Essays in International Macroeconomics and Climate Policy



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Introduction

This thesis presents three self-contained chapters which discuss topics within international macroeconomics and/or climate policy.

Chapter 1 analyses adaptation to climate change in the presence of sovereign risk. Many emerging markets face high borrowing costs as well as exposure to natural disasters. This chapter asks: how do fiscal constraints affect adaptation and therefore the losses associated with climate change? I outline a sovereign default model augmented with natural disasters and endogenous adaptation. The model is used to elucidate the 'adaptation trap': high borrowing costs increase the marginal cost of adaptation, reducing protective investment and leading to higher losses from disasters. This reduced resilience further increases borrowing costs by increasing the probability of a natural disaster related default event. In order to test these predictions I construct a novel measure of adaptation using text analysis to identify adaptation expenditures in government budgets. Consistent with the model, I document a robust positive relationship between sovereign ratings and adaptation as well as a positive causal effect of cyclone strikes on default risk that is attenuated by adaptation. The sovereign risk- adaptation channel is quantitatively important in the estimated model. In the Caribbean 10% of GDP losses from cyclones are due to default risk. This loss increases with climate change but can be mitigated by debt relief policies. In particular, the introduction of an adaptation contingent bond can substantially increase adaptation investment and lower the costs of natural disasters.

Chapter 2, which is co-authored with Martin Bodenstein, Federico Di Pace, Aydan Dogan, and Marco Garofalo, examines the effects of a levy on the carbon footprint of imported goods—commonly known as the Carbon Border Adjustment Mechanism (CBAM). The CBAM is often proposed as a solution to the competitive disadvantage faced by firms subject to domestic carbon pricing and to the risk that production shifts to less regulated economies: emissions leakage. We develop a heterogeneous-firm trade model following Melitz (2003) in which emissions are a byproduct of production which can be reduced via costly abatement. The CBAM poses a compliance problem: foreign firms may not be

aware of their individual emissions intensity, and reporting is costly. In the model, as in EU legislation, foreign exporters choose between a default tariff and a firm-specific regime that allows firms to pay based on their actual emissions after costly reporting. This compliance choice generates a novel sorting mechanism: more productive exporters self-select into the firm-specific regime, internalising the destination country's carbon price and investing in abatement, while less productive exporters pay the default tariff without changing their emissions intensity. The CBAM therefore affects foreign emissions through a scale channel, a compliance channel, and an abatement channel, the latter two absent from existing models that treat the CBAM as a uniform sectoral levy. We characterise the jointly optimal carbon tax and default tariff, showing the two are complements: a higher domestic carbon price raises the optimal default tariff. The welfare-maximising tariff exceeds the level that would simply equalise carbon costs across domestic and foreign producers, reflecting a terms-of-trade motive. Extending to a three-country setting, we show that CBAMs generate trade diversion toward cleaner economies, conferring a relative competitive advantage on countries with lower structural emissions intensity.

Chapter 3 investigates the effects of climate policy risk on asset prices. Shifts in climate policy have heterogeneous effects on firms' profitability. This chapter asks: does the market price this risk? Theory predicts that exposed firms have negative abnormal returns on policy announcement dates. I build a set of such dates and characterize return responses using *Risk Factors* discussions in 10-K filings. An NLP algorithm uncovers predictors of policy risk exposure in the text. Exposure is correlated with emissions, environmental lobbying, and is predictive out-of-sample. Higher exposure is not associated with a premium. Empirically identified green preference shifts can partly explain this absence of a climate policy risk premium.

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CHAPTER 1.

Climate Change, Adaptation, and Sovereign Risk

Abstract

Many emerging markets face high borrowing costs and exposure to natural disasters. How will fiscal constraints affect the adaptation to, and therefore the losses from, climate change in such economies? A sovereign default model augmented with natural disasters and endogenous adaptation predicts that i) climate change increases borrowing costs, ii) adaptation reduces borrowing costs, and iii) default risk constrains adaptation. These economies suffer from an 'adaptation trap': high borrowing costs restrict adaptation, leading to higher losses from disasters and higher borrowing costs in the future. To test these predictions I construct a novel measure of adaptation using text analysis to identify adaptation expenditures in government budgets. Consistent with the model, I document a robust positive relationship between sovereign ratings and adaptation as well as a positive causal effect of cyclone strikes on default risk that is attenuated by adaptation. The sovereign risk- adaptation channel is quantitatively important in the estimated model. In the Caribbean 10% of GDP losses from cyclones are due to default risk. This loss increases with climate change but can be mitigated by debt relief policies.

1.1. Introduction

Climate change is projected to increase both the frequency and severity of natural disasters in many countries. Emissions reductions will not fully address the consequences of these disasters, especially in the medium term. Therefore, the attention of policymakers is turning towards adaptation: investments to limit damages from natural disasters when they occur.[1] However, adaptive investments are costly and many of the countries that are most exposed to climate damages also have limited fiscal space due to their susceptibility to public debt crises. This paper studies the interactions between climate change, adaptation, and sovereign risk. I show that default risk magnifies the costs of natural disasters via restricted adaptation.

The contribution of this paper is threefold. First, I develop a theoretical framework which integrates natural disasters, sovereign risk, and endogenous adaptation capital. Second, I construct a database of adaptation expenditures in Latin America and the Caribbean which I use to validate the predictions of the theoretical model. Third, I discipline the model with this data to derive quantitative results on the relationship between climate change, adaptation, and sovereign risk, and to simulate counterfactuals. The analysis focuses on the risk of hurricanes. Hurricanes are responsible for the largest share of monetary damages of any natural disaster and are projected to increase in frequency and severity as climate change intensifies.[2] Together, this paper provides new evidence that sovereign risk exacerbates the costs of climate change for emerging market economies.

I augment a quantitative sovereign default model with natural disaster shocks and endogenous adaptation capital. Disasters reduce the resources available for consumption, but damages can be limited via investment in adaptation. The model features output costs of default and long term debt as in Hatchondo and Martinez (2009). The sovereign issues debt to support consumption and invest in adaptive capital but cannot commit to repaying. It has the option to default in each period. The price of government debt endogenously adjusts to compensate lenders for default risk which is in turn affected by climate change. This default risk will therefore shape the adaptation choices made by sovereigns. Elevated default risk tightens the budget constraint, limiting the amount the sovereign can borrow. In the model default risk will increase the costs of natural disasters by generating under-investment in adaptation.

In order to sharply characterize the channels at play I solve analytically for the spread in a restricted version of the model. In this simplified framework there are two periods, log utility and procyclical default costs. The model implies a spread on government debt over

[1] For example coastal protections to limit flooding from cyclones, or early warning systems to prevent wildfire casualties.

[2] IPCC AR6: `https://www.ipcc.ch/assessment-report/ar6/`
In this paper I will use the terms 'cyclone', and 'hurricane' interchangeably.

the risk free rate. I show that the spread is increasing in the probability of a disaster. The more likely a bad shock is in the future, the more likely the sovereign is to default. Further, I prove that the spread is declining in the level of adaptive investment. The more the sovereign invests in adaptation, the less vulnerable they are to disasters in the future, and so the less likely they are to default. The presence of this adaptation channel attenuates the effect of climate change on the spread. As climate change intensifies, the incentives to adapt also grow. Therefore the sovereign will increase its adaptive capacity with climate change, reducing the impact of climate change on borrowing costs.

