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International spillovers and carbon pricing Policies

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Abstract Globally coordinated climate action has resulted in sub-optimal emissions reductions and unilateral (second-best) climate policies have so far provided the bulk of emissions reductions. This paper argues that the development of new unilateral carbon pricing policies was fostered by international signalling and technological spillover effects. The strength of both effects hinges, for each jurisdiction, on trade relations with other CO2-abating jurisdictions. We provide a stylised theoretical discussion in support of our proposition and investigate it using data on a panel of 121national jurisdictions over the period 1990-2014. Results show a strong positive association between import-weighted exposure to CO2-pricing partners and domestic environmental policy. The analysis also supports the technological spillover channel: trade-weighted installed capacity of wind and solar energy seems to prompt implementation of and more stringent carbon pricing policies.

Keywords international spillovers, trade, carbon pricing

JEL Classification F18, Q56, Q58

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International spillovers and carbon pricing policies

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Abstract

Globally coordinated climate action has resulted in sub-optimal emissions reductions and unilateral (second-best) climate policies have so far provided the bulk of it. This paper proposes that the adoption of new (unilateral) climate policies – including carbon pricing – was fostered by a process of policy diffusion, supported by: (i) abatement technology development and deployment (i.e. demonstration); (ii) adoption of similar policies by foreign jurisdictions. We provide a theoretical framework for this proposition and investigate it empirically using data on a panel of 109 national jurisdictions over the period 1990-2014. The evidence suggests that technology demonstration and learning from past policy experience positively affect (domestic) policy developments; the impact of abatement technology development and diffusion on policy adoption could not, however, be confirmed.

Keywords: carbon pricing, climate policy, policy diffusion, technology diffusion

JEL Classification: F18, Q56, Q58

1 Introduction

Limiting the increase in Global Mean Temperature to 2°C above pre-industrial levels will require drastic reductions in greenhouse gas (GHG) emissions. Since CO_2 is a *global* pollutant, any environmentally effective solution requires a reduction in 'world' emissions. However, no World Government capable of enforcing worldwide reductions in GHG emissions exists. Instead, a multitude of sovereign states interact within the Westphalian system of International Relations and its founding principles (self-determination, legal equality of States and no third-party interference in internal affairs) make cooperation

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the only available option to efficiently address global public good problems like Climate Change (Barrett, 2003). It is precisely these principles – and their implications – that shaped the United Nations Framework Convention on Climate Change, formally established in 1992. In line with these developments and following Carraro and Siniscalco (1993), a substantial body of research has explored the conditions for *climate coalition* formation. However, notwithstanding mechanisms to improve the stability of such coalitions (Nordhaus, 2015) and as predicted by standard game theoretical discussions of environmental agreement negotiation (Barrett, 1994), this *top-down* cooperative approach failed to deliver emissions reductions consistent with stated objectives of Global Mean Temperature increase.[1] At best, jurisdictions implement their Nash equilibrium strategy and commit to (very) low, globally sub-optimal, levels of emissions reductions.[2] The relative failure of the multilateral process and the urgency of the climate problem justify renewed efforts to understand motivations for (and implications of) unilateral, second-best, GHG-abating policies.

In that respect, there are strong reasons to believe that climate policy developments are interdependent. For example, the evidence accumulated since the implementation of the first carbon pricing scheme in Finland in 1990 suggests that the adoption of such schemes is highly clustered both temporally – according to World Bank (2018), 5 carbon pricing schemes were introduced between 1990 and 1992, 12 (including the EU-ETS) were introduced over the period 2005-2011 and 26 were introduced between 2012 and 2018 – and spatially – see Figure 1. Following Simmons and Elkins (2004), we hypothesise that this clustering is due to processes of policy diffusion, which are related to two main mechanisms. First, an alteration of the net payoffs of domestic climate policy, which takes place through (a) a technology channel – abatement technology development, and subsequent

[1]Compared with the emission levels under least-cost 2°C scenarios, aggregate GHG emission levels resulting from the implementation of the Intended Nationally Determined Contributions are expected to be higher by 8.7 (4.5 to 13.3) Gt CO_2 eq (19 per cent, range 9-30 per cent) in 2025 and by 15.2 (10.1 to 21.1) Gt CO_2 eq (36 per cent, range 24-60 per cent) in 2030 (United Nations/Framework Convention on Climate Change, 2016).

[2]Incentives for unilateral provision of global environmental quality beyond the Nash equilibrium outcome have so far proven relatively weak. These can be broadly grouped into altruistic (e.g. self-enforcing collective identity (Olson, 1965), rule utilitarianism (Harsanyi, 1977), different domestic preferences, or genuine care for the global environment) and self-interested (e.g. strategic innovation,...).

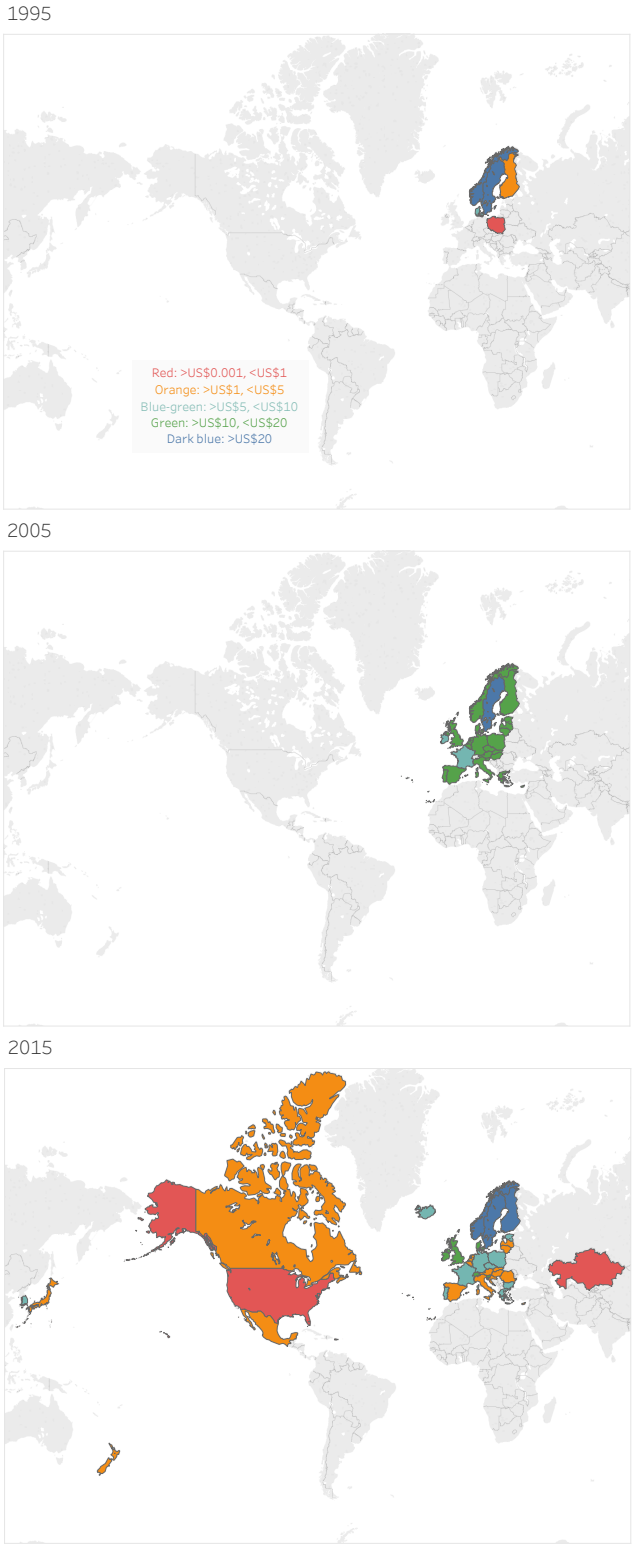
diffusion, by foreign jurisdictions reduces the cost of emissions reduction (see, e.g., Heal (1993)); and (b) a policy (adoption) channel – which alters the international competitiveness cost of more stringent domestic environmental policy.[3] Second, an update on the information about the benefits (or costs) of policy adoption derived from the adoption of a similar policy or the deployment of abatement technology in foreign jurisdictions. This information could be communicated through different cultural or institutional channels (common institutional membership EU, OECD,...). In addition, we hypothesise that the strength of these mechanisms depends on the nature and intensity of the relationship between bilateral partners (or, in other words, "distance").

This paper therefore relates the adoption of new climate change mitigation – including carbon pricing – policies to the (pre-)existence of technology and information diffusion networks. This, we believe, is of pivotal importance if we are to understand the emergence of new "unilateral" climate policy initiatives within informal yet interdependent groups of jurisdictions. Importantly, we note that the mechanisms of (climate) policy diffusion are not necessarily clear *a priori* but that the paper grounds the above hypotheses in a sound theoretical framework, thereby providing a robust guide for our empirical investigation. These hypotheses are then tested on a comprehensive dataset containing information on climate and carbon pricing policy developments over 25 years.

The remaining of this paper is organised as follows. Section 2 reviews the relevant strands of literature. Section 3 introduces a formal framework to support our empirical discussion; section 4 builds on it to introduce the hypotheses. Section 5 presents the data and the modelling strategy and section 6 presents the results. Finally, section 7 concludes.

[3]For example, the international competitiveness disadvantage created by more stringent carbon pricing policy is alleviated when all members of a 'closed' trading club implement it. Such a club could be closed *de facto* – in case a group of countries trade mostly among themselves – or *de jure* – in case a group of countries implements external CO_2 adjustment tariffs (see, e.g., Nordhaus (2015)).

Figure 1: Adoption of carbon pricing policies in national jurisdictions: 1990-2015



Note: a light grey shade indicates the absence of any carbon pricing scheme; The figure for Canada and US is the country-wide average price resulting from carbon pricing schemes implemented at the Provincial or State level

2 Related literature

The design of climate change mitigation strategies usually starts with the following question: *what (optimal) policy ought to be implemented?* Answers to that question vary mainly depending on: (i) assumptions made about the techno-economic context, in particular the state (and cost) of abatement technology; (ii) ethical judgements, especially those implicitly present in the choice of the discount rate (Beckerman and Hepburn, 2007). This is why a significant part of the negotiations of Climate Change Mitigation Agreements pertain to such technologies and their institutionalised transfer between (groups of) jurisdictions (e.g. UNFCCC, Article 4.5). It is also why a substantial body of work seeks to shed light on channels of (abatement) technology diffusion.[4] This literature has mainly focused on how bilateral transfers foster technology diffusion across jurisdictions and has noted three main market channels: (i) international trade in intermediate goods (e.g., export and import of equipment) – Grossman and Helpman (1991) have previously argued that knowledge varies according to the number of contacts between domestic and foreign agents and that these contacts are directly proportional to trade flows; (ii) foreign direct investments – for example, multinational corporations can bring home country clean production techniques to host countries; (iii) licensing.

Determining what policy to implement and on what technology a jurisdiction can rely to abate its emissions remain crucial questions; but these studies usually assume away the political hurdles that can stand in the way of policy implementation and therefore offer little insights regarding the probability of their adoption. Political economy studies of the development of environmental – and other – policies offer such insights but usually focus on domestic conditions in their attempt to rationalise policy developments. Yet, given the global nature of the GHG externality and the multi-dimensional interdependence of jurisdictions, it is unlikely that domestic factors alone will drive these developments.

