U.S.-Mexican border may arise because of the types of people in these places rather than the climate.

2.4 Conclusion

This chapter introduced panel data and highly detailed weather observations to the literature evaluating weather's effect on subjective well-being. We detect significant positive effects of global daily solar exposure and significant negative effects of daily mean wind speed and sea level air pressure at the time of the interview on life satisfaction.

[33] Within post codes there is not sufficient climate variation to identify its effects. Within states, two of which span roughly 20 degrees of latitude, there is considerable climate variability.

We investigated a leading hypothesis on the cause of this weather effect, namely that the cognitive demands of assessing overall life satisfaction lead respondents to apply heuristics that are based on contemporaneous transient factors. Supporting this hypothesis, we find no influence of weather variables on cognitively simpler domain-specific measures of SWB and we find that weather bias declines as individuals become more experienced with the life satisfaction question.

We have also provided evidence – complementary to Graham (2009) and Deaton (2012) – that individual life satisfaction is more resilient to longer-term changes. Panel data enables us to substantially narrow the potential causes of the documented relationship between climate and life satisfaction. Our results suggest that the impact of climate on life satisfaction is close to zero. Instead, we hypothesize that there is geographic clustering of individuals with higher life satisfaction in locations with higher wind speed and higher solar exposure. This finding suggests that the direct impact of anthropogenic climate change on life satisfaction is likely to be very small.

Our finding that individual fixed effects matter for estimating weather and climate effects suggests two interesting avenues for future research. First, although Australia is in many ways the ideal country for estimating weather effects, the extent to which our results are generalizable is an open question. In particular, no paper in the literature on weather and life satisfaction considers life satisfaction in developing countries, where respondents may be more exposed to the weather conditions and agriculture plays a larger economic role. Second, this and past studies have tended to focus on one common single-item measure of life satisfaction. We hypothesize that weather influences less cognitively demanding measures of life satisfaction less. However, this hypothesis is yet to be tested.

There are a number of practical implications of our research. First, in many important contexts, such as evaluating the effect of air pollution on life satisfaction, it is important to control for the weather. Not doing so omits an important factor that is correlated with the variable of interest. Second, steps should be taken in the design of SWB surveys to minimize weather bias. This could be achieved, by spacing surveys out over time within a given location. Third, because the severity of weather bias declines in longer panels, recently commissioned cross-sectional life satisfaction surveys such as the Gallup World Poll and the UK Office for National Statistics Integrated Household Survey may benefit substantially from supplementary panel surveys, capable of addressing weather bias.

2.A Tables

[TABLES BEGIN OVERLEAF]

Dependent variable: Life satisfaction	Model 1 Coefficient	t-statistic	Model 2 Coefficient	t-statistic	Model 3 Coefficient	t-statistic	Model 4 Coefficient	t-statistic
Weather - day of interview								
Solar exposure	0.00359***	(3.46)	0.00398***	(3.88)	0.00112	(1.14)	0.00191**	(2.11)
Precipitation	-0.0000168	(-0.02)	-0.0000950	(-0.10)	0.000247	(0.26)	0.000179	(0.21)
Wind speed (daily mean)	0.000808	(0.18)	0.00182	(0.41)	-0.0123***	(-3.05)	-0.00710*	(-1.90)
Weather - time of interview								
Mean sea level pressure	-0.00326***	(-3.77)	-0.00287***	(-3.40)	-0.00295***	(-3.62)	-0.00223***	(-2.97)
Temperature	-0.00310*	(-1.92)	-0.00357**	(-2.13)	-0.00242	(-1.57)	-0.00141	(-0.99)
Relative humidity	0.000938**	(2.53)	0.000922**	0.00000197	(0.01)	(2.46)	-0.000242	(-0.77)
Wind speed	0.00441	(1.46)	0.00455	(1.51)	0.00567*	(1.94)	0.00339	(1.29)
Wind direction (north)	0.0405***	(2.65)	0.0339**	(2.24)	0.0198	(1.37)	0.0190	(1.41)
Wind direction (east)	0.0355**	(2.50)	0.0271*	(1.93)	0.0224	(1.64)	0.0348***	(2.76)
Wind direction (west)	0.0114	(0.83)	0.0137	(1.00)	0.0123	(0.94)	0.00815	(0.67)
Other variables of interest								
Hour	-0.00936***	(-4.92)	-0.00917***	(-4.82)	-0.00501***	(-2.73)	-0.00496***	(-3.09)
Weekend	-0.0482***	(-3.73)	-0.0471***	(-3.64)	-0.0514***	(-4.08)	-0.00282	(-0.25)
Other present	0.0877***	(6.70)	0.0880***	(6.71)	0.0788***	(6.19)	0.0396***	(3.66)
Month fixed effects	Y		Y		Y		Y	
Wave fixed effects	Y		Y		Y		Y	
State fixed effects	N		Y		N		N	
Postcode fixed effects	N		N		Y		Y	
Individual fixed effects	N		N		N		Y	
R-squared	0.0941		0.0944		0.143		0.622	
F-stat (weather)	4.47		4.39		2.51		2.53	
F-stat p-value	0.0000		0.0000		0.0052		0.0048	
N	96472		96472		96472		96472	

Notes: Individual clustered standard errors of mean in parentheses. *0.1 level, **0.05 level, ***0.01 level. Dependent variable is life satisfaction from waves 1-9 of the HILDA Survey. In addition to those regressors listed in the left hand column, all models include controls for age and its square, number of household dependents aged between 0 and 24, the natural log of nominal household disposable income for the previous financial year in Australian dollars. Dummy variables are also included for disability status, employment status, marital status and education. See Tables 2.12 and 2.13 for detailed variable descriptions.

TABLE 2.1: Baseline estimates of weather's impact of life satisfaction

Dependent variable: Life satisfaction	Model 5 Coefficient	Model 6 Coefficient	Model 7 Coefficient
Weather - day of interview			
Solar exposure	0.00175*	0.00191**	
Precipitation	0.000382	0.000179	
Wind speed (daily mean)	-0.00813**	-0.00710*	
Weather - time of interview			
Mean sea level pressure	-0.00215***	-0.00223***	
Temperature	-0.00206	-0.00141	
Relative humidity	-0.000570**	-0.000242	
Wind speed	0.00346	0.00339	
Wind direction (north)	0.0203	0.0190	
Wind direction (east)	0.0346***	0.0348***	
Wind direction (west)	0.0107	0.00815	
Other variables of interest			
Hour		-0.00496***	-0.00452***
Weekend		-0.00282	0.000747
Other present		0.0396***	0.0391***
Controls			
Age		-0.0372***	-0.0366***
Age squared		0.000182***	0.000166***
Household dependents		-0.0381***	-0.0352***
ln(household income)		0.0240***	0.0275***
Disability (mild)		-0.0553***	-0.0537***
Disability (moderate)		-0.238***	-0.243***
Disability (severe)		-0.460***	-0.519***
Unemployed		-0.203***	-0.207***
Not in labour force		-0.0362*	-0.0310
Married		0.277***	0.267***
Defacto		0.297***	0.289***
Seperated		-0.398***	-0.424***
Divorced		-0.146**	-0.158***
Widowed		-0.126	-0.161**
Post graduate		-0.160	-0.132
Graduate diploma/certificate		-0.0828	-0.0879
Bachelor		-0.232***	-0.223***
Diploma		-0.211***	-0.217***
Certificate 3/4		-0.117**	-0.137***
Certificate 1/2		0.0723	0.0625
Certificate (unknown)		0.228	0.138
Year 12		-0.186***	-0.200***
Month fixed effects	Y	Y	Y
Wave fixed effects	Y	Y	Y
State fixed effects	N	N	N
Postcode fixed effects	Y	Y	Y
Individual fixed effects	Y	Y	Y
R-squared	0.617	0.622	0.614
F-stat (weather)	2.75	2.53	
F-stat p-value	0.0022	0.0048	
N	96493	96472	115989

Notes: Individual clustered standard errors of mean in parentheses. *0.1 level, **0.05 level, ***0.01 level. See Tables 2.12 and 2.13 for detailed variable descriptions.

TABLE 2.2: Omission of weather variables

Dependent variable: Life satisfaction	Model 8 - Male Coefficient	t-statistic	Model 9 - Female Coefficient	t-statistic
Weather - day of interview				
Solar exposure	0.00292**	(2.27)	0.00102	(0.79)
Precipitation	-0.000258	(-0.21)	0.000643	(0.56)
Wind speed (daily mean)	0.0000226	(0.00)	-0.0134***	(-2.58)
Weather - time of interview				
Mean sea level pressure	-0.00266**	(-2.44)	-0.00176*	(-1.68)
Temperature	-0.00120	(-0.61)	-0.00121	(-0.59)
Relative humidity	-0.000501	(-1.09)	0.0000146	(0.03)
Wind speed	0.00227	(0.59)	0.00447	(1.21)
Wind direction (north)	0.0168	(0.87)	0.0229	(1.23)
Wind direction (east)	0.0380**	(2.06)	0.0348**	(1.99)
Wind direction (west)	-0.00473	(-0.26)	0.0189	(1.14)
Other variables of interest				
Hour	-0.00546**	(-2.35)	-0.00474**	(-2.11)
Weekend	-0.00568	(-0.34)	-0.00429	(-0.27)
Other present	0.0380**	(2.50)	0.0450***	(2.89)
Month fixed effects	Y		Y	
Wave fixed effects	Y		Y	
Postcode fixed effects	Y		Y	
Individual fixed effects	Y		Y	
R-squared	0.646		0.616	
F-stat (weather)	2.11		1.4	
F-stat p-value	0.0203		0.1737	
N	45598		50874	

Notes: Individual clustered standard errors of mean in parentheses. *0.1 level, **0.05 level, ***0.01 level. In addition to those regressors listed in the left hand column, all models include controls for age and its square, number of household dependents aged between 0 and 24, the natural log of nominal household disposable income for the previous financial year in Australian dollars. Dummy variables are also included for disability status, employment status, marital status and education. See Tables 2.12 and 2.13 for detailed variable descriptions.

TABLE 2.3: Gender

Dependent variable: Life satisfaction	Model 10 Coefficient	t-stat.	Model 11 Coefficient	t-stat.	Model 12 Coefficient	t-stat.
Weather - day of interview						
Solar exposure	0.36	(0.81)	-0.104	(-0.15)	-0.0287	(-0.04)
Precipitation	-0.137	(-0.97)	0.214	(0.95)	0.137	(0.59)
Mean daily wind speed	0.255	(0.23)	0.0485	(0.05)	0.262	(0.24)
Weather - time of interview						
Mean sea level pressure	-0.231***	(-3.06)	-0.217***	(-2.89)	-0.223***	(-2.94)
Temperature	0.551	(0.92)	1.06	(1.18)	1.03	(1.11)
Relative humidity	-0.0228	(-0.71)	-0.0224	(-0.70)	-0.0222	(-0.70)
Wind speed	0.33	(1.25)	0.343	(1.30)	0.321	(1.21)
Wind direction (north)	1.79	(1.33)	1.94	(1.44)	1.79	(1.33)
Wind direction (east)	3.43***	(2.71)	3.53***	(2.80)	3.42***	(2.70)
Wind direction (west)	0.803	(0.66)	0.885	(0.73)	0.801	(0.66)
Weather - month interactions						
CD monthly average daily solar exposure	-0.0311	(-0.03)			0.187	(0.17)
CD monthly average daily wind speed	-0.0989	(-0.03)			2.3	(0.47)
CD monthly average daily max temperature	0.0685	(0.06)			-0.0493	(-0.04)
CD average monthly precipitation	0.00167	(0.04)			0.00644	(0.16)
Solar exposure day*month interaction	-0.00777	(-0.36)			-0.0145	(-0.63)
Wind speed day*month interaction	-0.218	(-0.88)			-0.559	(-0.62)
Max temperature day*month interaction	-0.0314	(-1.17)			-0.0194	(-0.47)
Precipitation day*month interaction	0.00196	(1.35)			0.00281*	(1.75)
Weather - year interactions						
CD annual average daily solar exposure			-3.27	(-1.05)	-3.49	(-1.12)
CD annual average daily wind speed			-2.86	(-0.46)	-5.12	(-0.65)
CD annual average daily max temperature			-4.34	(-0.68)	-4.32	(-0.66)
CD annual average monthly precipitation			-0.0298	(-0.99)	-0.0305	(-1.01)
Solar exposure day*year interaction			0.0159	(0.44)	0.0281	(0.73)
Wind speed day*year interaction			-0.195	(-0.76)	0.366	(0.39)
Max temperature day*year interaction			-0.0523	(-1.34)	-0.0316	(-0.51)
Precipitation day*year interaction			-0.0002	(-0.90)	-0.000354	(-1.53)
Other variables of interest						
Hour	-0.498***	(-3.09)	-0.503***	(-3.13)	-0.501***	(-3.11)
Weekend	-0.277	(-0.24)	-0.276	(-0.24)	-0.282	(-0.25)
Other present	3.94***	(3.64)	3.96***	(3.66)	3.95***	(3.65)
Month fixed effects	Y		Y		Y	
Wave fixed effects	Y		Y		Y	
Postcode fixed effects	Y		Y		Y	
Individual fixed effects	Y		Y		Y	
R-squared	0.622		0.622		0.622	
F-stat (weather)	1.8		1.75		1.46	
F-stat p-value	0.0201		0.0254		0.0611	
N	96472		96472		96472	

Notes: Individual clustered standard errors of mean in parentheses. *0.1 level, **0.05 level, ***0.01 level. In addition to those regressors listed in the left hand column, all models include controls for age and its square, number of household dependents aged between 0 and 24, the natural log of nominal household disposable income for the previous financial year in Australian dollars. Dummy variables are also included for disability status, employment status, marital status and education. See Tables 2.12 and 2.13 for detailed variable descriptions.