I compare the model to a counterfactual without default risk. In this counterfactual the sovereign commits to always repaying its debt and so can borrow at the risk free rate. Comparing the optimal adaptation choice under sovereign risk to the choice in the absence of default risk, I show that adaptation may be either higher or lower. The responsiveness of the spread to adaptation introduces an additional incentive to adapt. Greater investment in adaptive infrastructure reduces default probabilities and borrowing costs. However, the option to default also dampens adaptive investment by constraining the sovereign. Default risk tightens the budget constraint and so increases the marginal utility of consumption today, and reduces the marginal benefit of adaptation relative to the no-default benchmark. For emerging markets (relatively high spread economies), the second channel dominates and adaptation is constrained by default risk. Higher initial debt, lower default costs, and less patient sovereigns make the second channel more powerful. Economies with high existing debt burdens and climate change exposure are effectively 'locked-in' to low adaptation and a high likelihood of climate related defaults in the future - this is the adaptation trap. For these economies, adaptation is declining in borrowing costs.

I turn to the data to test the predictions of the model. I show that i) adaptation is declining in sovereign risk, ii) disasters cause sovereign risk to increase, and iii) adaptation attenuates that effect. In order to do this I construct a novel measure of adaptation. There is no available data on aggregate adaptation across countries. A contribution of this paper is to build such a measure, leveraging data from government budget documents. Budgets contain detailed information on the purpose of spending as well as the monetary amount allocated to each end. This data is therefore well suited to the task of measuring adaptation spending. I use a natural language processing approach, transfer learning, to identify adaptation related entries. A word embedding model pre-trained on adaptation-specific text generates a list of adaptation keywords. I search for entries containing these terms in each budget, and record the associated monetary value.

With this measure in hand I show that adaptation expenditure is increasing with sovereign rating. This result holds both across and within countries and is robust to controlling for institutional quality and natural disaster exposure. A one standard deviation

increase in sovereign credit rating is associated with an increase in annual adaptation expenditure of $250,000,000. Additionally, this direct measure of aggregate adaptation can be used to document descriptive statistics some of which are useful for calibrating the model. I show that economies in Latin America and the Caribbean spend on average 0.31% of GDP on adaptation, or 1.1% of total expenditure. Consistent with the model, adaptation is also increasing in exposure to natural disasters.

In order to establish that default risk is sensitive to natural disasters I exploit data on physical incidence of cyclone shocks from IBTrACS. I map the hurricane track data to affected countries and employ a local projection approach using data on CDS spreads for more than 30 countries, and default probabilities for 80 countries. I show that a hurricane strike increases CDS spreads by 1.5% six months after the event, accumulating gradually over the horizon. Additionally I show that a hurricane strike increases default probabilities by almost 3% three years after the event. Splitting the sample into high and low adaptation subsamples, I show that the effect is driven by the low adaptation group. For the set of countries with low adaptation expenditures, hurricanes cause a statistically significant increases in default probabilities while the effect is not distinguishable from zero for the high adaptation subsample. Consistent with the model this indicates that adaptation attenuates the impact of disasters on sovereign risk.

Having concluded that the predictions of the analytical model hold in the data I use these results to calibrate the quantitative version of the model. I estimate the endowment process for the set of Caribbean countries included in my sample. For these economies hurricanes are by far the most damaging hazard, allowing me to restrict attention to the disasters for which I have physical indicators. The process governing the effectiveness of adaptation is calibrated to match the data on adaptation investment. The model matches well the data on disaster incidence, borrowing, and default risk.

With this set up I quantify the importance of the sovereign risk - adaptation channel. Relative to a counterfactual without the default option, adaptation is substantially restricted. In the model without default risk, adaptation in the Caribbean is 13% higher than under sovereign risk. Default risk increases the GDP effects of cyclones by 10% relative to the no default risk benchmark. Therefore the sovereign risk - adaptation channel is quantitatively important for the aggregate affects of natural disasters. Moreover, the amount by which sovereign risk restricts adaptation is increasing as climate change intensifies. This implies that the GDP losses from cyclones are also diverging further from their no default risk counterparts as the probability and severity of those cyclones increases. In particular, with the projected 29% increase in cyclone probabilities and a 48.5% increase in severity by the end of the century, the GDP losses from cyclones are 13% higher than they would have been in the absence of the sovereign risk - adaptation channel.

Finally, I use the model as a laboratory to test the potential for debt relief policies.

These policies have the potential to be welfare improving by creating the fiscal space for adaptation. I consider two such policies. First, a long term risk free loan motivated by the IMF's Resilience and Sustainability Trust (RST). Second, an adaptation bond. Such a bond reduces coupon payments once the sovereign reaches a pre-specified adaptation target. The optimal size of the coupon reduction trades off two channels: i) the coupon reduction increases adaptation incentives and reduces default probabilities, and ii) the coupon reduction introduces a state contingency which demands a premium. The spread minimizing coupon reduction balances these effects. Both of these policies lead the sovereign to substantially increase their adaptation investment. This lessens the GDP losses from natural disasters and so eases the welfare burden of cyclones.

Related Literature and Contribution. This paper is related to numerous strands of the literature in macroeconomics and environmental economics.

First, this paper contributes to the literature on sovereign default in the tradition of Eaton and Gersovitz (1981), Aguiar and Gopinath (2006), Arellano (2008), and Chatterjee and Eyigungor (2012). Two existing papers embed natural disasters into a model of sovereign default. Mallucci (2022) considers the effect of these shocks on default risk for a sample of Caribbean countries. Phan and Schwartzman (2024) model the effect of sovereign risk on the economy's recovery from a disaster. Both papers consider the role for catastrophe bonds in limiting adverse effects. I contribute to this literature by embedding physical adaptation into a model of sovereign default with natural disasters. In this model the damages from disasters are therefore endogenous. I speak to the effect of sovereign risk on ex ante investment in climate resilience and therefore the losses from these disasters. Also related to this paper is Arellano, Bai, and Mihalache (2024) which considers debt relief policies in a sovereign default model with an epidemiological model of COVID. I consider similar policies in a setting with climate shocks and costly adaptation.

Second, I contribute to a quantitative-macro literature on adaptation to climate change. Fried (2022) develops a heterogeneous-agent model to quantify adaptation to climate change to severe storms in the US. Hong, Wang, and Yang (2023) model adaptation to climate change in the presence of learning about disaster risk. Cantelmo, Melina, and Papageorgiou (2023) find that self-financed adaptation infrastructure provides limited welfare gains for disaster-prone economies. Marto, Papageorgiou, and Klyuev (2018) argue for international donor support for resilience building in disaster-prone states. While the latter two papers consider the role of debt sustainability they do so in a reduced form way without explicit default risk. I contribute to this literature by considering how the option to default on debt affects the adaptation motive, and by providing estimates of adaptation investment useful for disciplining the model.

Third, I contribute to the empirical literature on adaptation to climate change. On the macro level, data on adaptation investment does not exist. Therefore, the dominant approach in the literature has been to treat adaptation as a latent variable. If the damages from a disaster of a given size are lower in areas with higher historical exposure (or if they decrease over time), this approach concludes that adaptation has taken place. The evidence has been mixed. Hsiang and Narita (2012) find that countries with more intense tropical cyclone climates suffer lower marginal losses from a given cyclone. Barreca et al. (2016) find that the mortality impact of high temperature days has fallen over time. Burke et al. (2024) find very limited evidence for adaptation. A small number of papers consider macro effects of particular adaptation strategies e.g. Molina and Rudik (2024) which considers the value of forecasts. On the micro level, direct measures of adaptation are more common. For example, Lane (2024) studies the role of credit market frictions in preventing farmers' adaptation to extreme weather. For a review of this literature see Carleton et al. (2024). I contribute to this empirical literature by building a direct measure of adaptation investment on the country-level. This measure allows me to consider how adaptation varies with other characteristics, such as fiscal space, and to disaggregate the components of adaptive investment.