The literature on policy diffusion offers an interesting route to rationalise the latest

[4]The focus of this paper is on the role played by bilateral relationships and, in that respect, differs from approaches adopted, for example, by Vega and Mandel (2018). Their approach "accounts for the impact of each country not only on its direct connections, but also on the global diffusion process" (p.462).

carbon pricing and climate policy developments. This literature emphasises the importance of foreign (policy) developments for domestic policy making, mainly through changes in the net payoffs or updated informational signal that policy adoption implies (see Fankhauser et al. (2016) and references therein). For example, governments often lack sufficient understanding of the consequences of a particular policy innovation (Simmons and Elkins, 2004), in which case *inaction* may simply reflect a lack of accurate information. Abatement policy development by better informed jurisdictions may serve as a signal about the (low) cost of the said policy, prompting a jurisdiction to "mimick" its (close) neighbour.

However, two important points must be noted. First, this literature usually focuses mainly on the altered payoff or informational signal following from the adoption of the same policy in partner jurisdictions, disregarding other equally important foreign developments which may affect policy adoption in the domestic jurisdiction. Second, such an approach departs from the standard economic analysis of environmental policy making in an international (trade) context, which usually addresses questions such as *how do environmental regulations affect trade flows?* and proposes answers based on considerations of relative input factor endowments, relative international prices, ... (see, e.g. Antweiler et al. (2001)).[5] Our study does not discount the important insights provided by this literature. In fact, the policy diffusion framework that we suggest accounts both for factors that standard economic analysis deems relevant to the shaping of domestic climate policy – such as international competitiveness and the availability of abatement technology – as well as factors usually put forward by the literature on policy diffusion – such as policy learning. The theoretical framework used to support our argument is presented in the next section.

[5]This latter literature formulates two main hypotheses. The *pollution haven hypothesis* which states that, insofar as environmental regulation raises the cost of manufacturing goods, pollution-intensive economic activity will relocate to jurisdictions with lower environmental standards, and the *factor endowment hypothesis*, which claims that standard forces such as factor endowments and technology determine the pattern of trade, not (only) environmental policy (Copeland and Taylor, 2003). Several empirical studies have provided evidence in support of the second hypothesis and, de facto, cast serious doubt on the first (Tobey, 1990; Grossman and Krueger, 1993; Jaffe et al., 1995).

3 Theoretical framework

To support our empirical investigation we provide a stylised multi-country general equilibrium model of international trade ($n > 2$) with transboundary pollution adapted from Copeland and Taylor (2003). The two main adjustments are: 1. an explicit recognition of the role played by (improvements in) abatement technology in the determination of domestic climate policy, and 2. a reinterpretation of the regulatory threshold as depending on expectations about the (economic and/or political) cost of policy intervention. The model is static, productive factors are in inelastic supply and environmental quality is a global public good. Jurisdictions are indexed by $i = 1, 2, \ldots, n$. Assume that n is large and that all countries have the same *relative* size so that each country cannot, individually, influence its terms of trade (Grossman and Helpman, 1991). Factor endowments vary across countries and determine trade patterns.

3.1 Technology

We distinguish between primary factors of production and consumption goods (Dixit and Norman, 1980). Our analysis will be conducted within a two factors $\mathbf{r} = (r_1 = K, r_2 = L)$ - two goods $\mathbf{t} = (t_1 = x, t_2 = y)$ model of international trade. Primary factors are non tradable while goods are. Labour is mobile across sectors but not across countries. We assume constant returns to scale technology (CRS) for both goods. That is, the set of technologically feasible (r, t), T, is convex. The production of good x generates pollution as a by-product while the production of good y doesn't.[6] The production function of y is:

$$y = F(K_y, L_y) \tag{1}$$

where F is increasing, concave, and linearly homogeneous.

In industry x, firms produce potential output $B(K_x, L_x)$ and can choose to redirect a fraction $\phi \in [0, 1]$ of inputs to the abatement process, which will, in turn, reduce output

[6]This is without loss of generality and it can easily be extended to a context with $m > 2$ goods exhibiting different emissions intensities. See Levinson and Taylor (2008) for a partial equilibrium example and Copeland and Taylor (1994) for a General Equilibrium discussion.

of good x. In other words, the net production of x is the difference between potential production and production foregone due to the use of resources in abatement activity, $(\phi K_x, \phi L_x)$. As a result, emission intensity in that sector is a choice variable. The joint production of x and e is given by

$$\begin{aligned} x &= B(K_x, L_x) - B(\phi K_x, \phi L_x) \\ &= (1-\phi)B(K_x, L_x) \qquad (2) \\ e &= \chi(\phi)\Omega B(K_x, L_x) \qquad (3) \end{aligned}$$

where the second line of equation (2) follows from the CRS assumption. $0 < \Omega \leq 1$ is the unabated level of pollution attached to each unit of the dirty good and can be interpreted as a technological parameter for the abatement activity.[7] A decrease in Ω then denotes an improvement in the abatement technology (Brock and Taylor, 2010) and, for given levels of production and abatement, a decrease in emissions. $\chi(\phi)$ is the abatement function, with more abatement efforts leading to less emissions, i.e. $\frac{d\chi}{d\phi} < 0$, and $\chi(0) = 1; \chi(1) = 0$.[8] In the absence of abatement $(\phi = 0, \chi(\phi) = 1)$, each unit of good x produces Ω units of pollution; conversely, if all resources are devoted to abatement $(\phi = 1,\ \chi(\phi) = 0)$, no production (nor pollution) takes place.

To simplify the analysis, we follow Copeland and Taylor (2003, 2004) and treat pollution as an input to the production process of good x. From (3), we note that $\phi = \chi^{-1}[e/(\Omega B(K_x, L_x))]$. It is then easy to see that

$$\begin{aligned} x &= (1-\phi)B(K_x, L_x) \\ &= \left(1 - \chi^{-1}\left[\frac{e}{\Omega B(K_x, L_x)}\right]\right) B(K_x, L_x) \qquad (4) \end{aligned}$$

[7]Restricting Ω to values below or equal to 1 ensures that emission intensity is below or equal to 1 and avoids unnecessary complexities in the firm's profit maximisation problem. In Copeland and Taylor (2003), Ω is constant and, by choice of units, set equal to 1.

[8]Adopting this specification is equivalent to assuming an explicit pollution abatement function. To see this, define the abatement technology as $A(e^P, v^A)$ where e^P is the potential amount of pollution produced and v^A is the (absolute) amount of resources allocated to abatement. $A(.)$ is a CRS activity. Then, $e = e^P - A(e^P, v^A) \Leftrightarrow e = e^P(1 - A(1, v^A/e^P))$. Now, recall that without abatement activity, $e^P = x = \Omega(\psi)B(.)$ and that $v^A/B(.) = \phi$. Hence $e = \Omega B(.)(1 - A(1, \phi))$ where we have defined $(1 - A(1, \phi))$ as $\chi(\phi)$.

with $\partial\chi^{-1}(.)/\partial e < 0, \partial\chi^{-1}(.)/\partial B(.) > 0$.[9] Imposing some more structure on $\chi(\phi)$ and defining $\chi(\phi) = (1-\phi)^{1/\alpha}$ we can rewrite (4) as

$$x = \left(\frac{e}{\Omega}\right)^{\alpha} B(K_x, L_x)^{1-\alpha} \tag{5}$$

where e/Ω is the *effective emissions* input, i.e. emissions per emissions required for a unit of output. Based on equation (5), three observations can be made. First, as emissions per unit of potential output (Ω) decrease, net output increases. That is, for a given e, as the abatement technology improves, the production of the dirty good expands. This is because improvements in abatement technology free up resources that were previously devoted to abatement and makes them available for actual production – see equation (2). Second, as abatement technology improves, the emissions intensity of the economy decreases. This observation uses a standard implication of Cobb-Douglas production functions, i.e. that the share of payments in total value added to a factor of production is equal to the associated output elasticity parameter. That is

$$\frac{\delta\frac{e}{\Omega}}{px} = \alpha \Leftrightarrow i \equiv \frac{e}{x} = \frac{\alpha\Omega p}{\delta} \tag{6}$$

where δ is the price of emissions and p is the relative price of good x (see section 3.2). Furthermore, equation (6) indicates that CO_2-intensity also depends on both policy (δ) and technology (Ω) – appendix B discusses that relationship further. The third observation is summarised in the following proposition.

Proposition 1. *The effect on the net output of x of a change in pollution emissions decreases in Ω. That is $\left|\frac{\partial x}{\partial e}\Big|_{\Omega^{Low}}\right| > \left|\frac{\partial x}{\partial e}\Big|_{\Omega^{High}}\right|$.*

Proof. The cost of tightening pollution policy in sector x is driven by the diversion of

[9] Define $C \equiv e/B(K_x, L_x)$. By the inverse function theorem, we know that $\chi^{-1}(.)$ satisfies $\partial\chi^{-1}(.)/\partial C < 0$. By definition of C, we have $\partial C/\partial e > 0$ and $\partial C/\partial B(.) < 0$. Hence we must have $\partial\chi^{-1}(.)/\partial e < 0, \partial\chi^{-1}(.)/\partial B(.) > 0$. This leads to the following observations: first, an increase in emissions allowance raises total output of good x; second, an increase in potential output $B(.)$ affects total output via a production channel and an abatement channel. The first one straightforwardly tends to raise production, higher potential production leads to higher actual production. The second tends to lower actual production and is more indirect: $\chi(\phi)$ gives the abatement efforts as a function of the ratio of unabated to total potential emissions. Hence when potential production (and emissions) increases, that ratio decreases, for a given level of actual emissions. This requires an increase in abatement efforts which, in turn depresses actual output. Whether one or the other effect dominates is eventually an empirical question but it seems plausible to assume that the former outweighs the latter.

resources from actual production to abatement activities. From (5) it is easy to see how net output changes as a result of a change in allowed emissions:

$$\frac{\partial x}{\partial e} = \alpha \frac{e^{\alpha-1}}{\Omega^{\alpha}} B(K_x, L_x)^{1-\alpha} > 0 \tag{7}$$

which increases as Ω decreases. □

Although proposition 1 might appear counter-intuitive, it reflects the increased opportunity cost of reducing emissions when the economy is already very efficient at abating.

3.2 Production decision and pollution demand

Equipped with these technological priors, we can now look at the production decisions of firms.[10] Good y is the numeraire with price p_y normalised to 1. We denote the relative price of good x in terms of good y as p. The optimal output vector $\mathbf{t} = (x, y)$ will depend on primary input endowments, $\mathbf{r} = (K, L)$, output prices, $\mathbf{p} = (p, 1)$ and, for pollution emitting sector(s), emissions e. That is, the firms' problem is

$$\max_{\mathbf{t}} \{\mathbf{p}.\mathbf{t} \mid (t, r) feasible\}$$

Since input factors (K,L) are supplied inelastically, the firms' decision determines the relative allocation of inputs to each sector. In the dirty good sector, the firm faces the additional decision of how much of these resources to devote to abatement. The solution to this problem defines the optimum (technologically feasible) vector of output

$$\hat{\mathbf{t}} \equiv t(\mathbf{p}, \mathbf{r}) \tag{8}$$

Consequently, the (maximum) revenue function can be defined as

$$g\left(p, K, L, \frac{e}{\Omega}\right) = \mathbf{p}.t(\mathbf{p}, \mathbf{r}) \tag{9}$$

The revenue function is convex in $\mathbf{p}$, $\bigtriangledown_{pp} g(\mathbf{p}, \mathbf{r}, e) > 0$, but concave in $\mathbf{r}$, $\bigtriangledown_{rr} g(\mathbf{p}, \mathbf{r}, e) < 0$.[11] In addition, it is increasing and concave in e ($\partial g(\mathbf{p}, \mathbf{r}, e)/\partial e > 0$, $\partial g(\mathbf{p}, \mathbf{r}, e)/\partial^2 e < 0$)

[10] The detailed production decision problem of firms in sectors x and y is presented in appendix A.
[11] For an informal justification of this statement, see Dixit and Norman (1980), p.31.

but decreasing and concave in Ω ($\partial g(\mathbf{p}, \mathbf{r}, e)/\partial\Omega < 0$, $\partial g(\mathbf{p}, \mathbf{r}, e)/\partial^2\Omega < 0$).[12] That is, as the abatement technology deteriorates, revenue falls at an increasing rate.