TABLE 2.4: Weather-season and weather-climate interactions (coefficients × 100)

Dependent variable: Life satisfaction	Model 13 Coefficient	t-statistic	Model 14 Coefficient	t-statistic
Weather - day of interview				
Solar exposure	0.000338	(0.10)	0.00230**	(2.09)
Precipitation	0.000474	(0.34)	-0.000335	(-0.27)
Wind speed (daily mean)	0.00925	(0.87)	-0.00471	(-1.09)
Weather - time of interview				
Mean sea level pressure	0.0414	(0.35)	-0.00276***	(-2.89)
Temperature	0.000536	(0.11)	-0.00311*	(-1.91)
Relative humidity	-0.000240	(-0.19)	-0.000340	(-0.96)
Wind speed	0.00411	(0.60)	0.00317	(1.04)
Wind direction (north)	0.0203	(1.50)	0.0204	(1.50)
Wind direction (east)	0.0361***	(2.86)	0.0375***	(2.95)
Wind direction (west)	0.00893	(0.73)	0.00824	(0.68)
Weather - non-linearities				
Solar exposure squared	0.0000458	(0.48)		
Precipitation squared	-0.00000475	(-0.20)		
Wind speed (daily mean) squared	-0.00157	(-1.60)		
Mean sea level pressure squared	-0.0000215	(-0.37)		
Temperature squared	-0.0000539	(-0.44)		
Relative humidity squared	-5.68e-08	(-0.01)		
Wind speed squared	-0.0000654	(-0.12)		
Weather - extremes				
Solar exposure low			0.0176	(0.73)
Solar exposure high			0.0157	(0.59)
Precipitation low				
Precipitation high			0.0150	(0.52)
Wind speed (daily mean) low			-0.0230	(-0.87)
Wind speed (daily mean) high			-0.0399	(-1.57)
Mean sea level pressure low			-0.0362	(-1.48)
Mean sea level pressure high			0.00155	(0.07)
Temperature low			-0.0310	(-1.32)
Temperature high			0.0386	(1.45)
Relative humidity low			0.000329	(0.01)
Relative humidity high			0.0327	(1.52)
Wind speed low			0.00772	(0.35)
Wind speed high			0.0204	(0.80)
Other variables of interest				
Hour	-0.00492***	(-3.04)	-0.00513***	(-3.18)
Weekend	-0.00249	(-0.22)	-0.00215	(-0.19)
Other present	0.0397***	(3.66)	0.0395***	(3.65)
Month fixed effects	Y		Y	
Wave fixed effects	Y		Y	
Postcode fixed effects	Y		Y	
Individual fixed effects	Y		Y	
R-squared	0.622		0.622	
F-stat (weather)	1.74		1.69	
F-stat p-value	0.0293		0.0210	
N	96472		96472	

Notes: Individual clustered standard errors of mean in parentheses. *0.1 level, **0.05 level, ***0.01 level. In addition to those regressors listed in the left hand column, all models include controls for age and its square, number of household dependents aged between 0 and 24, the natural log of nominal household disposable income for the previous financial year in Australian dollars. Dummy variables are also included for disability status, employment status, marital status and education. See Tables 2.12 and 2.13 for detailed variable descriptions.

TABLE 2.5: Non-linearities

Dependent variable: Life satisfaction	Model 15 Coefficient	t-statistic	Model 16 Coefficient	t-statistic
Weather - day of interview				
Solar exposure	0.00198**	(2.06)	0.00160	(1.60)
Precipitation	0.000114	(0.13)	0.000366	(0.42)
Wind speed (daily mean)	-0.00883*	(-1.73)	-0.00987*	(-1.93)
Weather - time of interview				
Mean sea level pressure	-0.00405	(-1.00)	0.0205	(0.35)
Temperature	-0.000708	(-0.20)	0.000992	(0.23)
Relative humidity	-0.000271	(-0.68)	0.000616	(0.80)
Wind speed	0.00393	(1.36)	0.00851*	(1.95)
Wind direction (north)	0.0177	(1.29)	0.0164	(1.19)
Wind direction (east)	0.0354***	(2.76)	0.0348***	(2.70)
Wind direction (west)	0.00761	(0.62)	0.00794	(0.65)
Mean sea level pressure$_{t-3}$	0.00342	(0.55)	0.0270	(0.46)
Temperature$_{t-3}$	-0.00117	(-0.31)	-0.00334	(-0.53)
Relative humidity$_{t-3}$	-0.0000172	(-0.03)	0.000538	(0.40)
Wind speed$_{t-3}$	-0.00121	(-0.39)	-0.00637	(-1.13)
Mean sea level pressure$_{t-6}$	-0.00174	(-0.48)	-0.000803	(-0.21)
Temperature$_{t-6}$	0.000634	(0.31)	0.00351	(0.58)
Relative humidity$_{t-6}$	0.0000997	(0.15)	0.000645	(0.50)
Wind speed$_{t-6}$	0.00230	(0.74)	0.0149**	(2.44)
MSLP*MSLP$_{t-3}$			-0.0000241	(-0.42)
Temp*Temp$_{t-3}$			0.0000948	(0.36)
RH*RH$_{t-3}$			-0.00000794	(-0.47)
Wind speed*wind speed$_{t-3}$			0.00103	(1.30)
MSLP*MSLP$_{t-6}$				
Temp*Temp$_{t-6}$			-0.000161	(-0.57)
RH*RH$_{t-6}$			-0.00000946	(-0.55)
Wind speed*wind speed$_{t-6}$			-0.00206**	(-2.37)
Other variables of interest				
Other present	0.0395***	(3.64)	0.0396***	(3.65)
Hour	-0.00446**	(-2.01)	-0.00455**	(-1.98)
Weekend	-0.00383	(-0.33)	-0.00350	(-0.30)
Month fixed effects	Y		Y	
Wave fixed effects	Y		Y	
Postcode fixed effects	Y		Y	
Individual fixed effects	Y		Y	
R-squared	0.622		0.622	
F-stat (weather)	1.64		1.34	
F-stat p value	0.0565		0.1231	
N	95894		95894	

Notes: Individual clustered standard errors of mean in parentheses. *0.1 level, **0.05 level, ***0.01 level. In addition to those regressors listed in the left hand column, all models include controls for age and its square, number of household dependents aged between 0 and 24, the natural log of nominal household disposable income for the previous financial year in Australian dollars. Dummy variables are also included for disability status, employment status, marital status and education. See Tables 2.12 and 2.13 for detailed variable descriptions.

TABLE 2.6: Lagged weather variables

Model Satisfaction with:	17 Job overall	18 Employ. opportunities	19 Financial situation	20 The home in which you live	21 Local community	22 Neigh'hood in which you live	23 Safety	24 Your health	25 Amount of free time
Weather - day of interview									
Solar exposure	0.00246	0.00212	0.000877	0.00265**	0.0000667	-0.000150	0.00157	0.000923	-0.00259
Precipitation	-0.000810	-0.000835	0.000279	-0.00113	-0.000781	-0.00193*	0.000290	0.000701	0.00154
Wind speed (daily mean)	-0.000178	-0.00106	0.00672	0.000670	-0.000554	-0.00806*	0.00538	0.00273	-0.00257
Weather - time of interview									
Mean sea level pressure	-0.000887	-0.00268*	-0.000825	-0.00158	-0.000166	-0.000195	0.000739	-0.000943	0.000686
Temperature	0.000247	-0.00241	-0.00429**	-0.00336*	0.00402*	0.00101	0.000138	0.00248	0.00205
Relative humidity	0.000461	0.000374	-0.000494	-0.000578	0.000554	0.0000262	0.000409	0.000399	-0.000673
Wind speed	-0.00293	-0.000941	-0.00416	0.00106	0.00113	0.00543	-0.00348	0.000495	0.00958**
Wind direction (north)	0.0100	-0.000273	0.00111	-0.0153	-0.0132	0.00135	0.0178	-0.00866	0.00978
Wind direction (east)	-0.00274	0.000128	0.0216	-0.0121	-0.00885	0.0253	0.0214	-0.00339	0.0268
Wind direction (west)	0.00464	0.00490	-0.0101	-0.00135	0.000984	0.00527	0.0221	-0.0192	0.0164
Other variables of interest									
Hour	-0.00268	0.00118	0.000150	0.00107	-0.00769***	-0.00603***	-0.00703***	-0.00133	-0.0208***
Weekend	0.00386	0.0218	0.0136	0.00103	0.0132	-0.0143	0.00248	0.0226*	-0.134***
Other present	-0.0658***	-0.0625***	-0.0422***	-0.00221	-0.0368**	-0.0365***	0.0332***	-0.0317**	0.0237
Month fixed effects	Y	Y	Y	Y	Y	Y	Y	Y	Y
Wave fixed effects	Y	Y	Y	Y	Y	Y	Y	Y	Y
Postcode fixed effects	Y	Y	Y	Y	Y	Y	Y	Y	Y
Individual fixed effects	Y	Y	Y	Y	Y	Y	Y	Y	Y
R-squared	0.531	0.653	0.651	0.564	0.607	0.585	0.583	0.702	0.598
F-stat (weather)	0.48	0.56	1.05	1.48	0.59	1.26	0.8	0.85	1.36
F-stat p-value	0.9067	0.8477	0.4013	0.1392	0.8234	0.2492	0.6333	0.5806	0.1906
N	61483	75687	96470	96461	96441	96461	96479	96497	96455

Notes: Individual clustered standard errors of mean in parentheses. *0.1 level, **0.05 level, ***0.01 level. In addition to those regressors listed in the left hand column, all models include controls for age and its square, number of household dependents aged between 0 and 24, the natural log of nominal household disposable income for the previous financial year in Australian dollars. Dummy variables are also included for disability status, employment status, marital status and education. See Tables 2.12 and 2.13 for detailed variable descriptions.

TABLE 2.7: Weather's impact on domain-specific measures of wellbeing

Dependent variable: Life satisfaction	Model 26 Coefficient	t-statistic	Model 27 Coefficient	t-statistic
Weather - day of interview				
Solar exposure	0.00312*	(1.74)	0.00534**	(2.11)
Precipitation	0.0000929	(0.05)	-0.00117	(-0.43)
Wind speed (daily mean)	-0.00957	(-1.22)	-0.0137	(-1.20)
Weather - time of interview				
Mean sea level pressure	-0.00392**	(-2.43)	-0.00762***	(-3.25)
Temperature	-0.00519**	(-1.99)	-0.00799**	(-2.16)
Relative humidity	-0.000942	(-1.60)	-0.000986	(-1.17)
Wind speed	0.00656	(1.17)	0.0120	(1.47)
Wind direction (north)	0.0149	(0.52)	-0.00392	(-0.09)
Wind direction (east)	0.0481*	(1.76)	0.0523	(1.33)
Wind direction (west)	0.0170	(0.64)	-0.0371	(-0.96)
Experience*solar exposure	-0.000289	(-0.81)	-0.000566	(-1.09)
Experience*precipitation	-0.00000551	(-0.02)	0.000182	(0.35)
Experience*wind speed (daily mean)	0.000540	(0.38)	0.00292	(1.46)
Experience*mean sea level pressure	0.000355	(1.23)	0.00105**	(2.50)
Experience*temperature	0.000802*	(1.79)	0.00145**	(2.25)
Experience*relative humidity	0.000145	(1.40)	0.0000977	(0.66)
Experience*wind speed	-0.000698	(-0.69)	-0.00211	(-1.45)
Experience*wind direction (north)	0.00101	(0.19)	0.00474	(0.62)
Experience*wind direction (east)	-0.00279	(-0.56)	-0.00306	(-0.42)
Experience*wind direction (west)	-0.00198	(-0.40)	0.00699	(0.99)
Other variables of interest				
Other present	0.0398***	(3.68)	0.0375**	(2.47)
Hour	-0.00494***	(-3.07)	-0.00542**	(-2.33)
Weekend	-0.00321	(-0.28)	-0.00662	(-0.40)
Month fixed effects	Y		Y	
Wave fixed effects	Y		Y	
Postcode fixed effects	Y		Y	
Individual fixed effects	Y		Y	
R-squared	0.622		0.646	
F-stat (weather)	4.59		1.62	
F-stat p value	0.0463		0.0402	
N	96472		45598	

Notes: Individual clustered standard errors of mean in parentheses. *0.1 level, **0.05 level, ***0.01 level. In addition to those regressors listed in the left hand column, all models include controls for age and its square, number of household dependents aged between 0 and 24, the natural log of nominal household disposable income for the previous financial year in Australian dollars. Dummy variables are also included for disability status, employment status, marital status and education. See Tables 2.12 and 2.13 for detailed variable descriptions.