Fourth, I contribute to an empirical literature on the fiscal effects of natural disasters and climate change.[3] Noy and Nualsri (2011) use a panel VAR to estimate the effects of disasters on fiscal outcomes. Klomp (2015) uses EM-DAT, a database of natural disasters mostly based on insurance claims or news stories, to estimate the effect of disasters on sovereign default premia. Auh et al. (2022) find price effects of natural disasters on US municipal bonds. Klusak et al. (2023) train a machine learning model to predict that sovereign ratings will be negatively affected by climate change. Cappiello et al. (2025) show that a higher frequency of disasters is associated with lower credit ratings. Closest to my approach is Klomp (2017) which estimates that natural disasters increase default probabilities. I contribute to this literature by using a local projection design and physical data on the incidence of hurricanes to estimate the effect of hurricanes on sovereign risk premia and default risk, accounting for the mediating role of adaptation.

Finally, I contribute to the literature on the relationship between disaster risk and asset prices along the lines of Barro (2009), Gourio (2012), and Nordhaus (2010). To this literature I add an additional feedback loop: adaptation can reduce the exposure of the economy to the diaster risk and so attenuate the effect on asset prices. However this adaptation investment is constrained by the value of government debt.

Outline. The rest of this paper proceeds as follows: Section 1.2 outlines the model and presents the analytical results. Section 1.3 outlines the empirical methodology and results.

[3] For a comprehensive review see Barrage (2024)

Section 1.4 outlines the quantitative analysis including policy counterfactuals, and Section 1.5 concludes.

1.2. Model

I augment a sovereign default model with natural disaster shocks and endogenous adaptation. The model features output costs of default, long term bonds as in Hatchondo and Martinez (2009), and natural disasters as in Mallucci (2022). To this framework I add public adaptation capital. A sovereign in a small open economy makes borrowing, investment, and default decisions to maximize utility of the representative agent. The endowment is subject to disaster shocks which reduce the endowment. Damages from these disasters can be limited through investment in adaptive infrastructure. International investors are risk neutral.

The sovereign's lifetime value is:

$$v_0 = \sum_{t=0}^{\infty} \beta^t \mathbb{E}\left(u\left(c_t\right)\right),$$

where $u(c_t)$ is the household's utility from consumption. The income process is given by:

$$y_t = y_{t-1}^{\rho}(1 - x_t d_t F\left(\Lambda_t\right))\, \epsilon_t^y,$$

where ρ allows for persistence in the endowment process and x_t is an indicator variable for the natural disaster shock with:

$$\mathbb{P}(x_t = 1) = p.$$

A disaster realization ($x_t = 1$) reduces the endowment. Disaster damage is given by the continuous variable d_t which is iid distributed according to the distribution Φ_d with support $[0, 1)$. The endowment shock $log(\epsilon^y)$ is normally distributed with mean zero. The stock of adaptation capital is denoted by Λ_t. Adaptation reduces the damages from a disaster. The function $F(\Lambda)$ governs the process by which adaptation reduces damages. I assume that $F(\Lambda)$ satisfies the Inada conditions. It is decreasing and convex in adaptation. The marginal product of adaptation is infinite at zero adaptation. Therefore all sovereigns will find it beneficial to invest in at least a small amount of adaptation.[4] The stock of adaptation follows the law of motion:

$$\Lambda_t = (1 - \delta)\Lambda_{t-1} + \lambda_{t-1},$$

[4]The data shows that adaptation investment is non-zero for all Latin American and Caribbean countries 2010-2025.

where λ_t is investment in adaptation. Adaptation investment accumulates into next period capital.

I assume the coupon structure from Hatchondo and Martinez (2009): a bond issued in period t promises an infinite stream of coupons, which decreases at a constant rate ψ. Therefore, the duration of a bond is $\frac{1+r^*}{\psi+r^*}$.

In each period the sovereign first chooses whether or not to default on its outstanding debt. Then they decide on bond issuance (if they did not default), and investment in adaptation. If the sovereign chooses to default, it loses access to financial markets and suffers the output cost of exclusion $\phi(y_t)$. In the following period the sovereign regains access to financial markets with exogenous probability η. The resource constraint is therefore given by:

$$c_t = (1 - D_t)y_t + D_t\left(y_t - \phi(y_t)\right) + (1 - D_t)q_t(b_{t+1} - (1 - \psi)b_t) - (1 - D_t)b_t - \lambda_t, \tag{1.1}$$

where q_t is the price the bond, b_t denotes the number of outstanding coupon claims, and D_t is a default indicator. $D_t = 1$ indicates that the sovereign is in the default state.

The price of the bond that gives risk neutral investors zero profit in expectation is given by:

$$q_t = \frac{1}{1+r}\mathbb{E}\left((1 - D_{t+1}) + (1 - \psi)(1 - D_{t+1})q_{t+1}\right), \tag{1.2}$$

where the first term on the right hand side is the next-period coupon payment promised by a bond. The second term is the expected value for all future coupon payments, denoted as the resale value of the bond next period.

1.2.1. Recursive Equilibrium

In equilibrium, the sovereign sets the policy for default, bond issuance, and adaptation investment to maximize welfare of the representative household, subject to the resource constraint, the constraint implied by foreign lenders' pricing of debt, and the law of motion for adaptation.

The equilibrium is formally defined by: 1) a set of value functions for the representative household: total value V, the value with market access V_{nd}, and the value in default V_d:

$$V = \max_D \left\{(1 - D)V_{nd} + DV_d\right\}, \tag{1.3}$$

$$V_{nd}(y, b, \Lambda) = \max_{b', \Lambda'} u(c) + \beta \mathbb{E}[V(y', b', \Lambda')], \tag{1.4}$$

$$V_d(y, 0, \Lambda) = \max_{\Lambda'} u(c) + \beta \mathbb{E}[(1-\eta) V_d(y', 0, \Lambda') + \eta V(y', b', \Lambda')], \tag{1.5}$$

2) government policies for default D, bond issuance b, and adaptation Λ, and 3) a government debt price function q such that:

- the debt price function is consistent with optimization by foreign lenders (1.2),
- the value functions of the household and the policy functions of the government solve the maximization problem,
- and the resource constraint of the household (1.1) is satisfied.

1.2.2. Analytical Characterization

In order to sharply characterize the relationship between sovereign risk, climate change, and adaptation and to derive some testable implications of the model I make a number of assumptions. First, I restrict the model to two periods such that the sovereign chooses adaptation and borrowing only in period one, and default only in period two. In period one adaptation capital is set to zero, and the endowment is normalized to one. For tractability I assume log utility:

$$u(c_t) = ln(c_t).$$

Default costs are procyclical as in Aguiar and Gopinath (2006) and Phan and Schwartzman (2024):

$$\phi(y_t) = y_2 \bar{l} e^{\psi g}.$$

This implies that the sovereign has more incentive to default in low-growth states. Such an assumption is common in the quantitative sovereign default literature as it helps to match cyclical movements of spreads.[5]

[5] I will consider quadratic default costs in the quantitative model. These default costs have better quantitative properties. Note: while the model is a model of the cycle and not the trend I call g 'growth' for simplicity: it is the rate of endowment growth between period 1 and period 2 in the simple model.