If we further assume that profit-maximising firms maximise national income, this revenue function can be interpreted as the *national income function*, $G(p, \delta, K, L, \frac{e}{\Omega})$ (Copeland and Taylor, 1994, 1995). Hence we write

$$I \equiv G\left(p, K, L, \frac{e}{\Omega}\right) = \max_{x,y}\left\{\mathbf{p}\cdot\mathbf{t} : \mathbf{t} \in T(K, L, \frac{e}{\Omega})\right\} \tag{10}$$

The national income function preserves all the properties of the revenue function. It is useful to note the relationship between the national income function and the price of emissions. For given prices and factor endowments, we can define the value of a pollution permit as the marginal effect on national income of additional pollution:

$$\delta \equiv \frac{\partial G(\mathbf{p}, \mathbf{r})}{\partial e} \tag{11}$$

δ is the opportunity cost of emissions or, put differently, the cost (in terms of lost national income) of reducing emissions by one – infinitely small – unit; equation (11) gives the demand schedule of firms for pollution which, since $G(.)$ is concave in e, is decreasing.

Proposition 2. *For a given scale of the dirty good sector, an improvement in the abatement technology reduces pollution demand. That is,* $\frac{\partial G(\mathbf{p},\mathbf{r})}{\partial e \partial \Omega} > 0$

Proof. First, note from equation (6) that the demand for pollution can be expressed as the emissions intensity times the production of good x, i.e. $e = i(p, \delta, \Omega) \times x(p, \delta, K, L)$. Now, using equation (6) again, it is easy to note that an improvement in abatement technology (i.e. a decrease in Ω) leads to a decrease in emissions intensity – a *technique* effect. Hence, for a given level of production in the x sector, an improvement in abatement technology decreases demand for pollution. □

[12] From (5) we know that for a given level of emissions, e, and capital & labour, $K\&L$, firms in the dirty sector can expand production when Ω decreases. In appendix A, we show that this expansion in potential output leads to an increase in net output through a reallocation of resources from the clean to the dirty sector. Moreover, the technological improvement will reduce pollution demand and depress equilibrium price of emissions which, in turn, will reduce resources allocated to abatement. Both effects work toward an increase of the net output in the dirty sector.

3.3 Consumers

Let us assume the existence of N identical consumers in each country. Consumers derive utility from the consumption of both goods and incur disutility – i.e. damage (D) – from global pollution E. The utility function is strongly separable with respect to consumption goods and environmental quality. Each consumer of jurisdiction i has the following utility[13]

$$U^i \equiv U^i(x, y, E) = u^i(x, y) - D(E) \tag{13}$$

where $E = \sum_i e_i$ and e_i denotes the emissions of jurisdiction i. $u^i_x(x, y)$, $u^i_y(x, y) \geq 0$, $u^i_{xx}(x, y), u^i_{yy}(x, y) < 0$ and $D'(E) > 0, D''(E) > 0$. Note, in addition, that $u^i(x, y)$ is homothetic.[14] Consumers maximise utility given goods prices – which determine the revenue function specified by (9) – and (global) pollution levels. Using duality, we can write consumer i's indirect utility function, which gives the maximum utility attainable for given prices and income, as:

$$V^i \equiv V(\mathbf{p}, I, E) = v(\mathbf{p}, I) - D(E) \tag{14}$$

Consumers earn their revenue from their ownership of factors of production, capital and labour, which are remunerated at the equilibrium market rate. In a perfectly competitive economy, the total value of payments to all factors of production is equal to the maximum value of production. It will thus depend on the composition of the economic production, the price at which said production is sold and environmental policy. Eventually, using the homotheticity assumption, function $v(.)$ can be written as a function of real income

[13]Note that equation (13) assumes that the consumer does not derive any utility from global environmental quality. One could take this form of altruism into account by attributing a strictly positive weight to the damage that domestic emissions impose on other jurisdictions. That is, e.g.,

$$U^i \equiv U^i(x, y, E) = u^i(x, y) - [\alpha D_1(E)] + \beta D_2(E)] \tag{12}$$

where $\beta = 1 - \alpha < 1$ and D_1 and D_2 denote domestic and foreign (or world) environmental damage, respectively. Care for the global environment will reduce equilibrium emissions level.

[14]With homotheticity, the analysis is simplified in two ways. First, the indirect utility function can be written as an increasing function of real income. Second, it ensures that relative consumption patterns do not change with income which, in turn, makes trade patterns dependent on factor endowments and relative costs only (Copeland and Taylor, 2003).

– $I/\omega(\mathbf{p})$, where $\omega(\mathbf{p})$ is a price index.

$$V^i(\mathbf{p}, I, E) = v(\mathbf{p}, I) - D(E) = v(1, I/\omega(\mathbf{p})) - D(E)$$

$$V^i(R, E) \equiv v(R) - D(E) \tag{15}$$

3.4 Optimal pollution supply

We consider a noncooperative Nash Equilibrium where pollution policy is endogenous and decided by a self-interested government, which maximises the utility of a representative consumer given world prices and Rest Of the World (ROW) emissions. Government policy is cast in terms of pollution targets, e_i. The problem of the government is as follows:

$$\max_{e_i} \quad V^i(R, E) \tag{16}$$

$$s.t.: \qquad R = [G(p, K, L, \frac{e_i}{\Omega})]/\omega(\mathbf{p}) \tag{17}$$

$$E = E_{-i} + e_i \tag{18}$$

where E_{-i} is the total aggregate emission of all jurisdictions bar the emissions of jurisdiction i. The optimality condition of this maximisation problem is:

$$\underbrace{V_R R_E}_{(1)} + \underbrace{V_R R_p p_e}_{(2)} + \underbrace{V_E}_{(3)} = 0 \tag{19}$$

That is, the government's decision reflects the tradeoff between the direct effect of emissions change on the nation's real income (1), the effect of the induced change in the price of the dirty good on real income (2), and the effect of emissions change on the consumer's utility (3). However, with exogenous world prices, (2) is equal to zero because there is no real income effect of a change in domestic prices. Hence,

$$R_E = \underbrace{-V_E/V_R}_{\equiv MD(R,E)} \tag{20}$$

with $V_E < 0$ and $V_R > 0$. Equation (20) equates the marginal benefit of increased emissions (i.e. the resulting increase in real income) to the domestic marginal damage of

pollution and defines the optimal level of emissions e^*. Given that domestic consumers only account for domestic benefits of emissions abatement, this outcome is suboptimal from a global planner's perspective.

Before turning to the formulation of our empirical hypotheses, we highlight two features of carbon pricing policy development that rest on equation (20) and relate directly to the hypotheses formulated in the next section. First, equation defines lower equilibrium emissions as abatement technology improves.

Proposition 3. *Assuming that the scale effect is smaller than the technique effect, an improvement in abatement technology reduces equilibrium emissions.*

Proof. From proposition 2 we know that an improvement in abatement technology induces a *technique* effect and from appendix A that it also induces a *scale* effect. For a given price of emissions, the former lowers total emissions in the dirty sector whereas the latter raises them. Formally, these two effects are apparent in $e = i(p, \delta, \Omega) \times x(p, \delta, K, L)$. Assuming that the decrease in emissions intensity (technique effect) more than outweighs the rise in dirty good production (scale effect), the demand for emissions decreases and total (equilibrium) emissions will fall. □

Second, the government's first decision (prior to choosing the emissions level) is whether to regulate (or not) and it will choose the option that maximises the representative consumer's utility. In the presence of regulation, pollution is chosen according to equation (20) and utility rises monotonically with income. In the no regulation option, the consumer faces ever increasing pollution which, assuming decreasing marginal utility of consumption and constant marginal disutility of pollution, implies that utility initially rises and ultimately declines with income. If the regulation is expected to require a fixed amount of primary inputs $\Phi \equiv (\bar{K}, \bar{L})$, regulatory activity will not occur until a threshold level of income above which the consumer's utility under regulation surpasses her utility under no regulation is reached. Equivalently,

Proposition 4. *A decrease in the (expected) fixed cost of regulation lowers the policy*

activity income threshold.

Proof. See appendix C. □

4 Hypotheses

Building on the framework presented in the previous section, we now formally introduce our hypotheses.

4.1 Changes in net payoffs

4.1.1 Abatement technology

As section 3.4 suggests – and as highlighted by integrated assessment modelling exercises (e.g. Kriegler et al. (2014)), abatement technology – Ω – is a key determinant of the economy's (optimal) level of emissions. Therefore, how this technology is developed and accumulated by a jurisdiction plays a significant role in the evolution of its CO_2 emissions and policy activity. One potential mechanism is learning from foreign technological developments (Bloom et al., 2013; Dechezlepretre and Glachant, 2011) or, in other words, technology diffusion. The jurisdiction-specific learning effect is denoted by ψ_i and assume that domestic abatement technology depends on foreign jurisdictions' abatement technology stock, $\Omega(\psi_i)$, with i.e. $\psi_i > 0$ and $\frac{\partial \Omega(.)}{\partial \psi_i} < 0$. This leads to the formulation of our first hypothesis.

Hypothesis 1 Higher access/exposure to foreign abatement technology improves domestically available abatement technology, and affects positively: i. (the probability of) implementation of any form of climate policy – including carbon pricing; ii. policy stringency.

We follow Grossman and Helpman (1991) and note that the strength of the technology diffusion effect is linked to bilateral trade relationships and that both import and export flows can affect domestic technology differently (Falvey et al., 2004). Imports of intermediate goods embody foreign knowledge that is extracted by the recipient country

and contributes to the domestic stock of (abatement) technology. This accumulation of technology might enhance home productivity, or prompt countries inside the technological frontier to imitate the products of frontier countries. For example, Lanjouw and Mody (1996) show that imported equipment is a major source of environmental technology for some countries. Exports, on the other hand, emphasise "learning-by-doing" and the "pure idea exchange and knowledge spillovers gained from formal and informal contacts"(Funk, 2001), which can encourage more efficient employment of resources or stimulate new indigenous technologies.[15]

4.1.2 Foreign climate policy stringency

For given international prices, increased domestic environmental policy stringency would lead to a loss of real domestic income, R – which follows straightforwardly from equation (11). This results from the diversion of some domestic resources to abatement activity in the dirty good sector, which in turn reduces its (optimal) supply by domestic producers and diverts some of the world demand to other world suppliers. However, the relative magnitude of this cost is inversely proportional to the gap between ROW and domestic stringency. Hence, the (coordinated) introduction of carbon pricing policies by foreign jurisdictions (i.e. an increase in foreign climate policy stringency) may reduce the domestic cost of more stringent domestic policy, alleviate the related political concerns, and thereby foster the implementation of more stringent domestic policy.[16] We denote relative foreign climate policy stringency by η and write $\frac{\partial R}{\partial e}|_{\eta^{high}} < \frac{\partial R}{\partial e}|_{\eta^{low}}$. That is, more stringent foreign climate policy reduces the domestic cost of policy strengthening. Therefore,

Hypothesis 2 The introduction of more stringent carbon pricing and other climate change mitigation policies by foreign jurisdictions leads to more stringent domestic policy.

[15]Competition in international markets might drive domestic exporters to acquire and adapt foreign technologies. Evidence of a 'trading up' effect, i.e. the fact that greater exports to jurisdictions with more stringent (environmental) regulations leads to a strengthening of domestic regulations, has been provided by Perkins and Neumayer (2012) for the automotive industry.

[16]In the extreme case where the ROW introduces equally stringent environmental policy, raising the world price of the dirty good, the domestic economy would be equally well off, should it make its own environmental policy more stringent.