TABLE 2.8: Panel experience and weather bias

Dependent variable: Life satisfaction	Model 28 Coefficient	t-statistic	Model 29 Coefficient	t-statistic	Model 30 Coefficient	t-statistic	Model 31 Coefficient	t-statistic
Weather - day of interview								
Solar exposure	0.00249**	(2.42)	0.00310***	(3.04)	0.00213**	(2.37)	0.00207**	(2.30)
Precipitation	0.000440	(0.46)	0.000487	(0.50)	0.000337	(0.40)	0.000311	(0.37)
Wind speed (daily mean)	-0.0103**	(-2.46)	-0.0107**	(-2.56)	-0.00620*	(-1.66)	-0.00626*	(-1.68)
Weather - time of interview								
Mean sea level pressure	-0.00348***	(-4.06)	-0.00342***	(-4.08)	-0.00184**	(-2.47)	-0.00188**	(-2.52)
Temperature	-0.00258	(-1.59)	-0.00352**	(-2.20)	-0.000748	(-0.53)	-0.000775	(-0.55)
Relative humidity	0.000340	(0.92)	0.000527	(1.44)	-0.000186	(-0.59)	-0.000192	(-0.61)
Wind speed	0.00386	(1.29)	0.00434	(1.45)	0.00276	(1.06)	0.00264	(1.01)
Wind direction (north)	0.0424***	(2.77)	0.0349**	(2.31)	0.0207	(1.55)	0.0200	(1.50)
Wind direction (east)	0.0360**	(2.54)	0.0259*	(1.85)	0.0365***	(2.92)	0.0354***	(2.84)
Wind direction (west)	0.0167	(1.22)	0.0189	(1.38)	0.0115	(0.95)	0.0121	(1.01)
Climate variables								
Annual ave. max tempertature	-0.00714*	(-1.72)	-0.00700	(-1.03)	-0.0107	(-1.46)	-0.00856	(-0.80)
Annual ave. wind speed	0.0335***	(3.17)	0.0420***	(3.75)	0.000122	(0.01)	0.00297	(0.16)
Annual ave. daily solar exposure	0.0138**	(2.57)	0.0186***	(3.13)	0.00658	(0.67)	0.00386	(0.38)
Annual rainfall	0.0000372	(1.21)	-0.0000220	(-0.59)	0.0000314	(0.51)	0.00000757	(0.11)
Other variables of interest								
Other present	0.0878***	(6.71)	0.0870***	(6.64)	0.0430***	(4.01)	0.0437***	(4.08)
Hour	-0.00730***	(-3.84)	-0.00774***	(-4.08)	-0.00478***	(-3.00)	-0.00476***	(-2.99)
Weekend	-0.0459***	(-3.54)	-0.0445***	(-3.43)	-0.00662	(-0.59)	-0.00663	(-0.59)
Month fixed effects	Y		Y		Y		Y	
Wave fixed effects	Y		Y		Y		Y	
State fixed effects	N		Y		N		Y	
Individual fixed effects	N		N		Y		Y	
R-squared	0.0949		0.0955		0.610		0.610	
F-stat (weather)	3.60		3.73		2.53		2.46	
F-stat (weather) p-value	0.0000		0.0000		0.0047		0.0061	
F-stat (climate)	6.97		9.19		0.68		0.25	
F-stat (climate) p-value	0.0000		0.0000		0.6089		0.9112	
N	96472		96472		96472		96472	

Notes: Individual clustered standard errors of mean in parentheses. *0.1 level, **0.05 level, ***0.01 level. Dependent variable is life satisfaction from waves 1-9 of the HILDA Survey. In addition to those regressors listed in the left hand column, all models include controls for age and its square, number of household dependents aged between 0 and 24, the natural log of nominal household disposable income for the previous financial year in Australian dollars. Dummy variables are also included for disability status, employment status, marital status and education. See Tables 2.12 and 2.13 for detailed variable descriptions.

TABLE 2.9: Climate and life satisfaction

Variable	Obs	Mean	Std.Dev	Min	Max	Source
Satisfaction - Life	116017	7.91	1.52	0	10	HILDA
Satisfaction - Job overall	73853	7.65	1.75	0	10	HILDA
Satisfaction - Employment opportunities	90941	7.00	2.43	0	10	HILDA
Satisfaction - Financial situation	116013	6.37	2.31	0	10	HILDA
Satisfaction - Home in which you live	116006	7.96	1.89	0	10	HILDA
Satisfaction - Feel part of local community	115981	6.74	2.23	0	10	HILDA
Satisfaction - Neighbourhood in which you live	116005	7.91	1.78	0	10	HILDA
Satisfaction - How safe you feel	116015	8.10	1.70	0	10	HILDA
Satisfaction - Your health	116048	7.34	1.99	0	10	HILDA
Satisfaction - Amount of free time	115991	6.66	2.57	0	10	HILDA
Age	116103	43.80	18.30	15	101	HILDA
Household dependents	116103	0.64	1.08	0	10	HILDA
Household equivalised income	116103	34528	25694	0	1132686	HILDA
Mild disability (dummy)	116103	0.08	0.27	0	1	HILDA
Moderate disability (dummy)	116103	0.17	0.37	0	1	HILDA
Severe disability (dummy)	116103	0.01	0.09	0	1	HILDA
Unemployed (dummy)	116103	0.04	0.18	0	1	HILDA
Not in labour force (dummy)	116103	0.33	0.47	0	1	HILDA
Married (dummy)	116072	0.50	0.50	0	1	HILDA
Defacto (dummy)	116072	0.12	0.33	0	1	HILDA
Seperated (dummy)	116072	0.03	0.17	0	1	HILDA
Divorced (dummy)	116072	0.06	0.24	0	1	HILDA
Widowed (dummy)	116072	0.05	0.22	0	1	HILDA
Postgrad (dummy)	116103	0.03	0.17	0	1	HILDA
Grad. Diploma/certificate (dummy)	116103	0.05	0.21	0	1	HILDA
Bachelor (dummy)	116103	0.12	0.32	0	1	HILDA
Diploma (dummy)	116103	0.08	0.28	0	1	HILDA
Certificate 3/4 (dummy)	116103	0.19	0.39	0	1	HILDA
Certificate 1/2 (dummy)	116103	0.01	0.12	0	1	HILDA
Certificate unknown (dummy)	116103	0.01	0.08	0	1	HILDA
Year 12 (dummy)	116103	0.15	0.36	0	1	HILDA
Other present (dummy)	116103	0.37	0.48	0	1	HILDA
Male (dummy)	116103	0.47	0.50	0	1	HILDA
Hour	116103	15.26	3.61	3	24	HILDA
Weekend (dummy)	116103	0.26	0.44	0	1	HILDA
Solar exposure	112488	19.29	6.43	0.22	35.29	BOM
Precipitation	115434	1.75	5.40	0	175.75	BOM
Wind speed (daily mean)	115405	3.94	1.91	0	19.05	BOM
Mean sea level pressure	100029	1016.03	7.08	979.72	1039.16	BOM
Temperature	113595	18.20	5.60	-2.90	45.29	BOM
Relative humidity	112849	62.39	20.03	1.12	100	BOM
Wind direction (north)	116103	0.20	0.40	0	1	BOM
Wind direction (east)	116103	0.23	0.42	0	1	BOM
Wind direction (west)	116103	0.29	0.45	0	1	BOM
Wind speed	113108	4.87	2.43	0	21.81	BOM
Daily solar exposure (monthly average)	116103	19.36	3.70	8.01	30.53	BOM
Precipitation (monthly average)	116103	54.09	25.76	0.14	517.14	BOM
Mean daily wind speed (monthly average)	116103	3.88	0.97	0.24	9.01	BOM
Maximum daily temperature (monthly average)	116103	21.74	4.21	5.40	38.62	BOM
Daily solar exposure (annual average)	116103	18.69	2.02	13.58	30.17	BOM
Precipitation (annual average)	116103	773.56	312.94	116.60	3340.30	BOM
Mean daily wind speed (annual average)	116103	3.63	0.96	0.85	7.59	BOM
Maximum daily temperature (annual average)	116103	22.87	2.98	10.22	34.90	BOM

TABLE 2.10: Summary of variables

	Solar exposure	Precipitation	Mean daily wind speed	Wind speed	Mean sea level pressure	Temperature	relative humidity
Solar exposure	1.00						
Precipitation	-0.22	1.00					
Mean daily wind speed	-0.11	0.14	1.00				
Wind speed	-0.01	0.08	0.70	1.00			
Mean sea level pressure	0.11	-0.10	-0.29	-0.29	1.00		
Temperature	0.49	-0.14	-0.11	0.08	-0.20	1.00	
Relative humidity	-0.35	0.18	-0.02	-0.09	0.02	-0.41	1.00

TABLE 2.11: Weather variable correlations

Variable	Description
Weather	
Solar exposure	Global solar exposure is the total amount of solar energy falling on a horizontal surface. The daily global solar exposure is the total solar energy for a day. Typical values for daily global solar exposure range from 1 to 35 MJ/m^2 (megajoules per square metre). The values are usually highest in clear sun conditions during the summer, and lowest during winter or very cloudy days. Details of data collection are here: http://www.bom.gov.au/climate/austmaps/metadata-daily-solar-exposure.shtml
Precipitation	Precipitation in the 24 hours before 9am (local time) in mm.
Wind speed (daily mean)	Mean daily wind speed in m/s.
Mean sea level pressure	Mean sea level pressure in hectopascals (hPa).
Temperature	Dew point temperature observation in degrees C.
Relative humidity	Relative humidity in percentage.
Wind speed	Wind speed measured in m/s.
Wind direction (north)	Indicator variable equal to one if wind direction is greater than 315 degrees and less than 45 degrees.
Wind direction (east)	Indicator variable equal to one if wind direction is greater than 45 degrees and less than 135 degrees.
Wind direction (west)	Indicator variable equal to one if wind direction is greater than 135 degrees and less than 225 degrees.
Wind direction (south)	Indicator variable equal to one if wind direction is greater than 225 degrees and less than 315 degrees.
Other variables of interest	
Hour	Time of interview rounded to the nearest of 0300h, 0600h, 0900h, 1200h, 1500h, 1800h, 2100h, 2400h.
Weekend	Indicator variable equal to one if interview occurred on Saturday or Sunday.
Other present	Indicator variable equal to one if respondent answered yes to the following questions: Were any other adults present during any of this interview?
Controls - continuous	
Age	Age last birthday at June 30 in the year the survey wave begins.
Household dependents	Number of dependent children aged 0-24.
Household income	Nominal household equivalized income. Calculated as household financial year disposable income divided by 1+(Number of adults 15 years and over-1)*0.5+(Number of dependents under 15 years)*0.3.

TABLE 2.12: Variable descriptions (I)

Variable	Description
Controls - indicators	
Disability (mild)	Respondent stated they had a long-term health condition, impairment or disability that restricts everyday activities, and has lasted or is likely to last, for 6 months or more and they stated that the long-term health condition had no impact on the type or amount of work done.
Disability (moderate)	Respondent stated they had a long-term health condition, impairment or disability that restricts everyday activities, and has lasted or is likely to last, for 6 months or more and they stated that the long-term health condition impacts type or amount of work done.
Disability (severe)	Respondent stated they had a long-term health condition, impairment or disability that restricts everyday activities, and has lasted or is likely to last, for 6 months or more and they stated that the long-term health condition means that the respondent cannot work.
Unemployed	Respondent stated their labour force status as unemployed.
Not in labour force	Respondent stated their labour force status as not in the labour force.
Employed	Respondent stated their labour force status as employed.
Single	Respondent stated their marital status as never married and not de facto.
Married	Respondent stated their marital status as married.
De facto	Respondent stated their marital status as de facto.
Separated	Respondent stated their marital status as separated.
Divorced	Respondent stated their marital status as divorced.
Widowed	Respondent stated their marital status as widowed.
Post graduate	Respondent stated their highest education level achieved as masters or doctorate.
Graduate diploma/certificate	Respondent stated their highest education level achieved as graduate diploma or graduate certificate.
Bachelor	Respondent stated their highest education level achieved as bachelor or honours.
Diploma	Respondent stated their highest education level achieved as advanced diploma or diploma.
Certificate 3/4	Respondent stated their highest education level achieved as certificate III or IV.
Certificate 1/2	Respondent stated their highest education level achieved as certificate I or II.
Certificate (unknown)	Respondent stated their highest education level achieved as certificate (not defined).
Year 12	Respondent stated their highest education level achieved as year 12.
Year 11	Respondent stated their highest education level achieved as year 11.

TABLE 2.13: Variable descriptions (II)

3

Environmental Policy, Agglomeration and Firm Location

John Feddersen[1]

Abstract

This chapter 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 (Section 3.3). Each region ratifies an international environmental agreement (IEA) which requires it to tax trans-boundary 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 (Section 3.4). Firm relocation in response to a given tax differential depends crucially on trade costs and the initial location (configuration) of industry.

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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 (Section 3.5). 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 liberalization 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.

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

3.1 Introduction

This chapter 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.

3.1.1 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.[2] 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.[3]

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 industrialized 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 industrialized parties have insisted that any global climate agreement include commitments to reduce GHG emissions by major

2 '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.

3 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.

industrializing 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).[4]

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 chapter.

A second complication, which is the focus of this chapter, arises because regions which are required to significantly economize 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 economization 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 chapter, 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).[5] There is currently strong empirical support for the PHE.[6]

The PHE poses an important policy challenge, especially for industrialized 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 policy) induces relocation

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4 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 committed to cut its emissions intensity per unit of GDP by 20 to 25 percent from 2005 levels, by 2020.

5 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 chapter 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.'

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

of GHG emissions rather than their reduction.[7,8] Carbon leakage makes environmental regulation less effective or even counterproductive.

These concerns have been expressed in the EU, USA and many other industrialized 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 chapter 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 minimized and suggesting how best to design international environmental agreements to ensure they are more acceptable to all parties. In Section 3.4 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 Section 3.5 I

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7 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 Reinaud (2008) for a detailed discussion of these channels.

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

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?*

3.1.2 Contribution

This chapter 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.

3.1.2.1 Contribution to the theory of the PHE (Section 3.4)

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.[9] Section 3.4 extends Venables' (1999) analysis on two fronts. First, the FE model in this chapter is easier to work with analytically than the vertical linkages (VL) model of Venables (1999).[10] Second, assumptions about the type of regulation and the way polluting firms respond to regulation in the model in this chapter 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 chapter enables results to be 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 chapter, tractability

9 In contrast to the FE model in this chapter, Venables (1999) adopts a vertical linkages (VL) model of the type first developed in Venables (1996).

10 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.'

enables the tipping points in the model to be determined analytically. Fourth, the model developed in this chapter is more readily extended to a competitive environmental policy setting in which governments select pollution tax rates by maximizing an objective function.[11] In the NEG tax competition literature, the FE model has already been used to consider tax policies by competing governments.[12]

As a consequence of the improved tractability, the model presented in this chapter 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 chapter is also more realistic for a situation in which GHGs are regulated. In contrast to Venables (1999), this chapter 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).[13]

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 liberalization 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 chapter the PHH, which predicts that trade liberalization between regions with differentiated environmental regulation leads to industry relocation, only holds under certain conditions. Indeed, trade restriction that makes industry more footloose may also lead to relocation of firms from stringently regulated regions, thereby reversing the PHH.

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11 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.

12 See Baldwin and Krugman (2004).

13 The fact that firm size responds to regulation is important for analysis undertaken in Section 3.5 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 chapter no longer hold.

This result may explain the relatively weak empirical support for the PHH compared to the PHE.[14]

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.