No Default Risk Benchmark

I begin by outlining a benchmark version of the model where there is no default risk. The sovereign cannot default on its debt and so repays the issued bonds in period two. This benchmark will be useful for examining the effects of the default option on adaptation. In this case consumption is given by:

$$c_1 = y_1 + \frac{1}{1+r}b - b_0 - \lambda, \qquad c_2 = y_1^{\rho}(1 - x_2 d_2 F(\lambda))\epsilon^{y} - b,$$

where b is bond issuance in period one. Debt is fully repaid in period two in this benchmark. As there is no default risk, the price of the bond is given by $\frac{1}{1+r}$ where r is the risk free rate. Adaptation investment λ is chosen in period one. The adaptation choice therefore trades off the costs of investment and the benefits of reducing damages next period.

PROPOSITION 1.1. *Adaptation is increasing in the probability of a disaster:*

$$\frac{\partial \lambda^*}{\partial p} > 0$$

FOC(λ)*:*

$$\frac{1}{c_1} = -p\beta\mathbb{E}\frac{d_2 F'(\lambda) y_1^{\rho}\epsilon^{y}}{c_2(x_2 = 1)} \tag{1.6}$$

where the proposition follows since $F(\lambda)$ is decreasing and convex. A higher value of p increases the likelihood of a negative shock next period. Therefore the expected benefits of adaptation are greater. This increases the sovereign's adaptation choice. [6]

Limited Commitment

Now consider the case where there is default risk. The sovereign can no longer commit to repaying the bond. In period 2 the sovereign decides whether or not to repay its debt. If the sovereign defaults, it is subject to the default cost:

$$\Phi(y_2) = y_2 \bar{l} e^{\psi g}.$$

where

$$g = log(\epsilon_2^{Y})$$

which has an iid normal distribution $\Phi(g)$.

Consumption in period 2 is denoted by c_R if the sovereign chooses to repay, and c_D if it defaults. The sovereign defaults if $c_D > c_R$, where:

[6] There is also an incentive for the sovereign to decrease its borrowing under climate change: a precautionary savings motive. See Appendix A.2.4

$$c_R = y_1^{\rho}(1 - x_t d_t F(\lambda))\epsilon^{y} - b, \qquad c_D = y_1^{\rho}(1 - x_t d_t F(\lambda))\epsilon^{y} - \phi(y_2). \tag{1.7}$$

This implies that default occurs if the stock of debt is greater than the cost of default:

$$b > \phi(y_2). \tag{1.8}$$

Equivalently, default occurs if the disaster adjusted growth rate $\tilde{g}$ is below an endogenous default threshold $\bar{g}$:

$$\underbrace{g + \frac{1}{1+\psi} ln(1 - x_2 d_2 F(\lambda))}_{\tilde{g}} < \underbrace{\frac{1}{1+\psi} ln(\frac{b}{\bar{l} y_1^{\rho}})}_{\bar{g}}, \tag{1.9}$$

where the endogenous default threshold is determined by the size of the default costs and the debt to GDP ratio. A higher debt to GDP ratio increases the default threshold $\bar{g}$ and so makes default more likely. Larger default costs lower the threshold and therefore make default less likely. In the absence of a disaster, the sovereign defaults if the growth rate g is below this endogenous default threshold. If a disaster hits, the growth rate falls to $\tilde{g} < g$. Therefore, a disaster makes default more likely.

Investors are risk neutral. Default risk implies that the price of the bond in period 1 will include a spread over the risk free rate. The price of the bond is given by:

$$q = \frac{1 - s}{1 + r}$$

where the spread is the probability of default:

$$\begin{aligned} s(b, \lambda) &= \Pr\left[\tilde{g}' < \bar{g}(b)\right] \\ &= (1 - p)\Phi_g(\bar{g}) + pE_{d'}\left[\Phi_g\left(\bar{g} - \frac{1}{1+\psi} ln(1 - d_2(F(\lambda))\right)\right] \end{aligned} \tag{1.10}$$

This implies the following two results:

PROPOSITION 1.2. *The spread is increasing in the probability of a disaster*

$$\frac{\partial s}{\partial p} = -\Phi_g(\bar{g}) + E_{d'}\Phi_g\left(\bar{g} - \frac{1}{1+\psi} ln(1 - d_2 F(\lambda)\right) > 0.$$

Proof. Appendix A.2.

PROPOSITION 1.3. *The spread is increasing in a first order stochastic dominance sense in the distribution of the severity of the disasters*

$$\hat{\Phi}_d \overset{fosd}{\geq} \bar{\Phi}_d \Rightarrow s(\cdot,\cdot|\hat{\Phi}_d) \geq s(\cdot,\cdot|\bar{\Phi}_d).$$

Proof. Appendix A.2.

An increase in the frequency or severity of disasters increases the likelihood of a low value for $\tilde{g}$. Therefore, in the model climate change increases default probabilities and so raises borrowing costs for the sovereign. In this model there is an additional effect through adaptation:

PROPOSITION 1.4. *The spread is decreasing in the level of adaptation*

$$\frac{\partial s}{\partial \lambda} = pE_{d'}\left[\phi_g\left(\bar{g} - \frac{1}{1+\psi}\ln(1-d(F(\lambda)))\right)\cdot\frac{d\cdot F'(\lambda)}{(1+\psi)(1-d\cdot F(\lambda)}\right] < 0$$

Proof. Appendix A.2.

The more the sovereign invests in adaptation, the lower the expected damages from a disaster shock are next period. Adaptation reduces the exposure of the economy to a bad shock in the future. This increases the disaster adjusted growth rate $\tilde{g}$ in the disaster state, and so reduces the probability of default. As adaptation reduces the probability of a disaster causing the sovereign to default, it also increases the market value of the government's debt.

Additionally, allowing for endogenous adaptation makes the spread less responsive to an increase in the probability of a disaster.[7] Adaptation reduces expected damages and so attenuates the effect of climate change on borrowing costs:

$$\frac{\partial s}{\partial p} < \left.\frac{\partial s}{\partial p}\right|_{\lambda=0}$$

The adaptation choice itself is affected by the presence of default risk. Given the bond price function derived above, the sovereign chooses b and λ in period one to maximize lifetime utility. Now:

$$c_1 = y_1 + \frac{1-s}{1+r}b - b_0 - \lambda,$$

and the expected value of consumption in period two is the given by the default probability and the default and repayment values as in (A.2.6). The sovereign internalises the effect

[7] This is also visible via the cross partial derivative: see Appendix A.2

of its adaptation choice on the price of its bond. The first order condition for adaptation is therefore given by:

$$\underbrace{\frac{1}{c_1}}_{MC} = \underbrace{\beta\mathbb{E}\left(\frac{y_2'(\lambda)}{c_R} - s(\lambda)\frac{y_2'(\lambda)b}{y_2 c_R}\right)}_{\text{MB damage reduction}} + \underbrace{\beta\mathbb{E}\left(s'(\lambda)(u(c_D) - u(c_R))\right)}_{\text{MB reduced default prob}} \underbrace{-\frac{\frac{1}{1+r}s'(\lambda)b}{c_1}}_{\text{MB lower spread}} . \tag{1.11}$$

The presence of default risk introduces two additional terms relative to the no default risk case (1.6): the marginal benefit of a reduced default probability, and the marginal benefit of lower borrowing costs. As shown in Proposition 1.4, the probability of default is declining in the level of adaptive investment. As long as utility is greater in the repayment state than in the default state in expectation, higher adaptation is therefore associated with a marginal benefit of reducing the probability of default. The second additional marginal benefit arises as adaptation lowers the spread and so reduces borrowing costs for the sovereign. These two additional terms increase the incentive for the sovereign to adapt relative to the no default risk case.