This effect is present regardless of whether the domestic jurisdiction exports to or imports from the carbon pricing jurisdiction(s): more stringent climate policy in both import and export markets would alleviate the domestic economic cost of carbon pricing, although via potentially different mechanisms. Two observations regarding this potential mechanism should be noted, however. First, one could also expect to observe a form of free riding effect whereby policy initiatives by other (significant) jurisdictions reduces the incentive to act since jurisdictions exporting to partners with more stringent environmental policy might be induced to weaken their own in order to strengthen their comparative advantage. Second, most carbon pricing schemes so far have either targeted non tradable sectors or exempted exports.

In addition to these effects, policy stringency can also be transferred via non-economic channels. For example, Fankhauser et al. (2016) suggest that peer pressure can play a role in the international diffusion of policy (stringency); Frankel and Rose (2005) further note that one may observe the international ratcheting of environmental standards: when a "significant" jurisdiction introduces more stringent environmental standards, others might follow suit. The legal literature on environmental policy refers to this effect as the 'California' effect (see, e.g., Vogel (1995); Perkins and Neumayer (2012)). Although this literature relates this closely to economic integration (the more integrated two economies are, the more likely they are to adopt each other's standards) and relative size (the relatively larger economy is more likely to be able to impose its standard), it is plausible that other forms of (economic) relationships influence the international transfer policy stringency. One possibility is Official Development Assistance; there is evidence, if only anecdotal, that several jurisdictions (e.g. Norway, the European Union) are taking relatively stringent emissions reductions commitment at home and are actively encouraging other jurisdictions to take steps towards climate change mitigation. Given the importance of extending climate policy regimes to all national jurisdictions in the world, especially nations whose emissions are currently growing under the combined effect of population and economic growth, it would be of significant interest to determine whether donor countries' policy stringency influence recipients' policy stringency.

4.2 Updated information

Substantial evidence indicates that governments often lack sufficient information to understand the political/societal cost of economic policy innovation (Simmons and Elkins, 2004) and/or expect the economic cost of implementation to be significant. In terms of climate policy this can represent the cost associated with the reallocation of resources from one industrial sector to another or the political cost of sustaining abatement policies (Mideksa, 2016).

Such cost is likely to delay implementation of (more stringent) environmental policy. Therefore, a reduction in the expected (fixed) political or economic cost of regulation is likely to prompt more policy activity or increase policy stringency. In that respect, we understand policy makers as drawing information from two main sources: 1. past (foreign) policy experience; 2. (abatement) technology deployment and demonstration. First, early policy experience reveals information about the actual cost of implementation as well as institutional design features which can reduce them (international competitiveness, carbon leakage,...). For example, at the international level, one can think of the EU-ETS as playing such role; at the sub-national level, California's ETS might be thought of playing a similar role with respect to other US States. Second, the proven availability of a (major) abatement technology is likely to play a role too. The deployment and demonstration of abatement technology provides information about the feasibility of deployment of specific technologies in the home jurisdiction.

Given the above, we hypothesise that the expected regulatory cost introduced in section 3.4 depends on accumulated foreign policy experience (α_i) as well as deployment and demonstration of abatement technologies (σ_i). Thus, we rewrite the fixed regulatory cost as $\Phi(\alpha_i, \sigma_i)$. As 'successful' policy experience is accumulated and/or abatement technology is deployed, the expected fixed regulatory cost decreases; i.e. $\frac{\partial \Phi(\alpha_i,\sigma_i)}{\partial \alpha_i} < 0, \frac{\partial \Phi(\alpha_i,\sigma_i)}{\partial \sigma_i} < 0$.

Hypothesis 3 Successful policy implementation and technology deployment by (partner) jurisdictions reduces the expected fixed cost of regulation for the domestic economy which, in turn, increases both the probability of implementation and the stringency of

(domestic) carbon pricing schemes.

While the altered payoffs mechanisms are intrinsically related to the relative strength of bilateral trade or financial flows, the transmission of information across jurisdictions is tied to (potentially numerous) communication channels. Previous literature considered channels based on (1) bilateral data (e.g. trade, number of telephone calls,...) and (2) affiliation data, e.g. membership of organisation, party to regional agreements,... (Simmons and Elkins, 2004). This paper considers two channels. First, cultural/geographical proximity, as there is evidence that geographically and/or culturally close neighbours tend to align their policies (Simmons and Elkins, 2004). Second, given that the EU as an organisation acts as a strong "coordination device" among its member states in several areas of public policy, involving repeated contacts between their respective civil servants, we suggest that information about climate policies may have been transmitted more easily between EU member states.[17]

Table 1: Main hypotheses

Category	Mechanism	Theoretical representation	Channel(s)	Data Source	Policy adoption	Policy stringency
Altered payoffs	Foreign abatement tech.	ψ_i	IM,EX	IMF (2017)	+	+
	Foreign policy stringency	η_i	IM,EX	IMF (2017)	n.a.	+
			ODA	OECD (2016b)	n.a.	+
Updated information	Policy demonstration	α_i	Cult. proximity	IMF (2017)	+/-	n.a.
			EU	Authors	+/-	n.a.
	Technology deployment	σ_i	Cult. proximity	IMF (2017)	+	+
			EU	Authors	+	+

5 Data and identification strategy

The empirical challenge ahead of us is now to (1) find proper proxies for the outcomes of interest (carbon pricing and other climate policies) as well as for the altered payoffs and informational update mechanisms that we discussed in the previous section; (2) evaluate their effect on policy developments, both adoption and stringency.

[17]Note that such investigation could be repeated for other multilateral organisations such as the OECD.

5.1 Policy developments

We analyse the adoption of both price and non-price climate change mitigation policies.[18] Since we investigate the dynamics of both policy adoption and stringency, policy developments within each jurisdiction are captured in two ways. First, a binary variable ($\mathbb{1}$) taking value 1 if a jurisdiction has adopted a given policy (in any sector of its economy) in a particular year, 0 otherwise.[19] Second, a variable capturing the stringency of the adopted policy. For carbon pricing policies, we use an Emissions-weighted Carbon Price (ECP) – see Figure 2a. The ECP is constructed using detailed information about the schemes' sector(-fuel)-level coverage and CO_2 price data collected by the authors – see appendix D for a description of the data collected and the methodology. The proxy for non price climate change mitigation policies, constructed based on GLOBE (2018), is the cumulative number of policies passed – see Figure 2b – and belonging to the following categories: Energy Demand, Energy Supply, Research and Development, Transport.

5.2 Covariates

Now, capturing the source and strength of policy diffusion mechanisms requires that: (i) we construct variables (Λ) that plausibly indicate changing payoff structures and new sources of relevant information; (ii) we identify the channels of diffusion, along with relevant proxies for the "distance" between (spatial) units. To account for (ii), we construct diffusion regressors that are defined as follows. For each jurisdiction i and year t, we can write

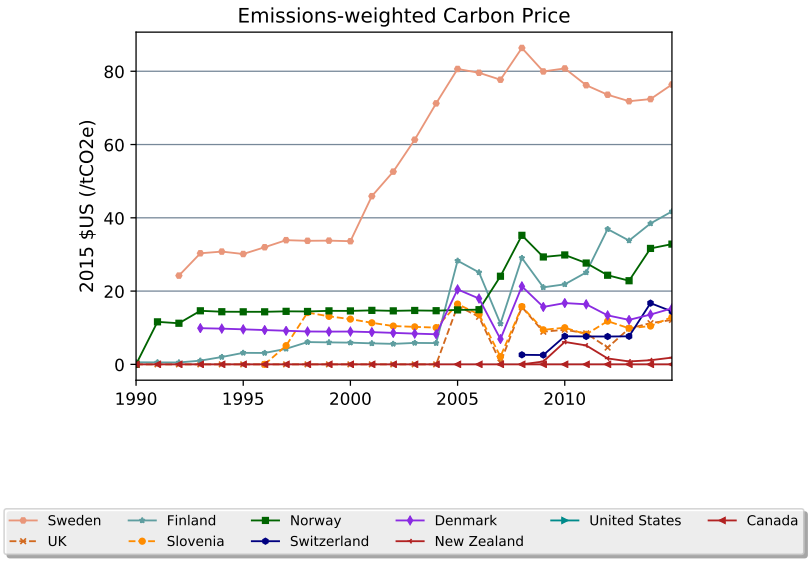
$$\Lambda_{i,t} \equiv \sum_{j \in \Theta_{i,t}} \Gamma_{i,j,t} x_{j,t}$$

where $\Theta_{i,t}$ is the set of all partner jurisdictions of jurisdiction i in year t, $\Gamma_{i,j,t}$ is the partner-specific bilateral weight in year t, and x_j is the partner-specific value of variable x in that same year. The choice of the bilateral weights matrix depends on whether they

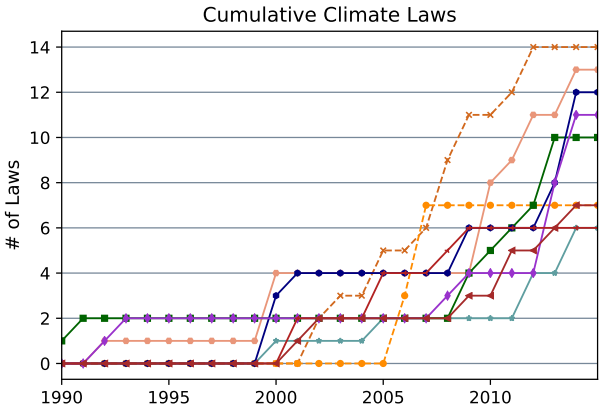
[18] Looking at the latter group of policies is motivated by the fact that carbon pricing schemes are not the only policy tools that have been implemented to abate GHG emissions. In fact, these policies, however important, are still relatively marginal when considered in the context of all climate change mitigation policies adopted.

[19] This assumes that there are only two "policy states" possible and the "policy event", i.e. introduction of *a* carbon pricing mechanism, occurs once.

Figure 2



(a)



(b)

constitute a proxy for a channel relevant to either the alteration of material payoffs or the transmission of information. The diffusion proxies are presented below.

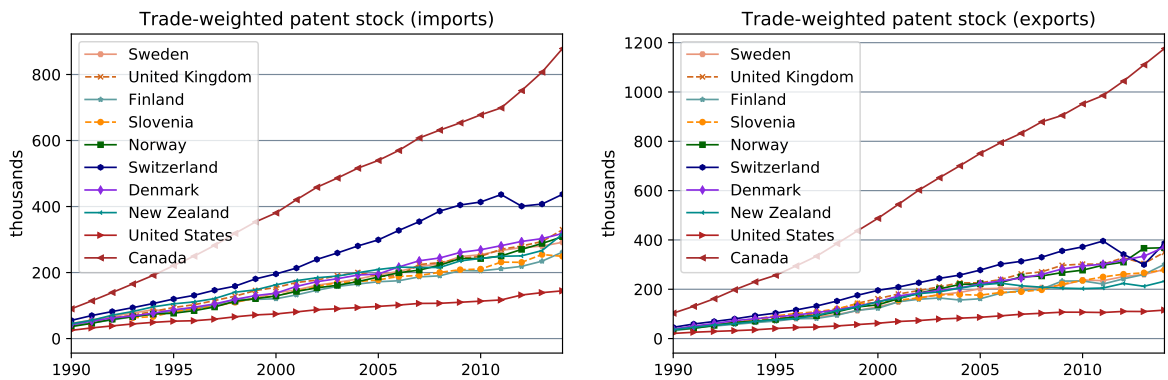
Foreign abatement technology (ψ) The state of abatement technology (in partner jurisdictions) is captured by the cumulative count of *climate change mitigation* technology patents since 1985 ($\bar{\kappa}$). For each country-year, the technology diffusion regressor is then defined as the import- or export-weighted aggregate of all abatement technology stock from trading partners – Figure 3.[20] The import-weighted measure captures the embodied

[20]This assumes that technology diffusion is not only a trade-related phenomenon but is also local in nature. It might be argued that what matters is a global technological pool, in which case technology

technology assumption whereas the export-weighted metrics emphasise the pure exchange of ideas.

$$\psi_{i,t}(IM) \equiv \sum_j \left[\frac{IM_{t,j,i}}{IM_{i,t}^{Tot}} \times \bar{\kappa}_{j,t} \right] \qquad \psi_{i,t}(EX) \equiv \sum_j \left[\frac{EX_{t,j,i}}{EX_{i,t}^{Tot}} \times \bar{\kappa}_{j,t} \right]$$

This approach builds on the literature suggesting the use of patent data as proxy for the output of the innovation process (Griliches, 1990) and has been used in recent studies looking at the diffusion of climate change mitigation technologies (e.g. Dechezlepretre et al. (2013)).