3.1.2.2 Contribution to the theory of carbon leakage (Section 3.5)

To my knowledge, no paper has evaluated the relationship between environmental policy and carbon leakage in an NEG framework.[15] However, firm location decisions, increasing returns to scale and agglomeration forces, all of which characterize the NEG framework, have been shown to be important determinants of the extent of carbon leakage.[16] A theoretical NEG model of carbon leakage is thus well overdue.

As noted above, this chapter 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.[17] 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 pollution. Once the carbon leakage genie is out of the bottle, it may be difficult to put it back in.

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

[15] Ishikawa and Okubo (2009) consider the relationship between trade liberalization 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 Section 3.2.

[16] For a review of policy literature see Reinaud (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 literature see Babiker (2005). For empirical evidence that agglomeration forces determine the location of polluting industries see Giarratani et al. (2007).

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

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.

3.1.3 Outline

This chapter proceeds as follows: Section 3.2 places this chapter within the literature; Section 3.3 presents a theoretical model of pollution taxation with endogenous firm location and derives the equilibrium when firm location is fixed (the short-run equilibrium); Section 3.4 extends the model to consider the relationship between environmental regulation and firm location; Section 3.5 extends the model to consider the relationship between environmental regulation and carbon leakage; Section 3.6 concludes the chapter by summarizing its main results, proposing an agenda for future research and outlining key policy implications.

3.2 Literature Review

This chapter extends and combines two related strands of the literature, those on the PHE and carbon leakage.[18] In this section I demonstrate the importance of the two central questions asked in Sections 3.4 and 3.5, and justify the adoption of the NEG approach in answering those questions, by briefly surveying the literature relating to both strands.

In sub-section 3.2.1 I review the literature on the PHE (particularly that which relates to firm relocation) and in sub-section 3.2.2 I review the literature on carbon leakage.[19]

3.2.1 The PHE

In this sub-section I discuss three theoretical approaches used to analyze the PHE. While a discussion of the existing literature is important in and of itself, the main purpose of this sub-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 sub-section demonstrates how the analysis undertaken within this chapter 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 specialization 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) specializes in production of the pollution intensive good. This is a typical property of perfectly competitive CRS models. In Pethig's model, trade liberalization causes production of the polluting good to migrate to the region with less stringent environmental regulation.

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

[19] 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 chapter. 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 analyze 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.[20]

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.[21]

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.[22] 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).[23] 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 willingness to relocate as the level of trade costs increases is hump-shaped (with the willingness increasing in

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

[21] This chapter adopts an NEG model of the interregional factor mobility type.

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

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

trade costs before eventually decreasing) rather than monotonically decreasing. Third, over some ranges of the parameter space, multiple equilibria are possible.[24]

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.

Section 3.4 of this chapter 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.[25] 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.[26] 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 chapter 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.[27] As both the speed and irreversibility of industry

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

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

26 This generalizes the main prediction of Markusen et al. (1993) to an NEG framework.

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

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

3.2.2 Carbon leakage

The contribution of this chapter 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 sub-section I survey the literature on carbon leakage with the aim of highlighting three important themes. First, firm relocation is an important channel of carbon leakage which may not have been adequately addressed. Second, to the best of my knowledge, 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 sub-section 3.2.1 which suggests that agglomeration forces are likely to characterize polluting industries, indicate that the analysis undertaken in Section 3.5 of this chapter 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.[28] Most (or all) of the leakage in perfectly competitive CRS models occurs through changes in factor prices rather than through firm relocation.[29]

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.[30] This chapter sets out conditions under which firm relocation may play a large role in determining the extent of carbon leakage.

Theoretical literature Markusen (1975) is amongst the earliest papers to consider transboundary pollution in an economic model. The welfare maximizing policy of a large country which can

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

[29] 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.'

[30] 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%.

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.[31] If trade policy is also available, the tax rate is optimally equalized 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 liberalization 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.[32] 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 extent to which trade freeness can be altered for environmental purposes, the tax differential is arguably a more

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

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

important policy variable to consider.[33] This chapter considers carbon leakage resulting from both trade liberalization and changes in the tax differential in this chapter.

Empirical literature There are few, if any, published papers estimating the extent of carbon leakage empirically. I conjecture three main reasons for this lack of empirical work.[34] 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?

[33] 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.

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

3.3 The General Model

This section develops a theoretical NEG model with pollution taxation. This section comprises two sub-sections. In sub-section 3.3.1 I outline the assumptions underlying the model. In sub-section 3.3.2 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 Section 3.4.

3.3.1 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 labor 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 chapter 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 labor exist.[35] 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 labor: (i) inter-regionally immobile unskilled workers and (ii) skilled workers who are inter-regionally mobile in the long-run.[36,37] Each worker (skilled or unskilled) produces one unit of labor. 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) is equal to

[35] Fujita at el. (1999, Chapter 14) provide evidence to suggest that labor 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 labor mobility models and VL models (see Robert-Nicoud (2005) for a summary of these) in order to generalize the findings of this chapter to situations in which vertical linkages are more likely to explain agglomeration forces.

[36] Empirical evidence on labor 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.

[37] An alternative interpretation, which recognizes that capital is significantly more mobile internationally than labor, 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.

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.

3.3.1.1 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:

$$U = C_M^{\mu} C_A^{1-\mu} - f(\Gamma + \Gamma^*) \tag{3.1}$$

$$C_M = \left(\int_0^{n+n^*} c_i^{1-\frac{1}{\sigma}} di \right)^{\frac{1}{1-\frac{1}{\sigma}}} ; 0 < \mu < 1, \sigma > 1 \tag{3.2}$$

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, $f(\Gamma + \Gamma^*)$, 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:

$$\int_0^{n+n^*} p_i c_i di + p_A C_A \leq I \tag{3.3}$$

Maximization of (3.2) subject to (3.3) yields the following indirect utility functions for skilled and unskilled workers:

$$\omega = \eta \frac{w_H}{P}, \omega_L = \eta \frac{w_L}{P}$$
$$P \equiv p_A^{1-\mu} P_M^{\mu}, \eta = \mu^{\mu} (1-\mu)^{1-\mu}, P_M \equiv \left(\int_0^{n^w} p_i^{1-\sigma} di \right)^{\frac{1}{1-\sigma}} \tag{3.4}$$

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.

3.3.1.2 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 chapter 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.[38]

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.[39]

3.3.1.3 Supply side

Agricultural products are produced in a perfectly competitive market with a CRS technology and unskilled labor is used exclusively in their production. The cost of producing each unit of output

[38] 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.

[39] As discussed in Section 3.2, 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.

is therefore $a_A w_L$, where a_A denotes the unskilled labor 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 labor as a fixed input in addition to a_M units of unskilled labor 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:

$$TC = w_H F + (w_L a_M + t\gamma)\, x \tag{3.5}$$

x is the output level. Equation (3.5) 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.[40]

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.

3.3.2 Deriving the short-run equilibrium

In this sub-section, a series of equations are derived, which define the model's equilibrium if skilled workers (and therefore firms) are 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.

[40] 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.

3.3.2.1 Agriculture

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

$$C_A = (1-\mu)\,\frac{E}{p_A} \tag{3.6}$$

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:[41]

$$\begin{aligned} p_A &= a_A w_L \\ p_A^* &= a_A w_L^* \end{aligned} \tag{3.7}$$

An assumption of zero trade costs for the agricultural product ensures $p_A = p_A^*$ and therefore $w_L = w_L^*$.[42,43] 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.

3.3.2.2 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:

$$n^w = \frac{H^w}{F} \tag{3.8}$$

---

[41] 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.

[42] 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.

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

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

$$c_j = p_j^{-\sigma}\left(\frac{\mu E}{P_M^{1-\sigma}}\right) \tag{3.9}$$

$$E = w_H H + w_L L \tag{3.10}$$

$$p_j = \frac{c_j^{-\frac{1}{\sigma}}}{C^{1-\sigma}}\mu E,\ C = \left(\int_0^{n+n^*} c_i{}^{1-\frac{1}{\sigma}} di\right)^{\frac{1}{1-\sigma}} \tag{3.11}$$

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:

$$MR = \left(1 - \frac{1}{\sigma}\right) p_j \tag{3.12}$$

The marginal cost of supplying domestic and foreign consumers is found by differentiating the manufacturing total cost function (3.5) with respect to x and adding any trade costs:

$$\begin{aligned} MC_d &= w_L a_m + t\gamma \\ MC_f &= \tau\left(w_L a_m + t\gamma\right) \end{aligned} \tag{3.13}$$

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

$$
\begin{aligned}
p_N &= \tfrac{w_L a_M + t\gamma}{1-\frac{1}{\sigma}}, \; p_S = \tau \tfrac{(w_L a_M + t\gamma)}{1-\frac{1}{\sigma}} = \tau p_N \\
p_S^* &= \tfrac{w_L a_M + t^*\gamma}{1-\frac{1}{\sigma}}, \; p_N^* = \tau \tfrac{(w_L a_M + t^*\gamma)}{1-\frac{1}{\sigma}} = \tau p_S^*
\end{aligned}
\tag{3.14}
$$

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 3.1, 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.

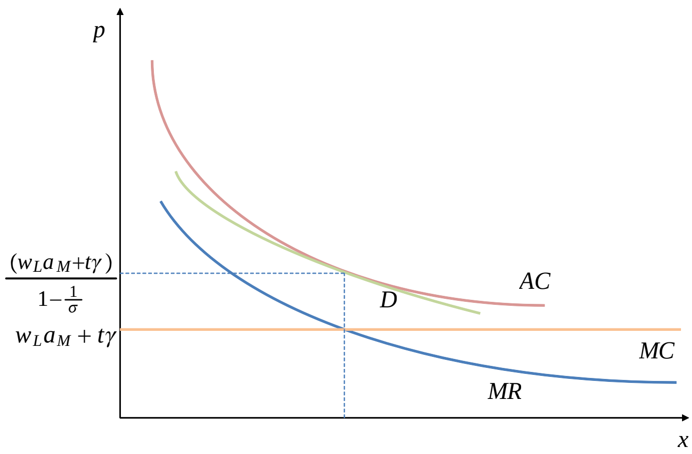

FIGURE 3.1: The fixed mark-up condition

As equation (3.14) 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 Section 3.5. As a consequence, I digress briefly to derive the firm size conditions.

Skilled labor 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:

$$\pi_j = \frac{p_N x_j}{\sigma} = \frac{w_L a_M + t\gamma}{\sigma - 1} x_j \tag{3.15}$$

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

$$\begin{aligned} x &= w_H F \tfrac{\sigma-1}{w_L a_M + t\gamma} \\ x^* &= w_H^* F \tfrac{\sigma-1}{w_L a_M + t^*\gamma} \end{aligned} \tag{3.16}$$

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 Section 3.5.

The firm size obtained in equation 3.16 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:

$$p_N x_j = p_N c_{j,N} + p_S c_{j,S} \tag{3.17}$$

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.

Utilizing 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 (3.17)), then substituting in equations (3.9), (3.10) and (3.14) yields the following (nominal) skilled wage in each region:

$$\begin{aligned} w_H &= bB\frac{E^w}{n^w} \\ w_H^* &= brB^*\frac{E^w}{n^w} \end{aligned} \tag{3.18}$$

where:

$$\begin{gathered} b = \frac{\mu}{\sigma}, \phi = \tau^{1-\sigma}, B = \left[\left(\frac{s_E}{\theta}\right) + \phi\left(\frac{1-s_E}{\theta^*}\right)\right], B^* = \left[\phi\left(\frac{s_E}{\theta}\right) + \left(\frac{1-s_E}{\theta^*}\right)\right], \\ \theta \equiv s_n + \phi\left(1-s_n\right)r = \frac{P_M^{1-\sigma}}{p_N^{1-\sigma} n^w}, \theta^* = \left(1-s_n\right)r + \phi s_n = \frac{{P_M^*}^{1-\sigma}}{p_N^{1-\sigma} n^w}, \\ E^w = E + E^*, n^w = n + n^*, r = \left[\frac{w_L a_M + t\gamma}{w_L a_M + t^*\gamma}\right]^{\sigma-1} \geq 1 \end{gathered} \tag{3.19}$$

Steps taken in the derivation of this expression are in Appendix 3.A.1. 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.[44] 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 $s_n B + (1 - s_n) rB^* = 1$.

3.3.2.3 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.[45] 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 maximize 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 below provide intuition as to how each works and of their relative sizes.

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44 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^*.

45 The third force, a cost of living effect, operates through the real wage and is examined in Section 3.4 once factor migration is introduced into the model.

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 ($s_n = \frac{1}{2}$).[46] 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 (3.18)). 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 equalized 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 (3.9)) 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.

[46] 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 (3.16) 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 equalized 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 labor 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 labor 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.

3.3.2.4 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 labor 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[47]:

$$E^w = \frac{w_L L^w}{1-b} \tag{3.20}$$

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:

$$\begin{gathered} s_E = (1-b)\, S_L + bBs_H, \; s_L \equiv \tfrac{L}{L^w}, \; s_H \equiv \tfrac{H}{H^w} = s_n \\ (1-s_E) = (1-b)\,(1-S_L) + brB^*\,(1-s_H) \end{gathered} \tag{3.21}$$

Equation (3.21) 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.[48]

Rearranging (3.21), substituting in (3.18) and, for simplicity, assuming a symmetric distribution of unskilled labor between regions ($L = L^*$) enables expression of the distribution of expenditure as a function of the distribution of skilled workers:

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47 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 $n^w = H^w$.

48 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 chapter.

$$s_E = \left[\frac{\frac{(1-b)}{2} + b\phi \frac{1}{\theta^*} s_H}{1 - b\frac{1}{\theta} s_H + b\phi \frac{1}{\theta^*} s_H} \right] \tag{3.22}$$

Derivations of (3.21) and (3.22) are in Appendix 3.A.2.

Equation (3.22) has two properties which assist with analysis in the following section. 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 (3.1).

Proposition 3.1 *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.A.3. ■

Proposition 3.1 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 3.1, Figure 3.2 plots s_H on the vertical axis and s_E on the horizontal axis for various values of r.