However, default risk also tightens the budget constraint and lessens the ability of the sovereign to consumption smooth. Therefore consumption is pushed forwards in time relative to the no default risk case: c_1 is lower relative to c_R. This increases the marginal cost of adaptation, and reduces the marginal benefit of damage reduction relative to the no default risk case. In this way, the presence of default risk constrains the sovereign, dampening the incentive to invest in adaptation.

The presence of default risk both introduces new benefits from adaptation through the default probability, and reduces the incentive to adapt through the budget constraint. Therefore, adaptation may be either higher or lower with default risk than without. Whether adaptation is higher or lower under default risk will depend on the relative size of these two channels. This will depend on the calibration of the model.

For low spread calibrations the first channel dominates and adaptation is higher under default risk than without. However, for calibrations giving reasonable spread values for emerging economies, the second channel dominates and adaptation is restricted relative to the no default risk benchmark. Economic fundamentals are important for determining whether a sovereign will be enabled or restricted from investing in adaptation by the presence of default risk.[8] Figure 1.1 shows a representative emerging market calibration where baseline spreads are high and adaptation is lower under default risk than without for all values of the probability of a disaster. Figure 1.2 shows that adaptation is also declining with the intensity of sovereign risk. For higher initial levels of debt, the spread

[8] Appendix A.2 outlines the forces determining this tradeoff. Adaptation will be higher under limited commitment only if spreads are very low while also being very responsive to adaptation. Such calibrations are counterfactual for emerging markets.

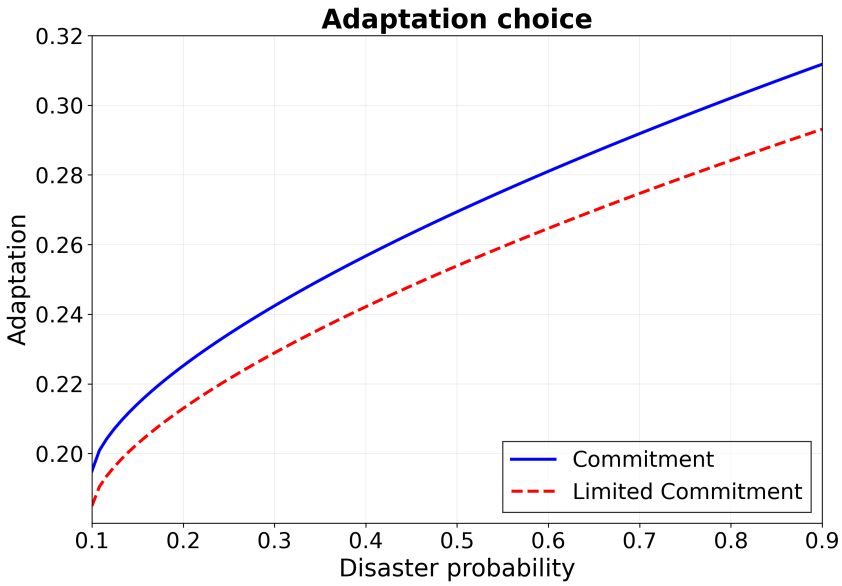


FIGURE 1.1. Optimal adaptation for a range of values of the probability of a disaster. The blue line shows the case with no default risk, the red dotted line shows the case with such risk. Parameter values are standard for emerging markets: $\beta = 0.9$, $b_0 = 0$, $\bar{l} = 0.7$, $\psi = 7$, $r = 0.01$.

is higher restricting adaptation via increased marginal costs.

It is worth drawing out two comparisons to the related literature. First, in this model with endogenous adaptation, the effect of climate change on default risk is attenuated. Previous literature has assumed that the size of climate damages are fixed (or increasing at a deterministic rate). This implicitly assumes away the potential for endogenous adaptation. Allowing for adaptation investment which responds to the probability of a disaster, even when that adaptation is constrained by default risk, reduces damages from future events. Therefore in this model the effect of climate change on borrowing costs will be less than in model such as Mallucci (2022) or Phan and Schwartzman (2024). Therefore the model predicts climate change will be less impactful for default probabilities than previous literature.

On the other hand, the model tells us that the presence of default risk may substantially affect the adaptation decision. Therefore, relative to the literature on adaptation without this friction (for example Hong, Wang, and Yang (2023)) the model predicts that climate change will be more damaging. From this exercise we learn that even when adaptation is very effective, and would therefore also be effective in reducing borrowing costs tomorrow, the presence of the constraint today may prevent the sovereign from accessing these benefits. This opens the door to the potential for debt relief policies to improve climate resilience.

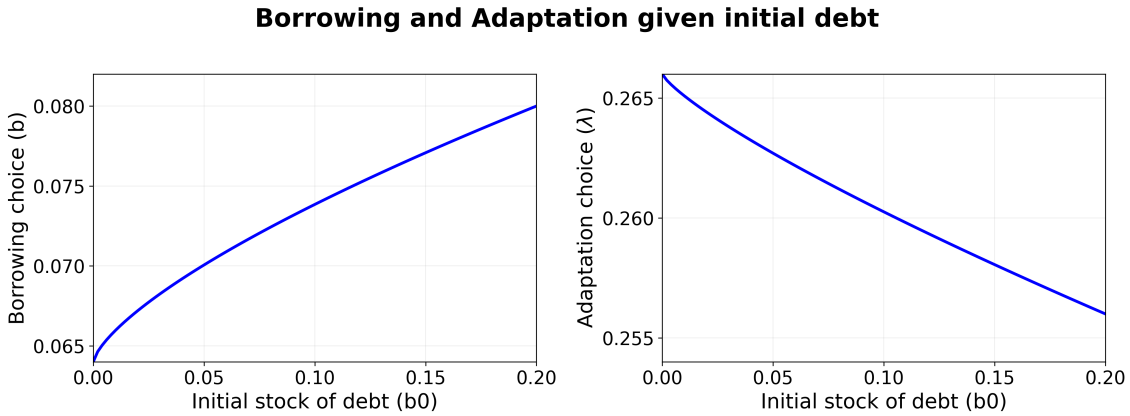


FIGURE 1.2. Adaptation and Borrowing choices for a range of initial debt levels. Probability of a disaster is set to $p = 0.5$. Remaining parameter values are as in Figure 1.1

1.3. Data

The model predicts that i) adaptation is declining in sovereign risk, ii) natural disasters increase default probabilities, and iii) adaptation attenuates that effect. I validate these predictions in the data.

1.3.1. A Novel Measure of Adaptation

The claim that more fiscally constrained economies are less able to invest in protecting themselves against future climate damages is a key pillar of the argument for debt relief for climate resilience. Does this relationship hold in practice? One obstacle to testing it is the lack of data on adaptation investments by country.

The literature on economy-wide adaptation to natural disasters has thus far employed a latent variable approach to test for the existence of adaptation using weather shocks. If the damages from a disaster of a given size are lower in areas with higher historical exposure (or if they decrease over time), this method infers that adaptation has taken place. Identification in this latent variable approach comes from panel variation and suffers from low power. Therefore it is not possible to directly test how the amount of adaptation varies across countries. It is also not possible to understand how exactly countries are adapting to climate change.[9] I build a direct measure of adaptation which can be used to understand how investment varies across countries, and its components.

[9] See Carleton et al. (2024) for a review of the empirical literature on adaptation to climate change.

Data and Methodology

Sample. I leverage data from government budgets. These documents contain detailed descriptions of spending by purpose and associated monetary allocations. Budgets are available on government websites in PDF format. I focus on Latin America and the Caribbean. Economies in this region are subject to the dual challenges of natural disaster exposure and elevated sovereign risk.