(a) (b)

Figure 3

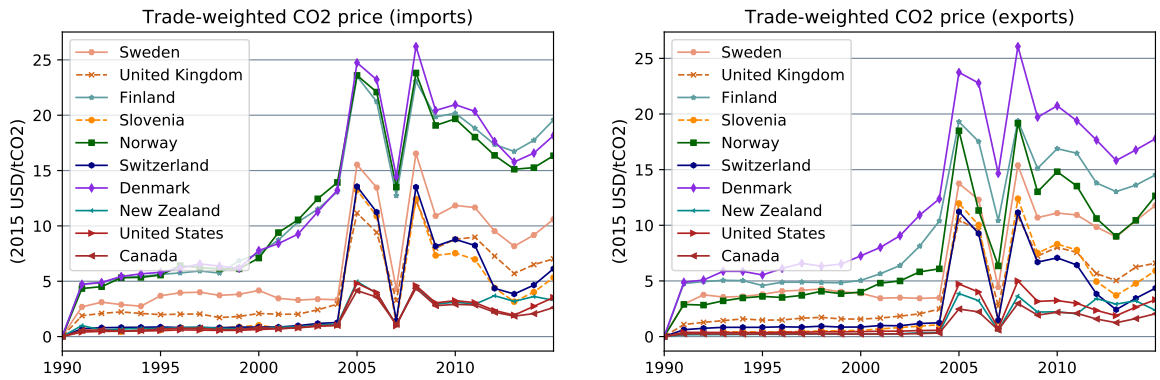
Foreign climate policy stringency (η^{CL}, η^{ECP}) To account for (foreign) climate policy stringency, we use the ECP and the cumulative number of climate laws passed in partner jurisdictions. As noted in the formal discussion, the price of polluting emissions (whether explicit or not) relates directly to abatement efforts, i.e. the share of resources devoted to abatement. Our theoretical framework allows for the response to more stringent foreign climate policy to differ depending on whether that stringency is raised by import or export partners. Therefore, once again, we distinguish between import and export channels.

development data aggregated at the world level would be sufficient. In addition, note that this proxy relies on the assumption that a positive correlation exists between aggregate trade flows and those for climate change mitigation technologies.

$$\eta_{i,t}^{CL}(IM) \equiv \sum_j \left[\frac{IM_{i,j,t}}{IM_{i,t}^{Tot}} \times CL_{j,t}\right] \qquad \eta_{i,t}^{CL}(EX) \equiv \sum_j \left[\frac{EX_{i,j,t}}{EX_{i,t}^{Tot}} \times CL_{j,t}\right]$$

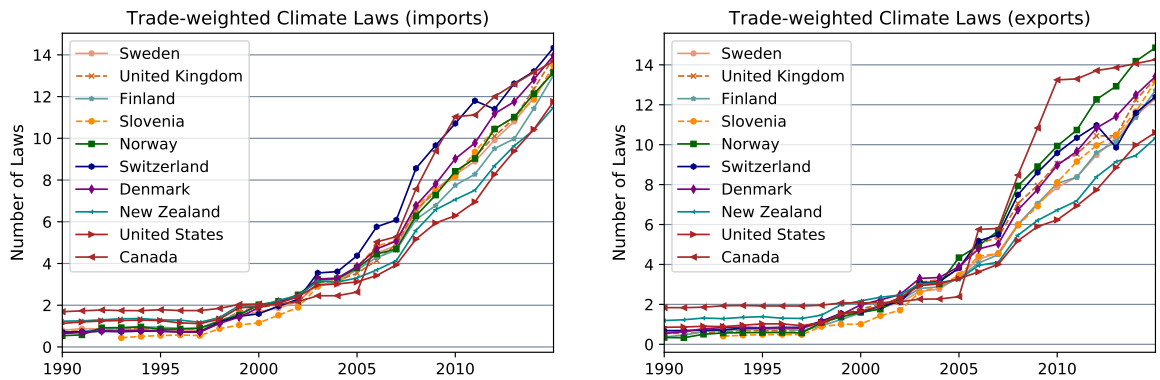
$$\eta_{i,t}^{ECP}(IM) \equiv \sum_j \left[\frac{IM_{i,j,t}}{IM_{i,t}^{Tot}} \times ECP_{j,t}\right] \qquad \eta_{i,t}^{ECP}(EX) \equiv \sum_j \left[\frac{EX_{i,j,t}}{EX_{i,t}^{Tot}} \times ECP_{j,t}\right]$$

Figures 4a and 4b present this metric for selected jurisdictions. This sheds light on the *external* effect of CO_2 pricing and the significant role played by the EU-ETS for non EU-ETS jurisdictions.



(a) (b)

Figure 4



(a) (b)

Figure 5

Foreign climate policy stringency – ODA To gauge whether bilateral development assistance is used to prompt recipient jurisdictions to introduce climate change mitigation legislation, we construct a proxy for partner jurisdictions' policy stringency where the bilateral weights are the bilateral shares of Official Development Assistance (ODA) between recipient and donor countries. The effect of this variable is tested on the stringency of non price climate change mitigation policies rather than carbon pricing legislation because carbon pricing schemes have been introduced mainly among OECD countries. As before, this stringency is proxied as the cumulative number of climate laws passed.

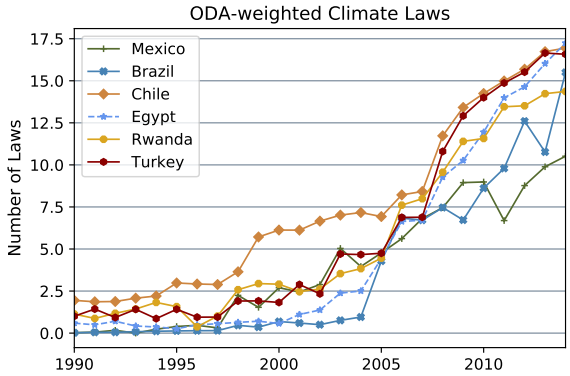


Figure 6

Policy learning $(\alpha^{CL}, \alpha^{P})$ The informational signal that each jurisdiction sends by implementing climate policies is captured by two variables: the number of partner jurisdictions having adopted at least one non-price climate policy or adopted a carbon pricing scheme (either a carbon tax or trading system).[21] The proxy for the aggregate signal received from all partner jurisdictions is then:

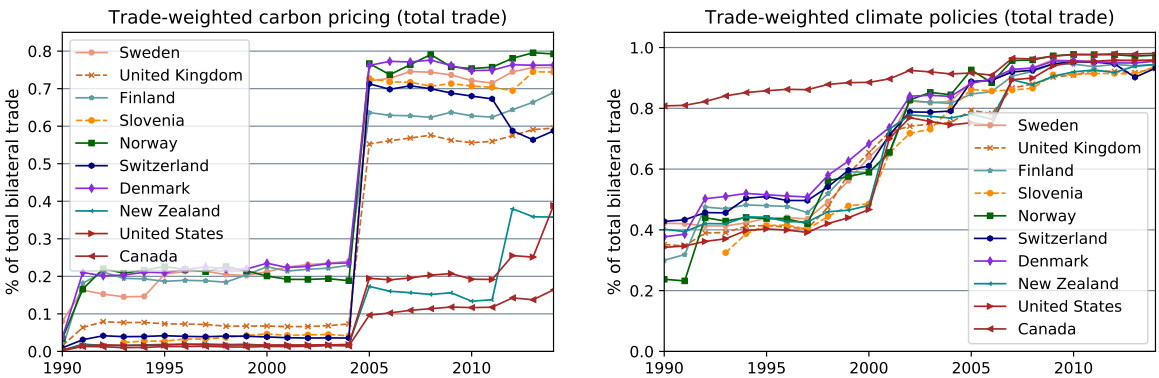
- the weighted average of all partner specific signals received where the weights are the share of each partner j's total trade with jurisdiction i in that jurisdiction's

[21] Policy adoption is interpreted as a sign of successful implementation.

total trade flows

$$\alpha_{i,t}^{CL}(IM+EX) \equiv \sum_j \left[\frac{(IM+EX)_{j,t,i}}{(IM+EX)_i^{Tot}} \times CL_{j,t}\right]$$
$$\alpha_{i,t}^{P}(IM+EX) \equiv \sum_j \left[\frac{(IM+EX)_{j,t,i}}{(IM+EX)_i^{Tot}} \times P_{j,t}\right]$$

In weighting the received signal by total bilateral (trade) relationship, we assume that the strength of the signal is related to the total bilateral relationship, which follows earlier literature (Simmons and Elkins, 2004). As can be observed on Figure 7, little climate-related legislative activity takes place before the late 1990s. Moreover, it is interesting to note that even countries that did not implement carbon pricing or other climate change mitigation policies domestically are "exposed" to it (see, for example, Canada and the United States).



(a) (b)

Figure 7

- EU membership dyadic matrix. We construct a matrix recording affiliation to the same organisation (the EU) for each pair of countries in the sample in any given year between 1990 and 2014.

$$\alpha_{i,t}^{CL}(EU) \equiv \sum_j [EU_{i,j,t} \times CL_{j,t}] \qquad \alpha_{i,t}^{P}(EU) \equiv \sum_j [EU_{i,j,t} \times P_{j,t}]$$

where $EU_{i,j,t}$ takes value 1 if both countries i and j are part of the EU in year t.

Technology demonstration (σ) Finally, our proxy for foreign abatement technology deployment and demonstration is the cumulative installed electricity generation capacity from wind and solar energy (RE).[22] Increased cumulative installed capacity provides evidence of an existing (and proven) alternative to fossil-fuel based electricity generation capacity.[23] As for the policy learning effect, the signal derived from technology demonstration is modelled as relating to either

- the strength of the total bilateral (trade) relationship

$$\sigma_{i,t}(IM + EX) \equiv \sum_j \left[\frac{(IM + EX)_{j,t,i}}{(IM + EX)_i^{Tot}} \times RE_{j,t} \right]$$

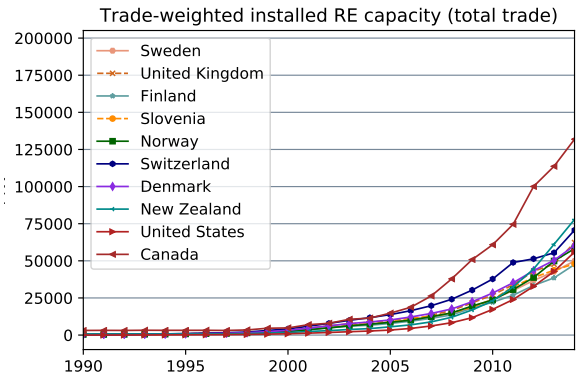


Figure 8

- EU membership dyadic matrix.

$$\sigma_{i,t}(EU) \equiv \sum_j [EU_{i,j,t} \times RE_{j,t}]$$

Control mechanisms In discussing the diffusion of policies across jurisdictions, it is important to control for domestic (political and economic) conditions that could influence

[22]This *de facto* restricts our attention to the power sector. However, given that it is one of the first economic to have been subject to decarbonisation efforts across almost all jurisdictions, it is safe to consider that it is representative of the technologies relevant to climate policy making so far.