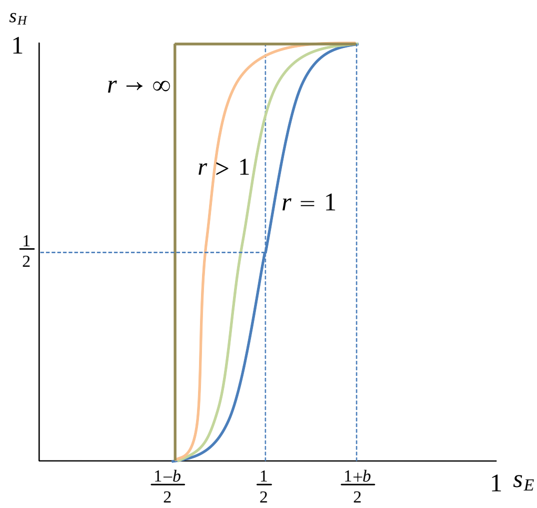

FIGURE 3.2: Expenditure share as a function of skilled population share

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 section (see equations (3.8), (3.14), (3.18) and (3.22)). Building on this, in order to consider the first key question of this chapter (*How does the degree of differentiation of environmental policy influence the extent of* *firm relocation?*), Section 3.4 analyses a situation in which skilled workers (and firms) are mobile between regions.

3.4 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

3.4.1 Introduction

This section asks the first key question of this chapter: *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 sub-section 3.4.2 I make a number of normalizations to avoid unnecessary notation and to improve focus on the critical exogenous parameters of the analysis, r and ϕ. Sub-section 3.4.3 defines the concepts of equilibrium and stability used in the remainder of this chapter. Sub-section 3.4.4 considers the first (and simplest) of three tax scenarios, a base case in which tax rates are equal to zero in both regions ($t = t^* = 0$). Sub-section 3.4.5 evaluates a scenario in which tax rates are positive but equal ($t = t^* > 0$). Sub-section 3.4.6 considers the most general case; one in which output taxes are both weakly positive and differentiated ($t > t^* \geq 0$). Sub-section 3.4.7 concludes the section.

3.4.2 Normalizations

Several normalizations 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 normalize.

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:

$$\begin{aligned} p_N &= \tfrac{1+t}{1-\frac{1}{\sigma}},\ p_S = \tau\tfrac{1+t}{1-\frac{1}{\sigma}}, \\ p_S^* &= \tfrac{1+t^*}{1-\frac{1}{\sigma}},\ p_N^* = \tau\tfrac{1+t^*}{1-\frac{1}{\sigma}}, \end{aligned} \tag{3.23}$$

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 normalization ensures the equivalence of skilled labor shares and skilled labor populations: $n = H = s_n = s_H$ and $n^* = H^* = 1 - s_n = s_H^*$. I normalize 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 normalization, 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.

3.4.3 Real wages, equilibrium and stability conditions

3.4.3.1 Deriving real wages

Real wages determine the migration of skilled labor in the model. For convenience, I restate the real skilled wages from (3.4) after accounting for normalizations:

$$\begin{aligned} \omega &= \eta\tfrac{w_H}{P},\ P \equiv P_M^{\mu}, P_M \equiv \left(\int_0^{n^w} p_i^{1-\sigma} di\right)^{\frac{1}{1-\sigma}} = p_N \left[s_n + (1-s_n)\,\phi r\right]^{\frac{1}{1-\sigma}} \\ \omega^* &= \eta\tfrac{w_H^*}{P^*},\ P^* \equiv P_M^{*\mu}, P_M^* \equiv \left(\int_0^{n^w} p_i^{*1-\sigma} di\right)^{\frac{1}{1-\sigma}} = p_N \left[\phi s_n + (1-s_n)\,r\right]^{\frac{1}{1-\sigma}} \end{aligned} \tag{3.24}$$

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 equalized across regions ($r = 1$) and therefore that production costs are also equalized. 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 $\phi r < 1$ ($\phi r > 1$).

3.4.3.2 Equilibrium and stability conditions

Skilled workers move to the region offering the highest real wage.[49] The dynamics between equilibria are not explicitly considered in this chapter 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:[50]

$$\dot{s}_H = (\omega - \omega^*)\, s_H\, (1 - s_H) \tag{3.25}$$

$\dot{s}_H$ 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 (3.25). Equation (3.25) implies that there are two types of equilibrium. The first type is a diversified equilibrium. Such an equilibrium occurs when real wages are equalized across regions ($\omega = \omega^*$) and neither region hosts

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

[50] 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.

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 (3.25) 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 formalized for the diversified, CPN and CPS equilibria respectively as follows:

$$\begin{gathered} \tfrac{d(\omega-\omega^*)}{ds_H} < 0 \text{ if } (0 < s_H < 1) \\ \omega > \omega^* \text{ if } s_H = 1 \\ \omega < \omega^* \text{ if } s_H = 0 \end{gathered} \tag{3.26}$$

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, $\omega - \omega^*$.[51] Substituting expressions for nominal wages (equation (3.18)) and the true cost of living indices into the real wage equations (3.24) and taking the log yields Ω as a function of the distribution of skilled workers and exogenous model parameters.[52]

$$\Omega = \log\left(\frac{\theta^* s_E + \phi\theta\,(1 - s_E)}{r\left[\phi\theta^* s_E + \theta\,(1 - s_E)\right]}\right) + a\log\left(\frac{\theta}{\theta^*}\right), a = \frac{\mu}{\sigma - 1} \tag{3.27}$$

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

[51] This is a consequence of the non-integer powers in the real wage equations.
[52] The price index ratio is derived in Appendix 3.B.1.

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 sub-sections 3.4.4, 3.4.5 and 3.4.6 in order to derive the effect of the pollution tax rates on firm location.

3.4.4 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:

$$\Omega = \log\left(\frac{\theta^* s_E + \phi\theta\,(1-s_E)}{[\phi\theta^* s_E + \theta\,(1-s_E)]}\right) + a\log\left(\frac{\theta}{\theta^*}\right) \tag{3.28}$$

The properties of the base case have been considered in significant detail in the literature.[53] In this sub-section I restate only those properties of the base case which are of particular importance for the purposes of this chapter.

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 3.3 and 3.4.

I follow convention and refer to Figure 3.3 as a 'wiggle' diagram. The functions in Figure 3.3, which 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.[54]

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

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

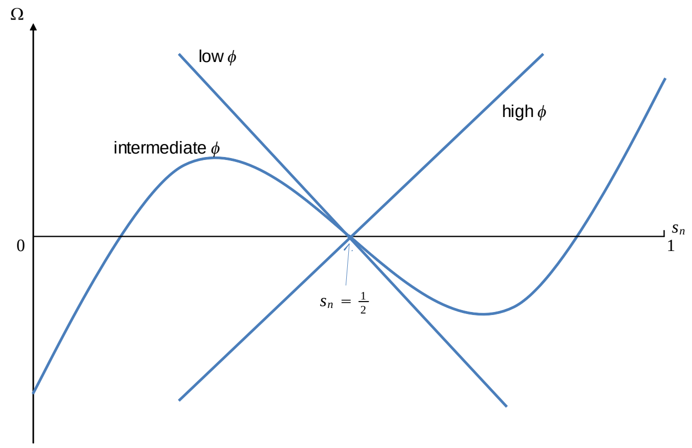

FIGURE 3.3: Wiggle diagram with no taxation

In Figure 3.3, $\Omega(s_n)$ is illustrated for three values of ϕ representing high, medium and low trade freeness. As shown in Figure 3.3, 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 3.4, 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 (3.29).[55,56]

$$\phi_b = \left(\frac{1-b}{1+b}\right)\left(\frac{1-a}{1+a}\right) \tag{3.29}$$

Second, the level of trade freeness above which both CP equilibria are stable (this is known as the sustain point), ϕ_s, is defined implicitly by the value of ϕ which solves equation (3.30):[57]

$$f(\phi) = \phi^a \left[\phi\frac{1+b}{2} + \frac{1-b}{2\phi}\right] - 1 \tag{3.30}$$

---

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

[56] For the remainder of this chapter 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).

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

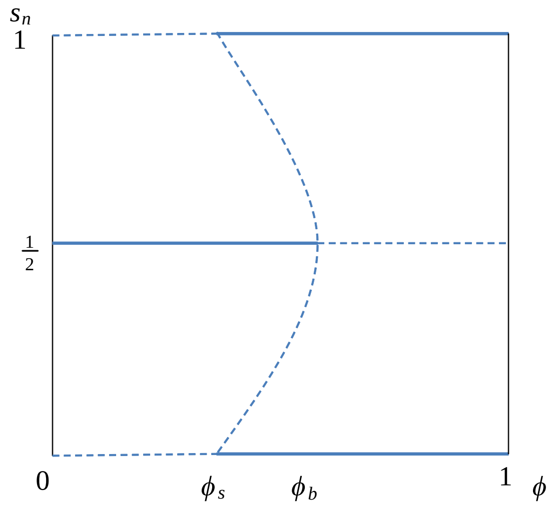

FIGURE 3.4: Bifurcation diagram with no taxation

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 equalized across regions for any distribution of skilled workers.

3.4.5 Case 2: Harmonized 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 unharmonized tax case in sub-section 3.4.6.

Recall from Section 3.3 that taxes affect nominal wages through the ratio of variable costs (reflected by the parameter r) only. As $r = 1$ whenever taxes are harmonized, nominal wages are identical to those in the zero tax case. I state this as Conclusion 3.1 .

Conclusion 3.1 *If taxes are harmonized, changes in the harmonized tax rate, $\bar{t}$, do not alter the nominal wage.*

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

$$
\begin{aligned}
P &\equiv p_N^{\mu}\theta^{a} = \left[\frac{1+\bar{t}}{1-\frac{1}{\sigma}}\right]^{\mu}\left[s_n + (1-s_n)\,\phi\right]^{a} \\
P^{*} &\equiv p_N^{\mu}{\theta^{*}}^{a} = \left[\frac{1+\bar{t}}{1-\frac{1}{\sigma}}\right]^{\mu}\left[\phi s_n + (1-s_n)\right]
\end{aligned}
\tag{3.31}
$$

When taxes are harmonized, increasing the tax rate reduces the real wage in both regions equally. Increases in the harmonized 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 harmonized tax rate do not alter the set of parameter values for which each type of equilibrium is stable. Evaluating equation (3.27) when $t = t^{*} > 0$ yields an expression which is identical to that established for the zero tax case (see equation (3.28)) 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 harmonized tax rate therefore never change the location of firms beginning from a stable equilibrium. I state this result as Conclusion 3.2.

Conclusion 3.2 *Under harmonized taxation the level of the harmonized tax rate, $\bar{t}$, does not alter the real wage ratio. The set of stable equilibria in the harmonized 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.[58]

One consequence of Conclusion 3.2 is that the stability properties of the harmonized tax equilibria are also summarized in Figures 3.3 and 3.4. Trade liberalization (represented by an increase in ϕ) can lead to relocation of firms, however, changes in the harmonized tax rate cannot.

[58] 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.

3.4.6 Case 3: Unharmonized taxation $(t > t^* \geq 0)$

Unharmonized taxation breaks the symmetry of Figures 3.3 and 3.4 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 3.10 and 3.11 at the end of this subsection to Figure 3.4 provides a concise illustration of the consequences of unharmonized taxation for firm location.

3.4.6.1 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:

$$\phi^a \left[\phi \frac{1+b}{2} + \frac{1}{\phi}\frac{1-b}{2}\right] - \frac{1}{r} < 0 \tag{3.32}$$

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:

$$f_{CPN}(\phi) = \phi^a \left[\phi \frac{1+b}{2} + \frac{1-b}{2\phi}\right] - \frac{1}{r} \tag{3.33}$$

$f_{CPN}(\phi)$ for $r = 1$ and $r > 1$ are illustrated in Figure 3.5.

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.

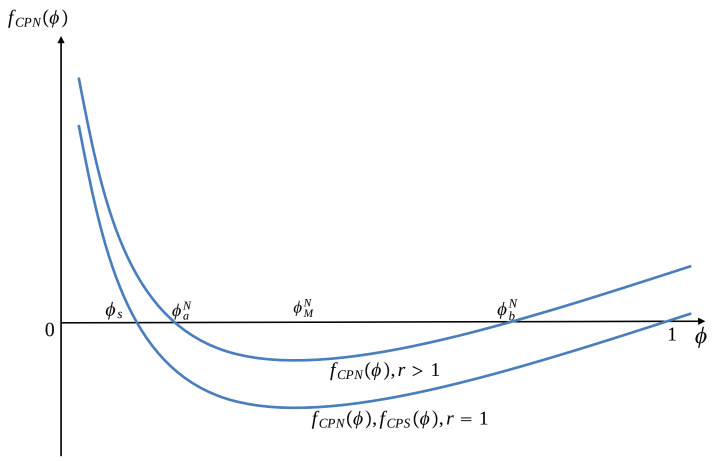

FIGURE 3.5: f_{CPN} for $r = 1$ and $r > 1$

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 (3.32) 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.[59] 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 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.

[59] 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 (3.32).

Figure 3.5 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 harmonized 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 liberalization without fear of loss of industry. In the presence of differentiated pollution taxation, trade liberalization *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.[60] 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.[61] 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 3.2.

Proposition 3.2 *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 3.B.2. ■

Proposition 3.2 illustrates the interdependence of trade freeness, ϕ, and the tax rate differential, r, for the determination of stability. For example, at a level of ϕ that is slightly larger than ϕ_a^N, a relatively small increase in r causes the CPN equilibrium to become unstable. For a higher level of ϕ, an identical increase in r has no effect on the stability of the CPN equilibrium.

---

60 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.

61 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.

It is possible to determine the level of trade freeness which allows the tax differential between regions to be maximized 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 3.3 *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 3.2 and 3.3 demonstrate the non-linear effect of trade liberalization on the footlooseness of firms in the presence of differentiated pollution taxation. I state this effect in Corollary 3.1.

Corollary 3.1 *Beginning from a value of ϕ less (greater) than ϕ_M^N, trade liberalization 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 3.1 illustrates how the introduction of agglomeration forces implies that the standard result in the international trade literature that trade liberalization makes firms more footloose in response to a tax disadvantage may not always hold. In the FE model, trade liberalization 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 liberalization 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 liberalized (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 Section 3.1, 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 chapter, which I discuss in Section 3.6. 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 maximize their domestic pollution tax rate without inducing relocation of firms by setting $\phi = \phi_M^N$ and $r = r^N$.