The key challenge is to generate a measure that is sufficiently complete and comparable. Adaptation encompasses many strategies including: early warning systems, physical infrastructure, ecological adaptations, and relocation or behavioral measures. In the context of the Caribbean in particular, governments have heavily invested in coastal protection infrastructure including sea walls, artificial reefs, and drainage systems. Nature-based solutions are also common. These strategies include planting of mangroves and reef management.[10] Governments may describe their investments in each of the strands of adaptation in different ways in their respective budgets as reporting is not standardized. I therefore build a general measure of adaptation utilising text analysis methods to flexibly account for a range of adaptation strategies. I show that my results are robust to i) including country fixed effects to account for differences in budgetary processes across sovereigns, and ii) using narrower measures of adaptation: meteorological services expenditure or disaster preparedness expenditure.

Methodology. I use tools from natural language processing to identify line items in government budgets that correspond to a broad notion of adaptation. This measure will be less sensitive to exactly how budgets categorize their spending than pre-specifying narrow subcategories of adaptation. The procedure for constructing this total adaptation measure follows six steps:

First, I supply a list of initial keywords which unambiguously describe adaptation. I draw this list of initial keywords from two sources: table 17.1 from chapter 17 of the IPCC AR6, and table SPM.4 from the IPCC AR4 summary for policymakers. Both of these tables list common ways by which countries adapt to climate risk. The set of initial keywords is listed in Appendix A.1.1. Second, I build a large corpus of text discussing adaptation. This allows me to train a model to recognize the niche language that is often used in discussing adaptation. This text comes from a number of sources listed in Appendix A.1.2, including UN adaptation reports and development bank reports. Third, I pre-process this raw text to obtain a set of terms, including bigrams and trigrams. After pre-processing there are $V = 65{,}971$ unique terms that appear a total of 43 million times in the corpus. Details of the text pre-processing are described in Appendix A.1.3.

Fourth, I construct word embeddings in this corpus using the GloVe model from

[10] See IPCC AR6 for a review.

the Stanford NLP group.[11] GloVe is an unsupervised machine learning model used for obtaining vector representations of words. The model uses co-occurrences of words to map them into a meaningful space where the distance between words relates to how similar they are semantically. The context of a term $w_{d,n}$ in a vocabulary V is defined as a window of terms surrounding that term:

$$C\left(w_{d,n}\right) = \left(w_{d,n-L}, \ldots, w_{d,n-1}, w_{d,n+1}, w_{d,n+L}\right). \tag{1.12}$$

Co-occurrences are defined by a VxV matrix where an entry $W_{i,j}$ is the number of times that term i appears within the context of j, and vice versa. As is standard, I chose the context window $L = 10$. Each term is associated with a vector $\boldsymbol{\rho}_v$ in $\mathbb{R}^K$ by the model. These vectors are chosen to solve:

$$\min_{\boldsymbol{\rho}_v} \sum_{i,j} f\left(W_{i,j}\right)\left(\boldsymbol{\rho}_i^T \boldsymbol{\rho}_j - \log\left(W_{i,j}\right)\right)^2 \tag{1.13}$$

where $f(\cdot)$ is a non-negative, increasing, and concave weighting function, such that rare word pairs count less in the objective. This minimizes the squared difference between the dot product of the word vectors, $\boldsymbol{\rho}_i^T \boldsymbol{\rho}_j$, and the empirical co-occurrence, $\log\left(W_{ij}\right)$. Terms that regularly co-occur tend to have vectors with a high dot product. The fitted vectors $\hat{\boldsymbol{\rho}}_v$ are the embeddings. These give similar representations to words that appear in similar corpus contexts and can be used to represent and compare vocabulary terms.

Fifth, I identify terms with a high semantic similarity to at least one of the initial keywords. I use the standard distance measure to compare vectors in text analysis: cosine similarity. This value is higher when the angle between the vectors is smaller i.e. when they share similar directions in the vector space. I select terms which have a cosine similarity of at least 0.7 with at least one of the initial keywords. The initial keywords plus these semantically similar terms comprises my final set of keywords.[12] Finally, I search for instances of the keywords in the budgets. I record the *monetary value* associated with each entry containing at least one of these keywords. The final measure of adaptation is the sum of monetary values associated with each of the flagged entries. In this final step I hand read all flagged entries to ensure there is no double counting. In this final step I also hand-prune a small number of false positive entries from the analysis.[13] As an example I include documentation of the line items included for the Bahamas in 2024 in Appendix

[11] For an overview of word embeddings, along with other text algorithms and their application in economics see Ash and Hansen (2023)

[12] For the final set of keywords see Appendix A.1.

[13] This pruning removes < 2% of the included line items.

A.1.

As well as this total measure of adaptation I consider two narrower measures. From hand reading all entries flagged by the algorithm I find that each document contains some entry related to 'disaster preparedness' expenditure. While budgets contain entries related to many specific projects to do with adaptation such as building a new sea wall or maintaining an existing dyke, governments also budget for a general disaster preparedness fund. This allows them to mobilize resources when a disaster is forecast. I take the value allocated to this end as my second measure of adaptation. This measure has the advantage of being included in every budget, of agreed meaning, and so is comparable across my sample.

Second, all countries also budget for their meteorological services. Early warning and forecasting of natural disasters is considered one of the key ways in which economies can adapt to the increasing frequency and severity of these disasters. Therefore I take the amount of meteorological service spending in each country as my final measure of adaptation.

As a measure of sovereign risk I use the average of the sovereign's previous three years of sovereign ratings from the World Bank Group cross-country database of fiscal space (Kose et al. 2022).[14] This results in an unbalanced panel of 19 countries in Latin America and the Caribbean with a sovereign rating from 2014-2025. [15]

Results

I find that adaptation expenditure is 0.31% of GDP on average for economies in this sample. This corresponds to 1.1% of total expenditure. Disaster preparedness expenditure is 0.11% of GDP on average. Summary statistics are reported in Table 1.1.

TABLE 1.1. Summary Statistics

	N	Mean	St. Dev.	Min	Max
Adaptation Total / GDP	163	0.31%	0.0011	0.001	0.0187
Adaptation Total / Expenditure	163	1.1%	0.0090	0.0038	0.0538
Disaster Preparedness / GDP	163	0.11%	0.0024	0.0001	0.0122
Meteorological / GDP	163	0.03%	0.0007	0.000	0.0009

These results imply that on average adaptation investment is about a tenth of health expenditure, or a fifth of agricultural spending.[16] The closest existing statistic is from

[14]This dataset on fiscal space results in the largest possible panel for my analysis. Results using alternative measures of sovereign risk (CDS spreads, EMBI spreads) are presented in Appendix A.1.13.

[15]Mexico, Argentina, Uruguay, Honduras, Guatemala, Colombia, Peru, Chile, Ecuador, Costa Rica, Dominican Republic, Grenada, Belize, Jamaica, Barbados, Bahamas, Turks and Caicos, St Vincent and the Grenadines, Panama. For details of sample construction see Appendix A.1.6

[16]Source: Economic Commission for Latin America and the Caribbean (ECLAC)

Hong, Wang, and Yang (2023). They compute average flood control spending for a sample of countries in Australasia, finding it to be around 0.3% of GDP. I find that total adaptation spending in Latin America and the Caribbean is of a similar magnitude to flood control spending in Australasia.

In order to validate the measures of adaptation I investigate how it varies with exposure to natural hazards. The existing literature on adaptation infers its presence from a negative relationship between historical exposure to natural disasters and damages from disasters of a given size. I can test the underlying assumption that adaptation is increasing with exposure using my dataset. Figure A.1 shows this relationship. As cyclones are the most damaging disaster in this region I take average historical wind speeds scaled by land area as a measure of natural disaster exposure. Countries with higher historical exposure to storms tend to invest more in adaptation. I find the same positive relationship between exposure to natural disasters and adaptation using a number of other measures of exposure. For details see Appendix A.1.9. This positive relationship between historical exposure to disasters and adaptation indicates that governments respond to their climatic conditions by investing in measures to build resilience.