[23]Increased cumulative installed capacity also has implications for technology learning. In terms of development/diffusion, additional installed capacity increases the stock of technology from which other jurisdictions can learn and contributes to the reduction of the (unit) cost of the technology through 'learning by doing' (Arrow, 1962). In the case of solar photovoltaics, for example, IRENA (2012) finds that costs decline by 22% for every doubling of capacity.

a jurisdiction's adoption of policies (Volden et al., 2008). This, because the observed adoption outcome(s) could also reflect the fact that similar jurisdictions respond similarly – yet independently – to the same issue. To control for these we use GDP per capita (PPP, thousand constant 2011 USD), an indicator of Democracy, and the degree of openness as proxied by the ratio of total trade over GDP. GDP per capita captures the standard income effect and, assuming that environmental quality is a normal good, should have a positive impact on both policy adoption and stringency.

Table 2: Summary statistics

Category	Variable	Source	Weight	Mean	Std. Dev.	Min.	Max.	N
Outcome - adoption	Pricing	Author created	-	0.12	0.33	0	1	2725
	Climate Law	Author created	-	0.46	0.5	0	1	2725
Outcome - stringency	ECP(2013)	Author calculations	-	1.68	7.65	0	95.21	2725
	Cum. Climate Law	Author calculations	-	2.39	3.67	0	21	2725
Technology stock	Patent stock	OECD (2019)	IM	79.14	58.2	2.45	439.34	2635
	– thousands		EX	93.255	81.93	0.05	630.45	2635
Foreign stringency	Carbon Price	Author's data	IM	2.44	3.36	0.002	26.2	2635
			EX	2.25	3.24	0.002	26.06	2635
	Climate Laws	Author's data	IM	3.69	3.39	0.03	14.1	2635
			EX	3.76	3.55	0	14.21	2635
			ODA	4.88	4.66	0	17.62	1263
Policy learning	Foreign Pricing	Author's data	IM+EX	0.16	0.22	0	0.83	2635
			EU	1.97	6.39	0	25	2700
	Climate Law	GLOBE (2018)	IM+EX	0.64	0.25	0.02	1	2635
			EU	1.79	5.01	0	19	2700
Tech. demonstration	RE capacity	UN Energy Stat. (2018)	IM+EX	6.44	9.89	0	82.79	2635
	– GW		EU	8.97	33.36	0	217.08	2700
Control	Democracy	VDEM (2018)	-	0.46	0.28	0.014	0.903	2715
	GDP per cap.	World Bank (2016)	-	16.46	17.04	0.35	111.07	2687
	Trade openness	World Bank (2016)	-	78.37	44.68	0.02	441.6	2645

5.3 Modelling approach

The analysis is performed on a dataset covering 109 national jurisdictions over the period 1990-2014.[24] We thus have (a maximum of) 2725 country-year observations. The modelling approach adopted is different for the policy adoption decision and the policy stringency.

Adoption The literature on policy adoption usually investigates such questions with event history or hazard models. Berry and Berry (1990) use a panel probit approach, observing the evolution of lottery adoption over the period 1964-1986 in 48 US States.

[24]The panel dimension of our dataset is limited by the data on the level of democracy whereas the time dimension is constrained by the availability of patent data from the OECD.

Simmons and Elkins (2004) model the adoption of liberal economic policies as a transition between two (mutually exclusive) states using a Weibull survival model. In these latter analyses, all units "enter" the sample in a – somewhat arbitrarily – determined year from which jurisdictions are "at risk" of adopting the policy and "leave" as soon as a failure (i.e. policy adoption) occurs. When looking at the adoption of domestic environmental policies, several international agreements in which these jurisdictions have taken binding commitments could be used as starting year. This is the approach taken in Fredriksson and Gaston (2000) to analyse the ratification of the UNFCCC by national jurisdictions following its signature in 1992. However, since the first carbon pricing scheme was adopted before any international legally binding agreement, we follow Berry and Berry (1990) and take the year of introduction of the first carbon pricing scheme, 1990, as our starting point. That is, every country enters the dataset in 1990 and the last observation recorded for each unit is the year in which the adoption of a given policy (either carbon pricing or the first 'non pricing' policy) occurred. Formally, we have:

$$\mathbb{1}_{i,t} = \beta \mathbf{X}_{i,t-1} + \lambda \mathbf{W}_{i,t-1} + \gamma \mathbf{C}_{i,t} + d_t + \epsilon_{i,t} \tag{1}$$

where $\mathbb{1}_{i,t}$ denotes the presence (1) or absence (0) of a carbon pricing scheme in any sector of jurisdiction i in year t, $\mathbf{X}$ is the set of variables capturing the changes in net payoffs, $\mathbf{W}$ includes the variables capturing policy learning, $\mathbf{C}$ is the set of 'control' variables; d_t is the vector of time dummy variables; β, λ and γ are vectors of dimensions m, n and p, respectively, each element of which corresponds to the estimated parameter of the associated explanatory variable. ϵ_{it} is the observation specific error term.

Stringency Because the stringency of carbon pricing policies is not measured in the same way as that of other climate policies – the former is a continuous variable whereas the latter is a non-negative discrete variable – we model these two outcome variables differently. The ECP is modelled as a standard linear process

$$ECP_{i,t} = \beta \mathbf{X}_{i,t-1} + \lambda \mathbf{W}_{i,t-1} + \gamma \mathbf{C}_{i,t} + \phi_i + d_t + u_{i,t} \tag{2}$$

where $ECP_{i,t}$ is the emissions-weighted average carbon price in jurisdiction i at time t and ϕ_i is the unobserved jurisdiction fixed-effect; u_{it} is the observation specific error term. The modelling approach used for non pricing climate policies follows that adopted in Fankhauser et al. (2016), i.e. a negative binomial fixed-effects model.

$$CL_{i,t} = \beta \mathbf{X}_{i,t-1} + \lambda \mathbf{W}_{i,t-1} + \gamma \mathbf{C}_{i,t} + \phi_i + d_t + u_{i,t} \tag{3}$$

Unlike the adoption equation, equations (2) and (3) are estimated on the full data sample, running from 1990 to 2014. In all equations, all covariates except the 'control' variables enter the model with a one year lag to reflect the fact that it takes time for policy and/or technology developments in partner jurisdictions to "diffuse" to the domestic jurisdiction and then translate into policy decisions.

6 Results

6.1 Adoption

The results in table 3 show that policy adoption, either carbon pricing or other, is related to past adoption of the same policy in geographically and/or culturally close partner jurisdictions. This is consistent with our third hypothesis and suggests that free riding on other jurisdictions' climate change mitigation policy initiatives is not a strong driver of domestic climate policy activity. This effect seems to be of a larger magnitude for carbon pricing schemes – estimations (1) and (2) – than for non price climate policies – estimations (3) and (4). Interestingly, the effect of an EU-related information transmission channel is only confirmed for carbon pricing policies, not for non price climate policies. Overall, this provides some support for our *policy learning* hypothesis and emphasises the potential for (a group of) jurisdictions to demonstrate the feasibility of specific policy innovations but casts doubt on the idea that the EU served as a key information transmission channel, especially for non price climate policies. Similarly, the deployment of renewable electricity generation capacity, which we assumed carries information about the availability of an abatement technology, relates positively to the adoption of carbon

pricing and other climate policies when weighted by the total bilateral trade relationship but not when [weighted] by the EU. The magnitude of the associated coefficient is larger for non price policies than for carbon pricing policies – except in estimation (2), where it is an order of magnitude larger for pricing policies. It must also be noted that, although the estimated coefficient might seem quite small, trade-weighted installed RE capacity is measured in GW and the maximum is 165.57 GW. Finally, the results for our proxy of the stock of climate change mitigation technologies does not allow us to confirm that an increase in the stock of such technologies in partner jurisdictions fosters policy adoption. Hypothesis 1 remains therefore unverified and would require further investigation.

GDP per capita and the level of democracy both affect positively the probability of adoption of price and non price policies, although the effect of the former is found to be meaningfully positive in estimation (1) only. It is unsurprising that these characteristics are found to have a stronger impact on the implementation of carbon pricing policies since these policies have been introduced among richer countries whereas other climate change mitigation policies have been introduced by relatively less well off jurisdictions. Lastly, we note the negative values of the estimated intercept parameter across all estimations, indicating that in the absence of the (positive) effect of our covariates, the probability of adoption of the policies under investigation is very low.

6.2 Stringency

The results in table 4 – estimation (5) – indicate that the stringency of carbon pricing policies was, over the sample period, mainly driven by the past average price in other jurisdictions. This effect is present regardless of whether the variable is weighted by imports or exports, suggesting that countries with a carbon price are closely integrated through trade. We nonetheless note that the magnitude of this effect is about 1.5 times larger for imports than exports, More precisely, an increase of \$1/tCO_2e in the import-weighted (export-weighted) average price of emissions is associated with an increase of \$0.29/tCO_2e (\$0.21/tCO_2e) in the domestic average price of carbon. This effect is most likely driven by EU jurisdictions, which have implemented a common carbon pricing

Table 3: Policy adoption

Category	Variable	Carbon Pricing		Climate Policy	
		(1)	(2)	(3)	(4)
Technology diffusion	$\psi(\text{IM})_{t-1}$	$-6.59e^{-7}$	$-1.98e^{-5}$	$7.71e^{-7}$	$1.85e^{-6}$
		$(1.72e^{-6})$	(1.69^{-5})	(1.24^{-6})	(2.49^{-6})
	$\psi(\text{EX})_{t-1}$	$6.59e^{-8}$	$4.47e^{-6}$	2.32^{-7}	5.51^{-7}
		$(1.15e^{-6})$	(1.01^{-5})	(6.73^{-7})	(1.36^{-6})
Policy learning	$\alpha^{P}(\text{IM+EX})_{t-1}$	1.68^{***}	11.21^{***}		
		(0.52)	(3.866)		
	$\alpha^{P}(\text{EU})_{t-1}$		1.89^{***}		
			(0.653)		
	$\alpha^{CL}(\text{IM+EX})_{t-1}$			0.78^{*}	0.73^{*}
				(0.41)	(0.421)
	$\alpha^{CL}(\text{EU})_{t-1}$				0.08
					(0.056)
Tech demonstration	σ $(\text{IM+EX})_{t-1}$	$1.27e^{-2*}$	$1.92e^{-1**}$	$3.27e^{-2***}$	$6.61e^{-2***}$
		$(6.84e^{-3})$	$(7.55e^{-2})$	$(1.1e^{-2})$	$(2.21e^{-2})$
	σ $(\text{EU})_{t-1}$		$2.66e^{-2}$		$-1.9e^{-2}$
			$(5.86e^{-2})$		$(2.17e^{-2})$
Control(s)	GDP per cap.	0.017^{***}	0.08	0.0002	-0.002
		(0.006)	(0.054)	(0.005)	(0.005)
	Trade openness	0.002	0.01	0.003^{*}	0.003
		(0.002)	(0.014)	(0.002)	(0.002)
	Democracy	2.99^{***}	12.72^{**}	0.44^{*}	0.35
		(0.68)	(5.014)	(0.242)	(0.257)
	Constant	-5^{***}	-20.98^{***}	-2.52^{***}	-2.49^{***}
		(0.59)	(5.995)	(0.236)	(0.244)
	Year FE	No	No	No	No
	Observations	2165	2141	1200	1197

Standard errors in parentheses

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

scheme in 2005 but were, and still are, closely (trade-)integrated. Interestingly, the stringency of foreign carbon pricing schemes seems to affect both the stringency of domestic price and non-price climate change mitigation policies. However, as far as the stringency of non price climate policies is concerned, the direction of the previous effect depends on whether stringency is increased in import partners (-) or export partners (+), giving some grounds to the existence of a potential free riding on other jurisdictions' mitigation efforts effect. However, the stringency of non price climate policies (whether weighted by imports or exports) does relate positively to domestic non price climate policy stringency.