3.4.6.2 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:

$$\phi^a \left[\phi \frac{1+b}{2} + \frac{1-b}{2\phi}\right] - r < 0 \tag{3.34}$$

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:

$$f_{CPS}(\phi) = \phi^a \left[\phi \frac{1+b}{2} + \frac{1-b}{2\phi}\right] - r \tag{3.35}$$

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

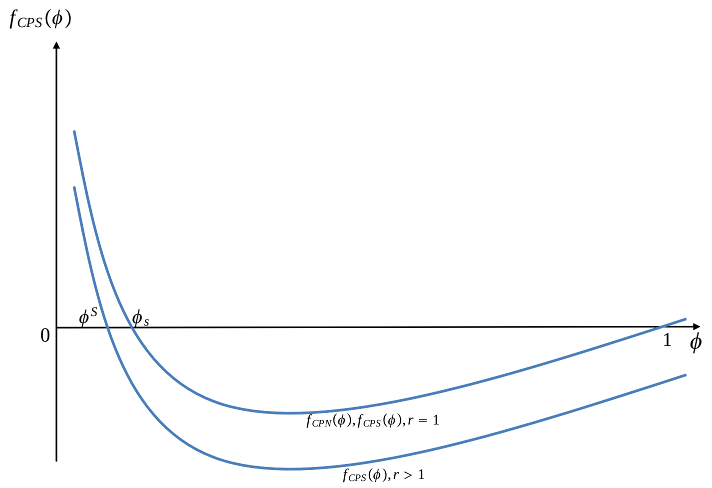

FIGURE 3.6: $f_{CPS}(\phi)$ for $r = 1$ and $r > 1$

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.[62] 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 $r \to \infty$.[63] 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.

It is possible to determine the minimum level of r required to make the CPS stable for a given value of ϕ. This value is given in Proposition 3.4.

[62] 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 (3.34).

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

Proposition 3.4 *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 3.B.3.* ■

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

3.4.6.3 Properties of the diversified equilibrium

In this sub-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 3.5.

Proposition 3.5 *Holding s_n fixed at any level in the economically meaningful interval* $[0, 1]$, $\frac{\delta\Omega}{\delta r} < 0$.

Proof. See Appendix 3.B.4. ■

Proposition 3.5 implies that the short-run real wage ratio for a given distribution of firms (s_n) is decreasing in r. The implication of Proposition 3.5 for the function $\Omega(s_n)$ is illustrated in Figure 3.7 for parameter values for which both CP and diversified equilibria are possible.

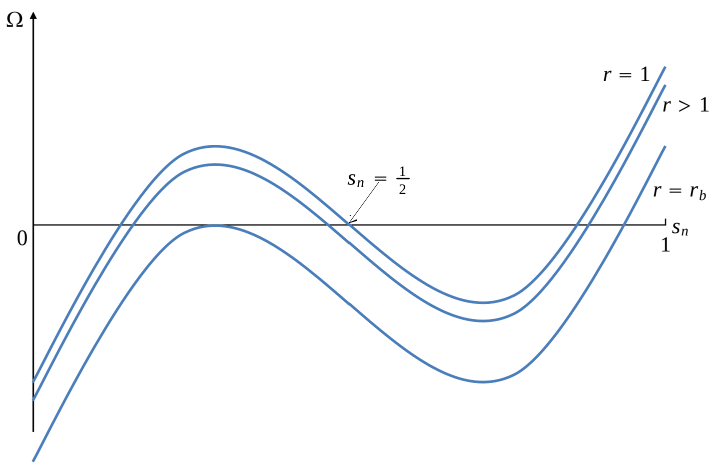

FIGURE 3.7: Wiggle diagram with unharmonised taxation

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.[64]

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 unharmonized.[65]

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 $\phi > 0$.[66]

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 3.7. 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.[67]

A second property of the diversified equilibrium, which is implied by Proposition 3.5, 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 equilibrium (if one exists) will occur for a lower value of s_n.[68,69] 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.

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64 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.

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

66 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 $s_n = 1$.

67 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 $\frac{2-(1+b)\left(1-\phi^2\right)}{2\phi^{1-\alpha}}$.

68 For an illustration, consider the symmetric stable diversified equilibrium in Figure 3.7 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 $\frac{1}{2}$.

69 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.

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 3.B.5.

The effect of ϕ on the stable diversified equilibrium First, I establish that under unharmonized 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 harmonized tax case, the unharmonized tax case must feature a break point, $\phi_b(r)$, however, it is a function of the tax differential. Proposition 3.6 states this:

Proposition 3.6 *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 $s_n \in (0, \frac{1}{2})$.*[70] *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.[71]

■

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

Proposition 3.7 *$\phi_b(r)$ 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 3.5, that the local maximum of $\Omega(s_n)$ for $s_n \in \left[0, \frac{1}{2}\right]$ is now less

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70 To distinguish between the unharmonised and harmonized 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 harmonized tax break point, which I write as ϕ_b, is a function of μ and σ only.

71 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.

than zero. Therefore, no stable equilibrium is now possible and $\phi_b\left(r^1\right) > \phi_b\left(r^2\right)$ by Proposition 3.6. 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).[72] Unlike the harmonized 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 unharmonized tax case (in contrast to the harmonized tax case in which trade liberalization 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 liberalization 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 chapter however I include it both for completeness and in order to identify an issue requiring further study.

Conjecture 3.1 *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 3.1 is supported by extensive simulation over the economically meaningful parameter space in which it has been found to hold without exception.[73,74] Conjecture 3.1 is illustrated in Figure 3.8. At the diversified equilibrium, the value of s_n decreases and the slope of $\Omega(s_n)$ becomes less negative as ϕ increases.[75] On the assumption that conjecture 3.1 is true for all parameter combinations, I proceed to analyze the effect of changing ϕ on the stability of the diversified equilibrium.

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

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72 This can be proven simply by simulated counterexample.

73 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.

74 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 harmonized, 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.

75 $\phi_b(r)$ is approximately equal to 0.16 in this case and there is no stable diversified equilibrium possible for $\phi = 0.17$.

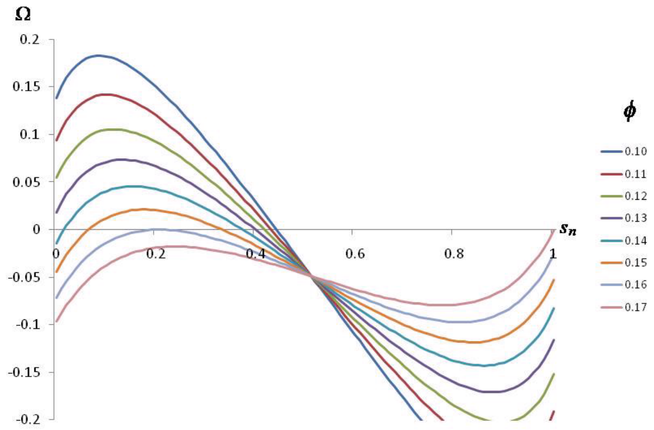

FIGURE 3.8: $\Omega(s_n)$ for various ϕ.

local maxima of Ω when $\phi = \phi_b(r)$. Figure 3.9 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 3.9 are illustrated for values of ϕ equal to $\phi_b(r^*)$ and $\phi_b(r^{**})$.

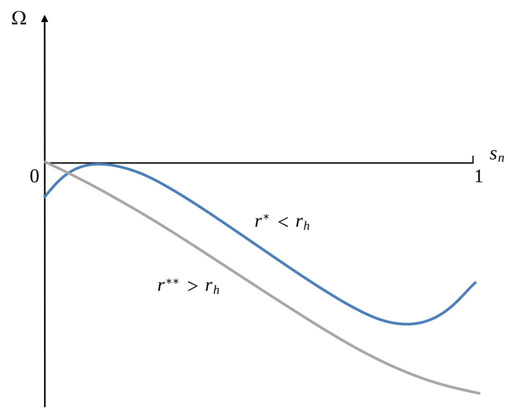

FIGURE 3.9: Wiggle diagram with catastrophic (blue) and non-catastrophic (grey) delocation as ϕ increases beyond $\phi_b(r)$

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 liberalization 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 liberalized 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 liberalized is smooth. I refer to the knife-edge value of r at which $\Omega'(0)|_{\phi=\phi^S} = 0$ as r_h.

3.4.6.4 Graphical summary of the unharmonized tax case

The major results of Section 3.4 are summarized in Figures 3.10 and 3.11, which demonstrate how the set of stable equilibria changes in response to changes in the two parameters of interest r and ϕ.

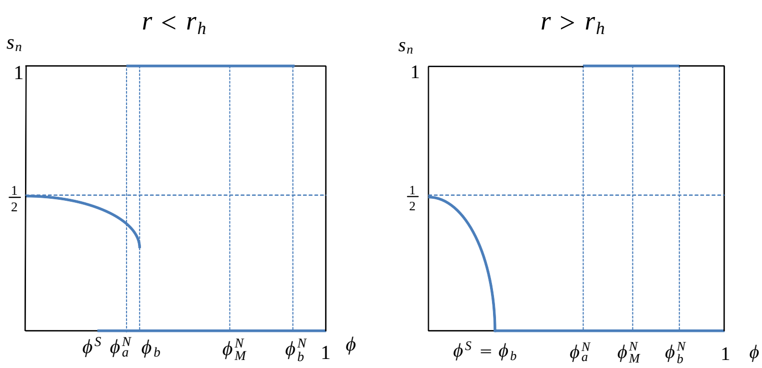

FIGURE 3.10: Asymmetric bifurcation diagram with catastrophic (left) and non-catastrophic (right) delocation

Figure 3.10 illustrates the effect of trade liberalization on the set of stable equilibria. This is the unharmonized tax version of the bifurcation diagram in Figure 3.4. The left hand pane illustrates the case in which there is an interior break point. Trade liberalization 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 3.10 illustrates the nature of the pollution haven hypothesis (PHH) described in Section 3.1 in this model.[76] The model suggests that empirical studies which assume a simple monotonic

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

relationship between firm location and trade costs may be incorrectly specified. In the model both trade liberalization (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.

Two qualifications for Figure 3.10 are in order. First, as established, it is possible that $\phi_a^N > \phi_b(r)$ in the left hand pane.[77] 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 3.11 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 $r = 1$.

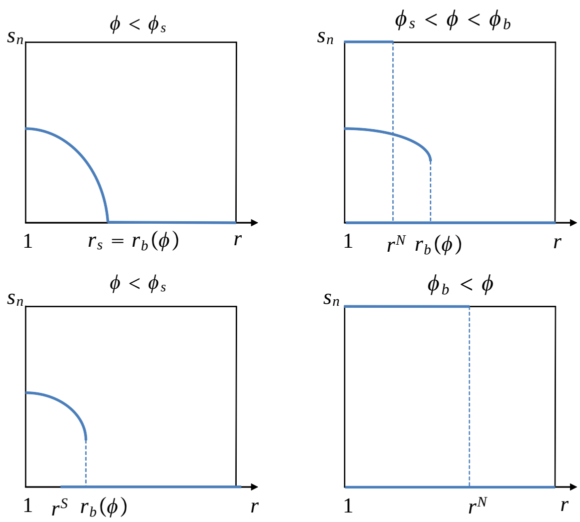

FIGURE 3.11: Stable equilibria as a function of r

The top right pane illustrates the stable equilibria for ϕ greater than ϕ_s but less than the harmonized 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.[78]

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

78 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

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.

3.4.7 Section conclusion

In Section 3.1 I stated the first key question of this chapter: *How does the degree of differentiation of environmental policy influence the extent of firm relocation?*. In Section 3.4 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.

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 chapter.

3.5 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

3.5.1 Introduction

In this section I extend the model of Sections 3.3 and 3.4 and consider the issue of carbon leakage as a consequence of differentiated GHG regulation. The second question introduced in Section 3.1 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 section proceeds as follows. In sub-section 3.5.2 expressions are derived for the level of emissions per firm and per region as a function of model parameters. In sub-section 3.5.3 I consider carbon leakage when taxes are harmonized. This provides a base case with which to compare an unharmonised taxation scenario. In sub-section 3.5.4 unharmonised taxation is considered. In sub-section 3.5.5 the section concludes with a summary of its main results.

3.5.2 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:

$$\Gamma = s_n \gamma x \tag{3.36}$$

$$\Gamma^* = (1 - s_n)\,\gamma x^* \tag{3.37}$$

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 (3.36) and (3.37) makes the two effects more explicit:[79]

$$\begin{aligned}
\Gamma &= s_n b \left[\left(\frac{s_E}{s_n + \phi(1-s_n)\left[\frac{1+t}{1+t^*}\right]^{\sigma-1}} \right) + \phi \left(\frac{1-s_E}{(1-s_n)\left[\frac{1+t}{1+t^*}\right]^{\sigma-1} + s_n\phi} \right) \right] \frac{\sigma-1}{1+t} \\
\Gamma^* &= (1-s_n)\, b \left[\phi \left(\frac{s_E}{s_n\left[\frac{1+t^*}{1+t}\right]^{\sigma-1} + \phi(1-s_n)} \right) + \left(\frac{1-s_E}{(1-s_n) + \phi s_n \left[\frac{1+t^*}{1+t}\right]^{\sigma-1}} \right) \right] \frac{\sigma-1}{1+t^*}
\end{aligned} \tag{3.38}$$

Firm scale effect Firm size equals 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 (3.38)) 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.[80] 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 Section 3.4. 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.

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79 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 3.1) is declining in r for a given level of s_n.

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

Firm relocation effect In Section 3.4 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.