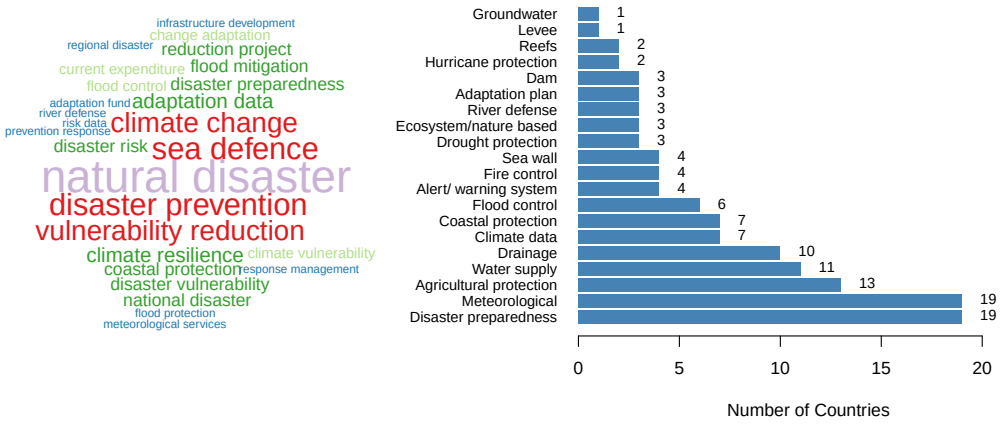


FIGURE 1.3. Adaptation is disaggregated by subtype. The left panel shows the most frequently used terms in budget entries flagged by the algorithm. The right panel shows the most common categories of adaptation by country in 2022.

With the measure of total adaptation spending I can also investigate the components of adaptation. The machine learning approach to building a measure of adaptation picks out budget entries that include at least one term from the key word dictionary. I process all of the text from each of these entries to understand the components of adaptation. The left panel of figure 1.3 shows a word cloud representing the most frequently used terms in adaptation related budget entries. Disaster response and flood protection are important

components of adaptation. For the Caribbean subsample cyclones are the most salient risk and coastal protection stands out further as an important channel of adaptation as shown in figure A.4. To further investigate the components of adaptation I categorize the search terms and construct count variables for each component. The right panel of figure 1.3 documents the most common components of adaptation. After disaster preparedness and meteorological expenditure, agricultural, water supply, and coastal protection are the most common forms of adaptation. Appendix A.1.9 shows that countries tend to spend more adapting to disasters they are relatively more exposed to.

I now use the validated adaptation measure to investigate how adaptation spending varies across countries' characteristics. In particular, I find a positive and significant relationship between sovereign ratings and adaptation spending. Figure 1.4 shows this relationship. The binned scatter plot shows that country-year observations with higher sovereign ratings are associated with higher adaptation expenditures. The result is robust to leaving out one observation at a time and is significant at the 10% level. It also holds for the two narrower measures of adaptation as shown in figure 1.5. To further examine the relationship I run the following regression:

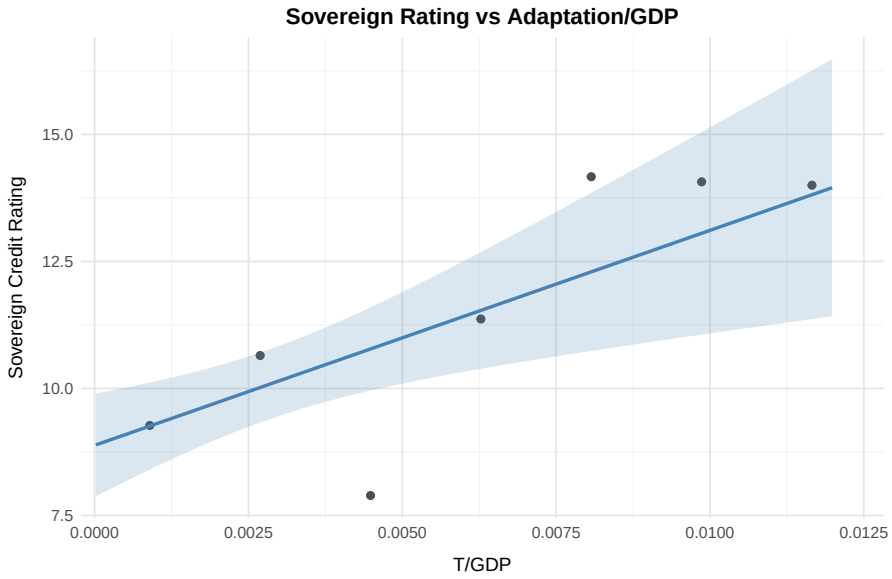


FIGURE 1.4. Adaptation Investment and Sovereign Ratings. Sovereign ratings are an average of the previous three years, on a scale from 0-21 from the World Bank fiscal space database (Kose et al. 2022). The adaptation measure is total adaptation spending as derived from the computational linguistics measure, shown as a proportion of GDP and in 8 bins. The shaded region shows standard errors at the 90% level.

$$\text{Adaptation}_{i,t} = \beta_0 + \beta_1 \text{sovrate}_{i,t} + \Gamma X_{i,t} + \mu_t + \varepsilon_{i,t}, \tag{1.14}$$

where *Adaptation* is the measure of adaptation as constructed above measured in 2017 US dollars and *sovrate* is the average of the sovereign's ratings over the previous three years on a scale from 0-21 from the World Bank fiscal space database (Kose et al. 2022). X is a vector of controls that includes GDP, a measure of exposure to natural hazards: average maximum historical wind speed, and an index of government effectiveness from the World Bank.[17] Table 1.2 shows the results of this estimation. The first column controls for exposure and government effectiveness, the second column instead includes a country fixed effect. In both cases there is a significant positive relationship between adaptation expenditure and sovereign rating. In particular, a one point increase in sovereign rating is associated with an increase in adaptation spending of approximately $67 million according to the first specification, and $31 million according to the second. Regression results for disaster preparedness and meteorological expenditure are shown in Appendix A.1.11.

	adapt	
sovrate	67,554,921***	30,901,342***
	(16,647,312)	(8,924,107)
gdp	0.0022***	0.0071***
	(0.0002)	(0.0017)
exposure	143,757,032**	
	(62,519,154)	
government effectiveness	121,350,937**	
	(48,299,257)	
Country Fixed Effects	No	Yes
Year Fixed Effects	Yes	Yes
Observations	98	151
R-squared	0.95	0.97
Note:	*p<0.1; **p<0.05; ***p<0.01	

TABLE 1.2. Regression Results. adapt and gdp are in millions of 2017 US dollars. sovrate is an index from 0-21. Exposure is historical average maximum windspeed scaled by land area, and standardized to have mean 0 and standard deviation 1. Government effectiveness is an index from the World Bank standardized to have mean 0 and standard deviation 1. Standard errors are clustered by country and year.

[17] For more information on the controls see Appendix A.1.8.