The deployment of renewable energy electricity generation capacity, which we interpreted as providing information about the availability and feasibility of domestic deployment of an abatement technology relates positively to the stringency of carbon pricing policies, be it weighted by the strength of the bilateral relationship or by affiliation to the European Union. For example, a 100GW increase in the weighted stock of RE installed capacity would, on average, induce a \$7.6/tCO_2e increase in the stringency of

carbon pricing policies – estimation (5). The development of abatement technology (as measured by the patent stock) does, however, relate negatively to the stringency of both price and non-price climate policies, although the estimated effect is only statistically significant in estimation (6) and only for the import-weighted variable.

The results also suggest that Official Development Assistance and the associated relationships constitute a significant driver of domestic policy stringency for recipients of ODA – estimation (7). Indeed, results indicate that an increase in the cumulated legislative activity in donor countries results in increased stringency in receiving countries. Given the way the proxy is constructed it is not possible to say whether this effect is driven by particular donor countries but it could constitute an interesting extension of the present work. Moreover, the coefficient on the import-weighted foreign non-price climate policy stringency suggests that recipients of ODA would, on average, lower the stringency of their own non price climate policy regime in response to an increase in the stringency in their import markets.

Finally, income per capita and trade openness increase the price of carbon by, on average, \$0.14/tCO_2e and \$0.004/tCO_2e respectively. No effect of these variables is detected on the stringency of non price climate policies, except in the case of receivers of ODA. For these countries, GDP per capita and trade openness positively affect the domestic stringency of non price climate policies.

6.3 Summary and discussion

The analysis conducted above sought to shed light on potential channels of climate policy diffusion and assess their empirical relevance. The results presented provide support for some of the suggested channels. In particular, we find evidence that policy adoption by foreign jurisdictions positively affects domestic policy adoption. This is in line with Fankhauser et al. (2016). However, we confirm that this diffusion effect may be more subtle than one might have assumed so far. The analysis indeed shows that two diffusion channels were particularly important. First, in our sample, climate policies diffused primarily to culturally close neighbours (as proxied by total bilateral trade). Second,

Table 4: Policy stringency

Category	Variable	ECP	Climate policies	
		(5)	(6)	(7)
Technology diffusion	$\psi(\text{IM})_{t-1}$	$-1.75e^{-6}$	$-1.70e^{-6***}$	
		$(4.65e^{-6})$	$5.61e^{-7}$	
	$\psi(\text{EX})_{t-1}$	$-3.23e^{-6}$	$-6.72e^{-8}$	
		$(2.79e^{-6})$	$3.95e^{-7}$	
Foreign policy stringency	$\eta^{ECP}(\text{IM})_{t-1}$	0.29***	-0.05***	0.05
		(0.079)	(0.018)	(0.047)
	$\eta^{ECP}(\text{EX})_{t-1}$	0.21***	0.05***	-0.03
		(0.079)	(0.018)	(0.034)
	$\eta^{CL}(\text{IM})_{t-1}$	0.17	0.05*	-0.19***
		(0.15)	(0.032)	(0.042)
	$\eta^{CL}(\text{EX})_{t-1}$	-0.20	0.06**	0.05
		(0.126)	(0.028)	(0.038)
	${}^{CL}(\text{ODA})_{t-1}$			0.04**
				(0.016)
Tech demonstration	$\sigma(\text{IM+EX})_{t-1}$	$7.46e^{-2**}$	$-4.01e^{-3}$	$-1.23e^{-2}$
		$(3.22e^{-2})$	$(5.45e^{-3})$	$(7.56e^{-3})$
	$\sigma(\text{EU})_{t-1}$	$4.13e^{-2***}$	$-1.56e^{-3***}$	
		$(3.4e^{-3})$	$(5.71e^{-4})$	
Control(s)	GDP per cap.	0.14***	-0.01	0.05*
		(0.025)	(0.001)	(0.029)
	Trade openness	0.004	-0.0004	0.006**
		(0.005)	(0.001)	(0.003)
	Democracy	-0.25	0.32	0.83
		(1.045)	(0.351)	(0.6)
	Constant	-1.36***	0.46	11.98
		(0.736)	(0.479)	(292.221)
	Year FE	Yes	Yes	Yes
	Observations	2438	2390	1068
	R^2	0.23	-	-

while carbon pricing policies have clearly diffused among a very specific group of countries, i.e. EU member states, it is not clear that this has been the case for non price climate policies.

Second, our results also suggest that technology demonstration played a role in policy adoption. This effect, which has not been discussed in earlier literature, bears particularly strong implications for the adoption of future (sector-specific) climate policies. Indeed, it indicates that the demonstration of particular abatement technologies at scale can not only foster their adoption directly but also favour the adoption of (more stringent) climate policies which, in turn, could trigger a higher uptake of the technology. A clearer understanding of such effects could be gained by extending the analysis to specific technologies and associated policies. In a world that is seeking to avoid dangerous climate change, this seems a legitimate avenue to explore.

Third, the analysis provides interesting insights for the diffusion of (non-price) climate policies to recipients of Official Development Aid. Indeed, it seems that there is a positive

relationship between donors and recipients' respective policy stringency. At this stage, we are only establishing the potential existence of such a relationship but are not making any claim as to the exact nature of the channel, a question which deserves further attention.

Finally, the analysis did not confirm the role of foreign technology development for either domestic climate policy adoption or stringency. Such result may be due to: (i) the genuine absence of such a relationship; (ii) inadequacy of our empirical proxy. Indeed, the proxy we constructed relies on the assumption that foreign technological development spills over to the domestic jurisdiction and contributes to the improvement of its own abatement technology stock. As we alluded to earlier, it may be the case that the transfer of climate change mitigation technologies follows different channels than bilateral trade networks. If this is the case, investigating the issue with the proxy used in Dechezlepretre et al. (2013), i.e. the number of patents filed in country j by inventors from country i, and constructed based on EPO Worldwide Patent Statistical database could provide a better proxy.

Table 5: Results summary

Category	Mechanism	Theoretical representation	Channel(s)	Policy adoption	Policy stringency
Altered payoffs	Foreign abatement tech.	ψ_i	IM	/	/
			EX	/	/
	Foreign stringency	η_i	IM	n.a.	+
			EX	n.a.	+
			ODA	n.a.	+
Updated information	Policy demonstration	α_i	Cult. proximity	+	n.a.
			EU	+	n.a.
	Technology deployment	σ_i	Cult. proximity	+	+
			EU	+	+

7 Conclusion

The last quarter century has witnessed the development of a significant number of carbon pricing and climate change mitigation policies. This paper holds that these developments are partly the result of a process of policy diffusion, which rests on (i) the transfer of abatement technology; (ii) technology and policy demonstration effects. It emphasises the importance of bilateral relationships for the implementation of domestic environmental policies, providing a new perspective on the emergence of bottom-up climate "coalitions"

and the role that international institutional 'architecture' may play in it. Relatedly, it also suggests that we might have to revisit our assessment of the multilateral approach to climate change mitigation. Indeed, although we must be disappointed when international environmental agreements set lenient targets, there is a possibility that its very existence and architecture fosters the bilateral exchange of policy ideas and/or abatement technologies which, in turn, would increase the "unilateral" ambition of jurisdictions. In that respect, we believe that the European experience holds particularly strong insights for future carbon pricing developments. Indeed, integration, be it through trade or broader institutional arrangements, seems to foster policy diffusion by enhancing access to technological advances within the integrated group and strengthening the policy signal.

From a policy perspective, these results are particularly important as they cast a new light on the external effects of (unilateral) domestic carbon pricing – and climate change mitigation – policy developments. In particular, in contrast to some of the results in the *top down* environmental coalition formation literature, they suggest that convincing "key" countries to adopt tighter climate change mitigation policy frameworks might matter for the (simultaneous or sequential) policy strengthening by other jurisdictions. For example, the implications (in terms of policy diffusion and strengthening) of China adopting a more stringent policy regime may well be much more significant than that of a similar action by, e.g. Vietnam.

In a world where globally coordinated action has failed to deliver environmentally efficient outcomes, we must find a deeper understanding of the external effects of unilateral policy development.

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A Firm's profit maximisation

The firm in the Y sector does not pollute and profit function is thus

$$\pi^y = pF(K_y, L_y) - wL_y - rK_y \tag{A.1}$$

In the X (dirty) sector,

$$\begin{aligned} \pi^x &= pX(K_x, L_x) - wL_x - rK_x - \delta e \\ &= \underbrace{p(1 - \alpha\Omega(\psi))}_{\text{net producer price}} X(K_x, L_x) - wL_x - rK_x \end{aligned} \tag{A.2}$$

We derive the second equality by substituting e for its value, given by (6), and rearranging the terms. Next, recalling that

$$\frac{\delta \frac{e}{\Omega(\psi)}}{px} = \alpha \tag{A.3}$$

and that $0 < \alpha < 1$ and $0 < \Omega(\psi) \leq 1$ it is easy to see that $\alpha\Omega(\psi)$ represents the share of pollution payments in total value added. We note two observations. First, assuming constant α, a decrease in the share of pollution payments can be interpreted as reflecting a decrease in $\Omega(\psi)$, i.e. an improvement in abatement technology. Second, as $\Omega(\psi)$ decreases, the (net) revenue (i.e. revenue net of pollution permit payment) increases.

This, together with the relative price of the good, determines the allocation of resources between sectors. Indeed, recalling our perfect competition assumption, Euler's theorem, and the fact that labour and capital are inelastically supplied, we have

$$F_K = p(1 - \alpha\Omega(\psi))X_K = r \ ; \ F_L = p(1 - \alpha\Omega(\psi))X_L = w$$

where X_K, X_L and F_K, F_L denote the marginal productivity of factors in sectors X and Y, respectively. That is, factors of production are remunerated at the value of their marginal product which, since both sectors trade inputs in the same markets, is equalised across sectors. Rearranging the above yields,

$$\frac{F_K}{X_K} = \frac{F_L}{X_L} = p(1 - \alpha\Omega(\psi)) \equiv S \tag{A.4}$$

When international spillovers increase, decreasing $\Omega(\psi)$ and therefore reducing "payments to pollution", more inputs are diverted toward the dirty good sector and production expands. In a general equilibrium context, the total effect of a (positive) technological change in abatement comes in two steps: first, for a given (equilibrium) price of emissions, demand for emissions decreases, reducing pollution payments, inducing a shift of inputs from the clean to the dirty sector and hence stimulating production in the latter; second, the subsequent (downward) adjustment in emissions price induces a reduction in resources devoted to abatement – i.e. causes pollution demand to increase – and further stimulates dirty sector production. The emission intensity of the dirty sector nevertheless decreases.

Lastly, equation (A.4) provides an interesting result: the effect of a change in relative price on resource allocation varies with the abatement technology $\Omega(\psi)$. That is, define Ω^{high} and Ω^{low}, denoting *poor* and *good* abatement technology, respectively. Then

$$\left.\frac{\partial S}{\partial p}\right|_{\Omega^{high}} < \left.\frac{\partial S}{\partial p}\right|_{\Omega^{low}} \tag{A.5}$$

When a jurisdiction has good abatement technology, a change in the relative price of the dirty good will induce a larger reallocation of resources from the clean to the dirty sector.