3.5.3 Case 1: Harmonized taxation

As carbon leakage can only occur when taxes are unharmonised, the harmonized tax case provides a maximum efficiency benchmark with which to compare the unharmonised tax case which is considered in sub-section 3.5.4. I denote the global level of emissions as χ, which is simply the sum of Γ and Γ^*. The harmonized tax rate is denoted by $\bar{t}$ in both regions. As $r = 1$ when taxes are harmonized 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 (3.38). 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.[81] Global emissions are thus monotonically decreasing in the harmonized tax rate, $\bar{t}$.

Diversified equilibrium Recall from Section 3.4 that the diversified equilibrium is always symmetric when taxes are harmonized. The global level of emissions is thus determined by setting $s_n = \frac{1}{2}$ in (3.38). This yields, $\Gamma = \Gamma^* = \frac{1}{2}b\frac{\sigma-1}{1+\bar{t}}$ and therefore $\chi = b\frac{\sigma-1}{1+\bar{t}}$.

[81] 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.

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 liberalized, the effect of greater access to the foreign market on firm scale is exactly offset by exposure to greater foreign competition.[82]

Two obvious consequences of this are stated in Proposition 3.8.

Proposition 3.8 *When taxation is harmonized, the diversified and CP equilibria yield identical levels of global emissions and the level of global emissions is independent of trade freeness.*[83]

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 $b\frac{\sigma-1}{\left(1+\bar{t}\right)^2}$.

The relationship between the level of global emissions χ and the parameters ϕ and $\bar{t}$ under harmonized taxation are illustrated in Figure 3.12. 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 harmonized tax rate $\bar{t}$, leaves the location of firms unchanged (this result was established in Section 3.4) and decreases the global level of emissions, χ, monotonically.

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

3.5.4 Case 2: Unharmonised taxation

In this sub-section I consider the global level of emissions when taxes are unharmonised. As demonstrated in Section 3.4, the tax differential, r, and trade freeness ϕ, are both important determinants of the location of firms.

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

83 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.

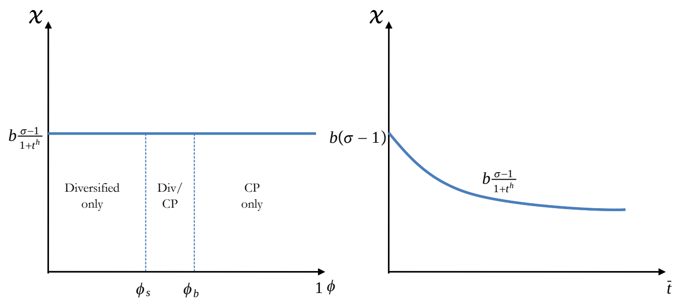

FIGURE 3.12: Global emissions with harmonised taxation

Unlike in Section 3.4 (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.

3.5.4.1 The CP equilibria

In this sub-section I assume that the core is initially in the north in order to ease exposition.[84]

[84] 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.

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 (3.38), the global level of emissions for the CPN and CPS equilibria are:

$$\chi = \Gamma + \Gamma^* = b\frac{\sigma - 1}{1+t} + 0, \text{ for the CPN equilibrium} \tag{3.39}$$

$$\chi = \Gamma + \Gamma^* = 0 + b\frac{(\sigma - 1)}{1+t^*}, \text{ for the CPS equilibrium} \tag{3.40}$$

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

The effect of t on χ Equations (3.39) and (3.40) suggest three useful conclusions.

Conclusion 3.3 *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 3.4 *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 3.5 *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 harmonized 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 $\frac{1+t}{1+t^*}$.[85]

[85] 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.

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 liberalization (such that $\phi > \phi_b^N$) and restriction (such that $\phi < \phi_a^N$) of trade 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 harmonized tax case, trade liberalization can also alter the global level of emissions in ways which may be difficult to reverse.

Figure 3.14 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 liberalization (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 liberalization 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 harmonized 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 3.14 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

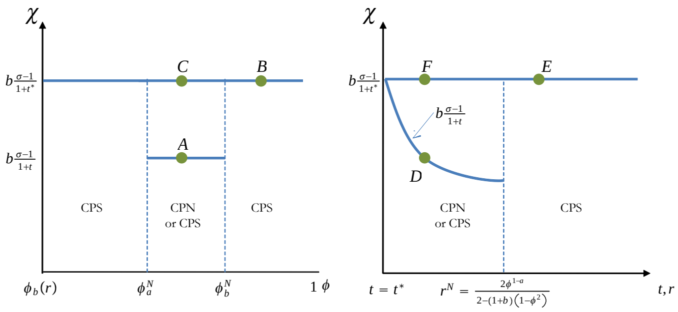

FIGURE 3.13: Global emissions at CP equilibria with unharmonised taxation

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.[86]

3.5.4.2 The diversified equilibrium

As was the case in Section 3.4 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 3.9 and 3.10 reveal this.

Proposition 3.9 *Beginning from the harmonized tax diversified equilibrium (that is, if $t = t^*$ and $s_n = \frac{1}{2}$),* $\frac{\partial \chi}{\partial t} < 0$.

Proof. See Appendix 3.C.1. ■

Proposition 3.9 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 3.10 establishes this result.

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[86] 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 (Reinaud 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.

Proposition 3.10 *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.[87] The result follows. ■

Propositions 3.9 and 3.10 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 3.14 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 harmonized 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 Section 3.4. 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 3.14 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.

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

Proof. See Appendix 3.C.2. ■

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.[88] Therefore, somewhat

[87] This result was established in Section 3.4.

[88] 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

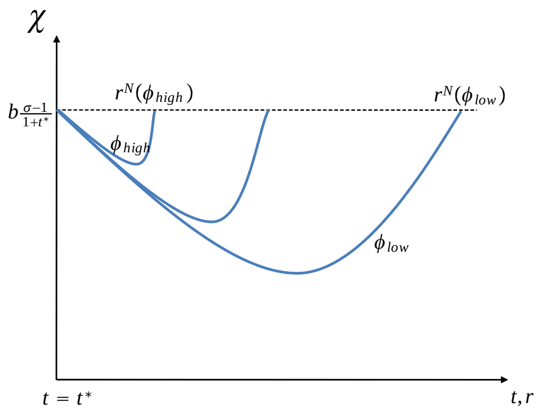

FIGURE 3.14: Global emissions at the diversified equilibrium

counter-intuitively (and in contrast to Conclusion 3.3 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.

3.5.5 Section conclusion

In Section 3.1 I stated the second key question of this chapter: *How does the degree of differentiation of environmental policy influence the extent of carbon leakage?*. In Section 3.5 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 section 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.

variable factor of production. In this chapter the lower carbon tax rate reflects this relative abundance in the south.

3.6 Conclusion

In the introduction to this chapter, 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 Section 3.2 I surveyed the existing economic literature in order to demonstrate the relevance of these two questions and the importance of my proposed approach. In Section 3.3 I introduced and solved an NEG model capable of addressing both questions. In Section 3.4 I considered the former question and in Section 3.5, the latter. Throughout this chapter I have considered a variety of related questions and contributed to the theoretical literature. In concluding this chapter I summarize its main contributions, suggest three avenues for future research and finally draw out the most important policy implications arising from my analysis.

3.6.1 Summary of contributions

3.6.1.1 Contributions to the theory of the PHE: Section 3.4

Section 3.4 set out two main contributions to the theory of the PHE. First, where trade liberalization 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.

3.6.1.2 Contributions to the theory of carbon leakage: Section 3.5

In Section 3.5 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 harmonized 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.

3.6.2 Extensions

3.6.2.1 Border taxation and side payments

I have shown that the harmonization of taxes can minimize 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 chapter therefore raises a further important question: *How can responsibilities be differentiated without differentiating regulations?*

This appears to be a critical question currently at the center 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 chapter. One such policy might be the imposition of border tariffs by more stringently regulated regions on carbon intensive goods produced in less regulated countries.[89] Incor-

[89] Hoel (2001) considers the optimal combination of border pollution taxation and side payments to reduce carbon leakage from differentiated regulation between industrialized and non-industrialized countries. He concludes that a combination of both measures is, in general, optimal.

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

3.6.2.2 Competitive environmental policy

The analysis undertaken in this chapter 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 chapter. However, a positive level of both leakage and deindustrialisation may be desirable for a welfare maximizing government for which an IEA is its only policy instrument. A setting in which competitive governments maximize the welfare of their local unskilled labor force would enable consideration of the trade-off between environmental and economic objectives in a model with agglomeration forces.

3.6.2.3 Computable general equilibrium modelling

Simple models such as that presented in this chapter 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.

3.6.3 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 this chapter, 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.[90]

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 minimize 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 chapter suggests that carbon leakage is a phenomenon which is best evaluated in the long-run. In the model in this chapter, 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.

[90] 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 $\phi \approx \phi_b^N$.

3.A Appendix to Section 3.3

3.A.1 Derivation of nominal skilled wages (equation (3.18))

Combining the expression for firm profit obtained in equation (3.15) with the market clearing condition in equation 3.17 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 $p_{j,S}$).

$$\pi_j = \frac{1}{\sigma}\left[c_{j,N}p_{j,N} + c_{j,S}p_{j,S}\right] \tag{3.41}$$

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

$$c_{j,N} = p_{j,N}^{-\sigma}\left(\frac{\mu E}{P_M^{1-\sigma}}\right) \text{ and } c_{j,S} = p_{j,S}^{-\sigma}\left(\frac{\mu E^*}{P_M^{*1-\sigma}}\right) \tag{3.42}$$

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

$$\pi = \frac{\mu}{\sigma}p_N^{1-\sigma}\left[\left(\frac{E}{P_M^{1-\sigma}}\right) + \phi\left(\frac{E^*}{P_M^{*1-\sigma}}\right)\right] \tag{3.43}$$

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

$$\pi = \frac{\mu}{\sigma}p_N^{1-\sigma}\left[\left(\frac{s_E}{\frac{P_M^{1-\sigma}}{n^w}}\right) + \phi\left(\frac{1-s_E}{\frac{P_M^{*1-\sigma}}{n^w}}\right)\right]\frac{E^w}{n^w} \tag{3.44}$$

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

Expanding the denominators inside the square brackets yields:

$$\pi = \frac{\mu}{\sigma} p_N^{1-\sigma} \left[\left(\frac{s_E}{s_n p_N^{1-\sigma} + \phi \left(1 - s_n\right) p_S^{*1-\sigma}} \right) + \phi \left(\frac{1 - s_E}{\left(1 - s_n\right) p_S^{*1-\sigma} + \phi s_n p_N^{1-\sigma}} \right) \right] \frac{E^w}{n^w} \tag{3.45}$$

Simplification yields:

$$\pi = \frac{\mu}{\sigma} \left(w_L a_M + t\gamma\right)^{1-\sigma} \left[\begin{array}{c} \left(\frac{s_E}{s_n (w_L a_M + t\gamma)^{1-\sigma} + \phi (1-s_n) (w_L a_M + t^* \gamma)^{1-\sigma}} \right) \\ + \phi \left(\frac{1 - s_E}{(1-s_n)(w_L a_M + t^* \gamma)^{1-\sigma} + \phi s_n (w_L a_M + t\gamma)^{1-\sigma}} \right) \end{array} \right] \frac{E^w}{n^w} \tag{3.46}$$

Simplification yields:

$$\pi = \frac{\mu}{\sigma} \left[\left(\frac{s_E}{s_n + \phi \left(1 - s_n\right) \left[\frac{w_L a_M + t^* \gamma}{w_L a_M + t\gamma} \right]^{1-\sigma}} \right) + \phi \left(\frac{1 - s_E}{\left(1 - s_n\right) \left[\frac{w_L a_M + t^* \gamma}{w_L a_M + t\gamma} \right]^{1-\sigma} + \phi s_n} \right) \right] \frac{E^w}{n^w} \tag{3.47}$$

Which can be expressed as:

$$\pi = bB \frac{E^w}{n^w}, \tag{3.48}$$

with:

$$\begin{gathered} b = \tfrac{\mu}{\sigma}, B = \left[\left(\tfrac{s_E}{\theta} \right) + \phi \left(\tfrac{1 - s_E}{\theta^*} \right) \right], \\ \theta \equiv s_n + \phi \left(1 - s_n\right) r, \theta^* = \left(1 - s_n\right) r + \phi s_n, r = \left[\tfrac{w_L a_M + t^* \gamma}{w_L a_M + t\gamma} \right]^{1-\sigma} \end{gathered} \tag{3.49}$$

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

$$\pi^* = brB^* \frac{E^w}{n^w}, \tag{3.50}$$

with:

$$B^* = \left[\phi\left(\frac{s_E}{\theta}\right) + \left(\frac{1-s_E}{\theta^*}\right)\right] \tag{3.51}$$

3.A.2 Derivation of expenditure shares

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

$$s_E = \frac{E}{E^w} \tag{3.52}$$

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

$$s_E = \frac{w_L L + w_H H}{\frac{w_L L^w}{1-b}} \tag{3.53}$$

Substitute in skilled wages w_H:

$$s_E = (1-b)\, S_L + \frac{w_H H\,(1-b)}{w_L L^w}, s_L \equiv \frac{L}{L^w} \tag{3.54}$$

Expand and simplify:

$$s_E = (1-b)\, S_L + bBs_H, s_H \equiv \frac{H}{H^w} \tag{3.55}$$

Substitute in B:

$$s_E = (1-b)\, S_L + b\left[\frac{s_E}{\theta} + \phi\frac{1-s_E}{\theta^*}\right] s_H \tag{3.56}$$

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

$$s_E = \frac{\frac{(1-b)}{2} + b\phi\frac{1}{\theta^*}s_H}{\left[1 - b\left(\frac{1}{\theta} - \phi\frac{1}{\theta^*}\right)s_H\right]} \tag{3.57}$$

3.A.3 Proof of Proposition 3.1.

The north's expenditure share can be expressed as:

$$s_E = \left[\frac{\frac{(1-b)}{2} + b\phi\frac{1}{\theta^*}s_H}{1 - b\frac{1}{\theta}s_H + b\phi\frac{1}{\theta^*}s_H}\right] \tag{3.58}$$

As $s_E \leq 1$ by definition:

$$\frac{(1-b)}{2} + b\phi\frac{1}{\theta^*}s_H \leq 1 - b\frac{1}{\theta}s_H + b\phi\frac{1}{\theta^*}s_H \tag{3.59}$$

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

$$\frac{\partial\left[\frac{(1-b)}{2} + b\phi\frac{1}{\theta^*}s_H\right]}{\partial r} < \frac{\partial\left[1 - b\frac{1}{\theta}s_H + b\phi\frac{1}{\theta^*}s_H\right]}{\partial r} \tag{3.60}$$

The numerator is less than the denominator in equation (3.58) and I showed in equation (3.60) that the numerator declines in r faster than the denominator. The result follows.

3.B Appendix to Section 3.4

3.B.1 Derivation of price index ratio with unharmonised taxation

The true cost of living indices are:

$$\begin{array}{c} P = \left[s_n p_N^{1-\sigma} + \phi \left(1 - s_n\right) p_S^{*1-\sigma} \right]^{\frac{\mu}{1-\sigma}} = \left(s_n p_N^{1-\sigma} + \phi \left(1 - s_n\right) p_S^{*1-\sigma} \right)^a, a = \frac{\mu}{1-\sigma} \\ P^* = \left[\phi s_n p_N^{1-\sigma} + \left(1 - s_n\right) p_S^{*1-\sigma} \right]^{\frac{\mu}{1-\sigma}} = \left(\phi s_n p_N^{1-\sigma} + \left(1 - s_n\right) p_S^{*1-\sigma} \right)^a \end{array} \tag{3.61}$$

The ratio of the true cost of living indices is:

$$\frac{P}{P^*} = \left[\frac{\left(s_n + \phi \left(1 - s_n\right) \left[\frac{p_S^*}{p_N} \right]^{1-\sigma} \right)}{\left(\phi s_n + \left(1 - s_n\right) \left[\frac{p_S^*}{p_N} \right]^{1-\sigma} \right)} \right]^a \tag{3.62}$$

$$= \left[\frac{\left(s_n + \phi \left(1 - s_n\right) r \right)}{\left(\phi s_n + \left(1 - s_n\right) r \right)} \right]^a \tag{3.63}$$

$$= \left[\frac{\theta}{\theta^*} \right]^a \tag{3.64}$$

3.B.2 Derivation of r^N

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

$$\begin{array}{c} f_{CPN}\left(\phi\right) = \phi^a \left[\phi \frac{1+b}{2} + \frac{1-b}{2\phi} \right] - \frac{1}{r} \\ \therefore r = \frac{2\phi^{1-a}}{2-(1+b)(1-\phi^2)} \end{array} \tag{3.65}$$

3.B.3 Derivation of r^S

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

$$\begin{array}{c} f_{CPS}\left(\phi\right) = \phi^a \left[\phi \frac{1+b}{2} + \frac{1-b}{2\phi} \right] - r \\ \therefore r = \frac{2-(1+b)\left(1-\phi^2\right)}{2\phi^{1-a}} \end{array} \tag{3.66}$$

3.B.4 Proof that for a given level of s_n, $\frac{\partial \Omega}{\partial r} < 0$

Expand the log real wage ratio:

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

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:

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

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:

$$\frac{\partial\begin{pmatrix}\log\left(\theta^* s_E + \phi\theta\left(1-s_E\right)\right)\\ -\log\left(\phi\theta^* s_E + \theta\left(1-s_E\right)\right)\\ -\log\left(r\right)\end{pmatrix}}{\partial r} = \begin{array}{c}\frac{1}{(\theta^* s_E+\phi\theta(1-s_E))}\begin{bmatrix}\frac{\partial s_E}{\partial r}\left[\theta^*-\phi\theta\right]\\ +\left[\left(1-s_n\right)-\phi^2\left(1-s_n\right)\right]s_E\\ +\phi^2\left(1-s_n\right)\end{bmatrix}\\ -\frac{1}{(\phi\theta^* s_E+\theta(1-s_E))}\begin{bmatrix}\frac{\partial s_E}{\partial r}\left(\phi\theta^*-\theta\right)\\ +\left(\phi\left(1-s_n\right)-\phi\left(1-s_n\right)\right)s_E\\ +\phi\left(1-s_n\right)\end{bmatrix}\\ -\frac{1}{r}\end{array} \tag{3.67}$$

$$= \begin{array}{c}\frac{1}{(\theta^* s_E+\phi\theta(1-s_E))}\left[\frac{\partial s_E}{\partial r}\left[\theta^*-\phi\theta\right]+\left[\left(1-s_n\right)-\phi^2\left(1-s_n\right)\right]s_E+\phi^2\left(1-s_n\right)\right]\\ -\frac{1}{(\phi\theta^* s_E+\theta(1-s_E))}\left[\frac{\partial s_E}{\partial r}\left(\phi\theta^*-\theta\right)+\phi\left(1-s_n\right)\right]-\frac{1}{r}\end{array} \tag{3.68}$$

$$= \begin{array}{c} \frac{\partial s_E}{\partial r} \overbrace{\left[\frac{[\theta^* - \phi\theta]}{(\theta^* s_E + \phi\theta(1-s_E))} - \frac{(\phi\theta^* - \theta)}{(\phi\theta^* s_E + \theta(1-s_E))}\right]}^{\text{1st term}} + \overbrace{\left[\frac{(1-s_n)\left(1-\phi^2\right)s_E}{(\theta^* s_E + \phi\theta(1-s_E))} - \frac{1}{r}\right]}^{\text{2nd term}} \\ +\phi\left(1-s_n\right)\underbrace{\left[\frac{\phi}{(\theta^* s_E + \phi\theta(1-s_E))} - \frac{1}{(\phi\theta^* s_E + \theta(1-s_E))}\right]}_{\text{3rd term}} \end{array} \tag{3.69}$$

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:[91]

$$\begin{array}{c} [\theta^* - \phi\theta] = \left[r\left(1-s_n\right) + \phi s_n - \phi s_n - \phi^2 r\left(1-s_n\right)\right] = r\left(1-s_n\right)\left[1-\phi^2\right] \geq 0, \\ (\phi\theta^* - \theta) = \left[\phi r\left(1-s_n\right) + \phi^2 s_n - s_n - \phi r\left(1-s_n\right)\right] = s_n\left[\phi^2 - 1\right] \leq 0, \\ \frac{\partial s_E}{\partial r} \leq 0 \text{ for } s_n \text{ fixed} \end{array} \tag{3.70}$$

It follows that:

$$\frac{\partial s_E}{\partial r}\left[\frac{[\theta^* - \phi\theta]}{(\theta^* s_E + \phi\theta\left(1-s_E\right))} - \frac{(\phi\theta^* - \theta)}{(\phi\theta^* s_E + \theta\left(1-s_E\right))}\right] \leq 0 \tag{3.71}$$

To establish that the second term is less than or equal to zero I note that:[92]

$$\frac{\left(1-s_n\right)\left(1-\phi^2\right)s_E}{(\theta^* s_E + \phi\theta\left(1-s_E\right))} - \frac{1}{r} = \frac{\frac{1}{r}\left(1-\phi^2\right)}{1-\phi^2\left(1-\frac{1}{s_E}\right) + \frac{s_n}{(1-s_n)}\frac{\phi}{s_E}\frac{1}{r}} - \frac{1}{r} \leq 0 \tag{3.72}$$

The numerator of the left hand term is less than or equal to $\frac{1}{r}$.[93] The denominator of the left hand term is greater than one.[94] The result follows.

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91 The third property is proven in Proposition 3.1.
92 Manipulations are excluded but can be provided upon request.
93 As $\left(1-\phi^2\right) \leq 1$.
94 As $\left(1-\frac{1}{s_E}\right) \leq 0$.

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:

$$\phi\left(1-s_n\right)\left[\begin{array}{c}\frac{\phi}{\left(\theta^* s_E+\phi\theta(1-s_E)\right)} \\ -\frac{1}{\left(\phi\theta^* s_E+\theta(1-s_E)\right)}\end{array}\right]=\phi\left(1-s_n\right)\left[\begin{array}{c}\frac{1}{\left(\frac{\theta^* s_E}{\phi}+\theta(1-s_E)\right)} \\ -\frac{1}{\left(\phi\theta^* s_E+\theta(1-s_E)\right)}\end{array}\right] \quad (3.73)$$

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 $\frac{1}{\left(\phi\theta^* s_E+\theta(1-s_E)\right)}$. 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.

3.B.5 Conditions for catastrophic relocation for the diversified equilibrium

Refer to Figure 3.15 for an illustration of conditions under which relocation of firms will be catastrophic and non-catastrophic as r increases above r_b.

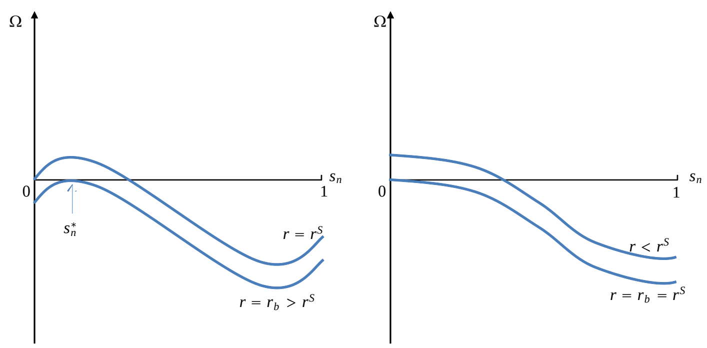

FIGURE 3.15: Wiggle diagram with catastrophic (left) and non-catastrophic (right) delocation

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).[95] 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 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 $r_b = r^S$.

3.C Appendix to Section 3.5

3.C.1 Proving $\left.\frac{\partial \chi}{\partial t}\right|_{t=t^*=0} < 0$

Global emissions can be expressed as:

$$\chi = b(\sigma-1)\left[s_E\left[\frac{1}{1+t}+\phi q\frac{1}{1+t^*}\right]\frac{1}{(1+\phi q)}+(1-s_E)\left[\phi\frac{1}{1+t}+q\frac{1}{(1+t^*)}\right]\frac{1}{(q+\phi)}\right],\ \frac{1-s_n}{s_n}r = q \tag{3.74}$$

Taking the derivative yields:

95 Recall that r is equal to r^S and the CPS equilibrium is only marginally stable when $\Omega(0)$ is equal to 0.

$$\frac{\partial \chi}{\partial t} = b(\sigma - 1) \left[\begin{array}{c} \frac{\partial s_E}{\partial t} \left[\frac{1}{1+t} + \phi q \frac{1}{1+t^*} \right] \frac{1}{(1+\phi q)} + s_E \left[\frac{\partial q}{\partial t} \frac{\phi}{1+t^*} - \frac{1}{(1+t)^2} \right] \frac{1}{1+\phi q} \\ - \frac{\phi \frac{\partial q}{\partial t}}{(1+\phi q)^2} s_E \left[\frac{1}{1+t} + \phi q \frac{1}{1+t^*} \right] + \frac{\partial (1-s_E)}{\partial t} \left[\left[\phi \frac{1}{1+t} + q \frac{1}{(1+t^*)} \right] \frac{1}{(q+\phi)} \right] \\ + (1-s_E) \left[\frac{\partial q}{\partial t} \frac{1}{1+t^*} - \frac{\phi}{(1+t)^2} \right] \frac{1}{(q+\phi)} - (1-s_E) \left[\phi \frac{1}{1+t} + q \frac{1}{(1+t^*)} \right] \frac{\frac{\partial q}{\partial t}}{(q+\phi)^2} \end{array} \right] \tag{3.75}$$

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

$$\frac{\partial \chi}{\partial t} = b(\sigma - 1) \left[\frac{\partial s_E}{\partial t} + \frac{1}{2} \left[\frac{\partial q}{\partial t} \phi - 1 \right] \frac{1}{1+\phi} - \frac{\phi \frac{\partial q}{\partial t}}{(1+\phi)} \frac{1}{2} + \frac{\partial (1-s_E)}{\partial t} + \frac{1}{2} \left[\frac{\partial q}{\partial t} - \phi \right] \frac{1}{(1+\phi)} - \frac{1}{2} \frac{\frac{\partial q}{\partial t}}{(1+\phi)} \right] \tag{3.76}$$

Cancelling terms yields:

$$\frac{\partial \chi}{\partial t} = -\frac{1}{2} b(\sigma - 1) < 0 \tag{3.77}$$

3.C.2 Proof higher taxing region has larger firms in a diversified equilibrium

Recall expressions for the real wages in each region:

$$\begin{array}{c} \omega = \eta \frac{w_H}{P}, P \equiv P_M^{\mu}, P_M \equiv \left(\int_0^{n^w} p_i^{1-\sigma} di \right)^{\frac{1}{1-\sigma}} = p_N \left[s_n + (1-s_n) \phi r \right]^{\frac{1}{1-\sigma}} \\ \omega^* = \eta \frac{w_H^*}{P^*}, P^* \equiv P_M^{*\mu}, P_M^* \equiv \left(\int_0^{n^w} p_i^{*1-\sigma} di \right)^{\frac{1}{1-\sigma}} = p_N \left[\phi s_n + (1-s_n) r \right]^{\frac{1}{1-\sigma}} \end{array} \tag{3.78}$$

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

$$P_M - P_M^* = p_n \left[[1-\phi] \left[s_n - [1-s_n] r \right] \right]^{\frac{1}{1-\sigma}} \tag{3.79}$$

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:

$$x = w_H \frac{(\sigma - 1)}{1 + t} \tag{3.80}$$

Therefore:

$$\frac{x}{x^*} = \left[r^{\mu} \frac{[s_n \phi + r [1 - s_n]]}{[s_n + r\phi [1 - s_n]]} \right]^{\frac{\mu}{\sigma - 1}} \tag{3.81}$$

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

$$r [1 - s_n] > s_n \tag{3.82}$$

Alternatively, this can be expressed as:

$$r [1 - s_n] = s_n + \Delta \tag{3.83}$$

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

$$s_n \phi + s_n + \Delta \tag{3.84}$$

The denominator in the fraction inside the square brackets is:

$$s_n + \phi\left[s_n + \Delta\right] = \phi s_n + s_n + \phi\Delta \tag{3.85}$$

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

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