B Emission intensity and abatement efforts

It now becomes possible to derive an expression of ϕ in terms of prices. Using (6) to note that total emissions are equal to $e = ix$, we can rewrite the production function (4) as

$$x = \left(\frac{ix}{\Omega(\psi)}\right)^{\alpha} B(K_x, L_x)^{1-\alpha}$$

Yet, we also know that $x = (1-\phi)B(K_x, L_x)$. Hence

$$i = (1-\phi)^{(1-\alpha)/\alpha}\Omega(\psi) \tag{B.1}$$

which suggests that the emission intensity of the economy decreases in two cases: when more resources are devoted to abatement and when the abatement technology improves.

Now, substituting i for its expression in equation (6) yields

$$\frac{\alpha\Omega(\psi)p}{\delta} = (1-\phi)^{(1-\alpha)/\alpha}\Omega(\psi)$$

and we can therefore write

$$\phi = 1 - \left(\frac{\alpha p}{\delta}\right)^{\alpha/(1-\alpha)} \tag{B.2}$$

As it turns out, abatement effort is independent from Ω, the abatement technology quality. However, a change in abatement technology will affect equilibrium abatement effort through its effect on equilibrium emissions price.

C Regulatory threshold

The present discussion is based on Copeland and Taylor (2003). We adopt a constant relative risk aversion utility function for the consumption component of utility and a constant marginal disutility of emissions. Therefore, the indirect utility function becomes

$$V(p, I, E) = \frac{[I/\omega(\mathbf{p})]^{1-\eta}}{1-\eta} - \lambda E, \text{ with } \eta \neq 1$$

where $E = E_{-i} + e_i$. For simplicity, it is assumed that the economy produces only one (dirty) good so that income is

$$I = p\left(\frac{e_i}{\Omega}\right)^{\alpha} B(K, L)^{1-\alpha}$$

To find equilibrium emissions we derive the inverse pollution demand

$$\alpha p\left(\frac{e_i}{\Omega}\right)^{\alpha-1}\Omega^{-1}B(K,L)^{1-\alpha} \Leftrightarrow \alpha\,\underbrace{p\left(\frac{e_i}{\Omega}\right)^{\alpha} B(K,L)^{1-\alpha}}_{=I}\left(\frac{E_i}{\Omega}\right)^{-1}\Omega^{-1} \Leftrightarrow \frac{\alpha}{e_i}I \tag{C.1}$$

and the pollution supply

$$-\frac{V_{E_i}}{V_R} \Leftrightarrow -\frac{-\lambda}{\left[\frac{(I/\beta(p))^{-\eta}}{\beta(p)}\right]} \Leftrightarrow -\frac{\lambda\beta(p)}{R^{-\eta}} \tag{C.2}$$

Equating C.1 and C.2 and solving for e_i yields

$$e_i = \frac{\alpha}{\lambda}R^{1-\eta} \tag{C.3}$$

Substituting C.3 in the utility function leads to

$$V^R(p, I, E) = \left[\frac{1}{1-\eta} - \alpha\right] R^{1-\eta} - \lambda E_{-i} \tag{C.4}$$

In the no regulation case, no abatement takes place so that real income is equal to (potential) output and emissions are directly proportional to it. Utility is then defined as

$$V^{NR}(p, I, E) = \frac{R^{1-\eta}}{(1-\eta)} - \lambda R - \lambda E_{-i} \tag{C.5}$$

It can be shown that C.5 first rises and then declines with real income. V^{NR} increases over $[0, \sqrt[\eta]{1/\lambda}[$ and decreases over $]\sqrt[\eta]{1/\lambda}, +\infty$. Indeed, $\frac{\partial V^{NR}}{\partial R} = R^{-\eta} - \lambda$ is positive over $[0, \sqrt[\eta]{1/\lambda}[$, equals 0 in $R = \sqrt[\eta]{1/\lambda}$ and is negative over $]\sqrt[\eta]{1/\lambda}, +\infty$. Since V^R is monotonically increasing over the interval $[0, +\infty$, there exists a unique level of income such that $V^R = V^{NR}$ and beyond which $V^R > V^{NR}$. Moreover, as the fixed regulatory cost decreases, real income under the regulation option rises *for any level of potential output*. This, in turn, raises the utility level of the representative consumer and lowers the income threshold beyond which regulation is introduced.

D Emissions-weighted Carbon Price

D.1 Data sources

D.1.1 Prices

For each jurisdiction and each year we collect carbon price data in nominal local currency. Most jurisdictions quote the price of greenhouse gases (including CO_2) per tonne of CO_2e; others (essentially those with carbon taxes) express the carbon price per natural unit of the fuel. In the latter case, we convert the price to express it per tCO_2e using conversion factors from the World Resource Institute (World Resources Institute, 2015). All values are then converted into 2015 $US using the Official Exchange Rate (Local Currency Unit/$US) and inflation rate from the World Bank (2016).

Emissions Trading Schemes

Table 1: ETSs prices – details

Jurisdiction	*Price information*
EU-ETS	European Union emissions Allowances (EUA) futures price. Annual average of daily prices. Source: Bloomberg
Korea, Rep.	The market for Korean Allowance Units (KAUs) has been characterised by high illiquidity due to the absence of sellers amid concerns that the market is under-allocated. The last trade took place on March 15, 2016 at a price of $15.53. Source: South Korea Exchange
New Zealand	Annual average of daily spot prices of New Zealand Allowances (NZU). Source: Bloomberg.
Switzerland	As of 2015, no transaction of Swiss emissions allowances (CHU) had taken place over a centralised platform. Consequently, the price quoted in this study is the volume-weighted average price at auction. Source: Swiss Emissions Registry
California(-Quebec)	Annual average of daily California Carbon Allowances (CCA) futures contract price. Source: California Carbon Dashboard
RGGI	Volume-weighted annual average of spot transactions. Source: RGGI CO_2 Allowance Tracking System (COATS).

CO_2 taxes Information on sectoral fuel tax rates has been retrieved from a wide range of sources. A full list of sources is available upon request. These sources include (but are not limited to): OECD Database on Instruments used for Environmental Policy (OECD, 2016a), International Energy Agency Energy Price and Taxes publication (IEA, 2016), jurisdictions' budget proposals (as in the case of, e.g., Norway or Denmark), customs' agencies documentation, academic journal articles, policy assessment reports.

D.1.2 Scheme's coverage

This methodological appendix further details the steps involved in the computation of the coverage figures. Computing coverage figures requires defining a sectoral disaggregation of the economy. For the sake of consistency with International Energy Agency (2016) and CAIT (2015) data, we adopt the sectoral disaggregation recommended by the IPCC (2006) Guidelines for National Greenhouse Gases Inventories, which is itself based on the United Nations International Standards Industrial Classification (ISIC), Revision 4. Table 1 summarises the sectoral disaggregation.

The scope of an emissions trading scheme is defined at the sectoral level regardless of the fuel from which CO_2 – and other GHG – emissions originate. Therefore, an emissions trading scheme requires the measurement of GHG emissions at the point of emission. The design of carbon (or any other GHG)-taxes is different in that they can applied to specific fuel(s) within particular sectors. The sectors subject to it are determined independently.

Table 1: IPCC 2006 Sectoral disaggregation

IPCC sector name	**IPCC sector label**
Electricity Generation*	1.A.1.a.i
Combined heat and Power Generation*	1.A.1.a.ii
Manufacturing industries and construction*	1.A.2
Domestic Aviation	1.A.3.a.i
Road Transportation	1.A.3.b
Commercial and public services	1.A.4.a
Residential	1.A.4.b
Agriculture/forestry	1.A.4.c
Industrial Processes – cement	2.A.1
Waste	5

*In some countries and in some years, these sectors are covered by a tax and an emissions trading system. Sometimes, however, the tax schemes are designed to exempt those installations that are covered by the relevant ETS. Since CO_2 emissions data is disaggregated at the sector-fuel level and does not, within it, distinguish between those covered by the ETS and those that are not, it is not possible to account for this unless one makes an assumption about the proportion of emissions represented by the installations covered by the ETS.

The relevant physical unit to be measured in the case of a carbon tax is therefore the fuel consumption (and associated CO_2 emissions) at the user-fuel level. The fuel categories used in this study are: Coal/peat, Oil, Natural Gas.

The coverage information is recorded, for each jurisdiction and year, at the sector-fuel level as a binary variable (0 if the sector-fuel is not covered, 1 if it is). This coding is based on various sources, which vary from one country to the other. As for the carbon prices, a complete list of sources used to create the data points is available upon request. Table 2 summarises the information recorded.

Table 2: Institutional design

	Carbon Tax	Emissions Trading System
Price signal	Tax rate (nominal - local currency)	(Spot/Futures) Allowance price (nominal - local currency)
Sectoral coverage	✓	✓
Fuel coverage	✓	n.a.
GHG-gas coverage	*	✓
Sector-fuel exemptions	✓	n.a.

*The only GHG covered by carbon taxes is obviously CO_2.
Note: For each jurisdiction and year, except price, all information is coded as a binary entry.

Calculating total coverage (as a share of total GHG emissions) of carbon pricing schemes at the level of a jurisdiction is then performed according to the following formula

$$Coverage_{i,t} = \frac{\sum_j \sum_k q_{i,t,j,k} \times \mathbb{1}_{i,t,j,k}}{q_{i,t}^{GHG}}$$

where $q_{i,t,j,k}$ represents jurisdiction i's CO_2 emissions from sector j arising from the combustion of fuel k in year t; $\mathbb{1}_{i,t,j,k}$ is an indicator variable taking value 1 if fuel k in sector j of country i in year t is covered by the scheme, 0 otherwise; $q_{i,t}^{GHG}$ is the total greenhouse gases emissions in jurisdiction i in year t. Note that in the case of ETSs, the aggregation starts at the sector level, since all fuels are, by definition, covered.

The calculations make use of sector and sector-fuel CO_2 emissions data. National jurisdictions: International Energy Agency (2016); US States: CAIT (2015); Canadian Provinces and Territories: Statistics Canada (2018). Total GHG emissions (excluding land use change) are taken from the CAIT (2015) of the World Resources Institute.

D.2 Methodology

Equipped with this information, the emissions-weighted price (ECP) can be computed at the sectoral or economy-wide level. In the former case, the weights are the emissions as a share of a sector's total GHG emissions; in the latter, the weights are the emissions as a share of the jurisdiction's total GHG emissions. Formally, the ECP of sector j of country i in year t is expressed as

$$ECP_{i,t,j} = \frac{\sum_k [\tau_{i,t,j,k} \times (q_{i,t,j,k}^{tax} + q_{i,t,j,k}^{ets,tax}) + p_{i,t,j,k} \times (q_{i,t,j,k}^{ets} + q_{i,t,j,k}^{ets,tax})]}{q_{i,t,j}^{GHG}}$$

where $\tau_{i,t,j,k}$ is the carbon tax rate applicable to fuel k in sector j of country i at time t, $q_{i,t,j,k}^{tax}$ is the amount of CO_2 emissions covered by a tax only, $p_{i,t,j}$ is the price of an emission permit, $q_{i,t,j,k}^{ets}$ is the amount of CO_2 emissions covered by an ETS, $q_{i,t,j,k}^{ets,tax}$ is the amount of CO_2 emissions covered by both an ETS and a tax and $q_{i,t,j}^{GHG}$ is the quantity of GHG emitted by sector j of country i in year t.

An economy-wide ECP is then computed as a weighted average of the carbon rates across sectors, where the weights are the quantity of emissions subject to each individual carbon rate:

$$ECP_{i,t} = \sum_j (ECP_{i,t,j} \times \gamma_{i,t,j})$$

where $\gamma_{i,t}$ represents the GHG emissions of sector i as a share of the economy's (jurisdic-

tion's) total GHG emissions, i.e. $\frac{q_{i,t,j}^{GHG}}{q_{i,t}^{GHG}}$. For the purpose of the present study, only the economy-wide ECP is computed and both a time-varying and fixed weights version of the ECP are calculated. The fixed-weights ECP uses 2013 emissions data.