This positive relationship between adaptation and sovereign ratings is consistent with the model. The model predicts both that higher sovereign ratings cause adaptation to be higher, and that greater adaptation spending reduces sovereign risk. None of the major rating agencies explicitly include adaptation in their rating methodologies. Therefore it is likely that the empirical results as presented indicate that sovereign risk restricts adaptation expenditure. This is consistent with statements from borrowing constrained governments.[18]

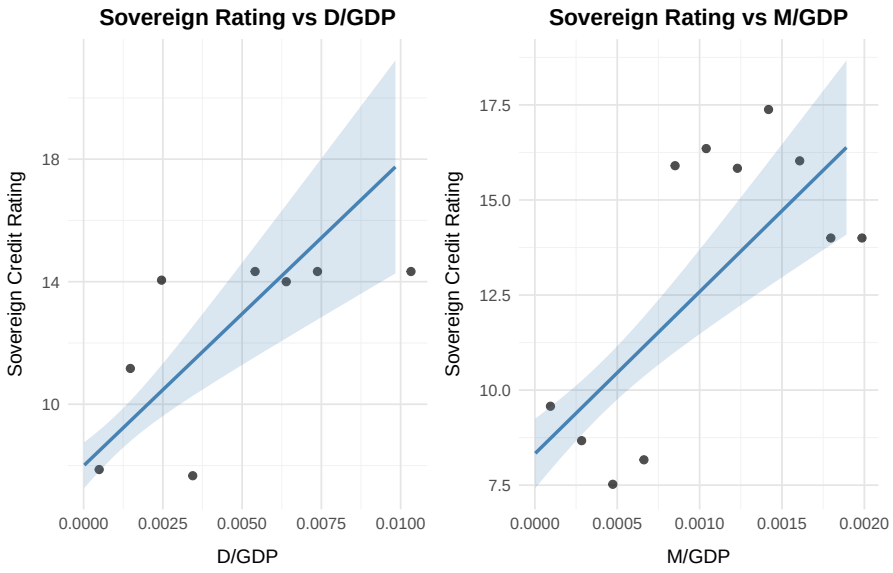


FIGURE 1.5. Adaptation Investment and Sovereign Ratings. Sovereign ratings are an average of the previous three years, on a scale from 0-21 from the World Bank fiscal space database (Kose et al. 2022). The adaptation measures are disaster preparedness expenditure and meteorological services expenditure, both scaled by GDP.

1.3.2. Natural Disasters and Sovereign Risk

Having validated that adaptation is declining in sovereign risk I investigate the additional predictions of the model. How does climate change affect sovereign risk? How is this relationship mediated by adaptation? I provide a causal estimate of the effect of a hurricane strike on sovereign risk premia and default probabilities, and show that the response differs with adaptation expenditure.

Much of the existing literature examining the macroeconomic effects of natural disasters uses data from EM-DAT. The EM-DAT database collates damages from natural disasters using insurance claims and news articles as its source.[19] Felbermayr and Gröschl (2014),

[18] For additional narrative evidence and discussion of rating agency methodologies see Appendix A.1.14.

[19] `www.emdat.be`

show that the use of such data leads to estimation bias when estimating growth effects of disasters on a global panel as selection correlates with GDP. In advanced economies disasters are more likely to be covered in the news and/or result in insurance pay-outs. As a result disasters in these countries are more likely to be recorded in EM-DAT then those in emerging economies. Felbermayr and Gröschl (2014) find that using physically collected data on disaster strikes flips the result on the growth effect of natural disasters from marginally positive to large, negative, and statistically significant.

Similarly, selection into EM-DAT correlates with sovereign risk premia, as advanced economies tend to be perceived as less risky. Therefore, the use of EM-DAT would also bias existing estimates of the effect of disasters on risk premia. The contribution of this section is to provide causal estimates of *physically identified* hurricane strikes on sovereign risk, and to validate the second and third predictions of the model.

Data

The data for physical storm incidence comes from the *International Best Track Archive for Climate Stewardship* (IBTrACS). This data is provided by the *National Climatic Data Center of the National Oceanic and Atmospheric Administration* (NOAA) which records data of individual storms along with their location and intensity at six hourly intervals. This information is collated from a variety of sources including satellites, ships, and aircraft. The hurricane track data provides no information on the countries affected. Therefore I map the data to countries using longitude and latitude, accounting for the fact that hurricanes that do not make landfall but pass close to coastlines can also cause significant destruction. I create an indicator D_{it} that is equal to one if country i experiences a storm of at least category one hurricane force in time t. A storm is counted if it achieves a maximum sustained windspeed of at least 74 mph.

The sample runs from 1980-2025, extending earlier datasets linking IBTrACS to the country level which finish in 2010 (Felbermayr and Gröschl 2014; Hsiang and Jina 2014). Summary statistics for countries which experience at least one such storm are presented in Appendix A.1.17. On average in this sample of cyclone exposed economies, a country experiences a storm of at least 74 mph once every five years.

As dependent variables I use sovereign credit default swap (CDS) spreads, as well as a dummy for a sovereign debt crisis. Sovereign CDS are credit protection contracts, similar to insurance for a holder of a sovereign bond against possibility of default. [20] The owner of the CDS makes periodic payments to the seller and receives a payoff if the underlying sovereign bond undergoes a credit event. The premium on the CDS therefore depends on the credit risk of the government issuing the underlying bond. Therefore, the CDS spread reflects the market assessment of the sovereign's riskiness. I obtain monthly data

[20] The difference being that one can own a sovereign CDS without also owning the underlying bond.

on 5-year CDS spreads from Bloomberg from 2000 to 2025 and match it with the cyclone data. This results in a sample of 36 countries who experience at least one hurricane and for which CDS data are available. Summary statistics are presented in Appendix A.1.17.

Additionally I employ data from the Global Macro Database (Müller et al. 2025). This dataset includes a dummy variable for a country experiencing a sovereign debt crisis, as well as data on government budget deficits at annual frequency. The coverage of this dataset is larger. When matched with the hurricane data I obtain a sample of 80 economies.

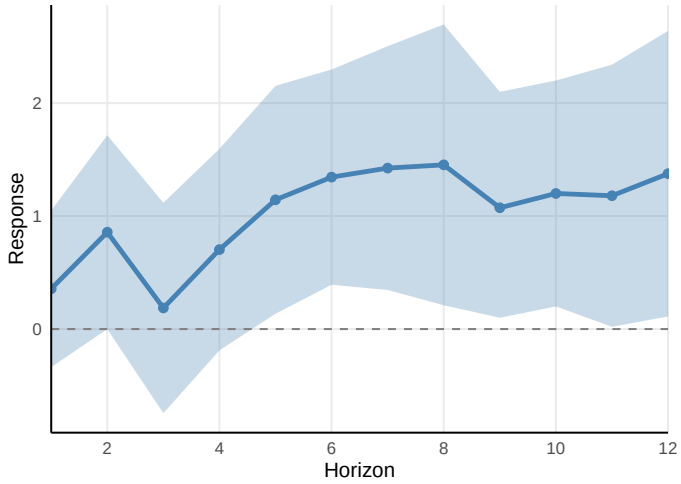


FIGURE 1.6. Impulse Response Function of CDS spreads to a cyclone shock over a horizon of twelve months. 90% confidence bands are shaded in blue.

Estimation

My goal is to study the dynamic causal effect of cyclones on sovereign risk and how this might vary with adaptation. For this purpose I follow the local projection method proposed by Jordà (2005) to estimate impulse response functions. I proceed in two steps. First I estimate the unconditional effect of a cyclone on sovereign risk using the following specification:

$$y_{i,t+h} - y_{i,t-1} = \alpha_i + \alpha_t + \beta_h D_{i,t} + \epsilon_{i,t+h}, \tag{1.15}$$

where $h = 0, ...H$ is the horizon, y is the dependent variable of interest - here either $log(CDS)$ or $SovCrisis$ - and D is the cyclone indicator variable. Equation 1.15 is estimated using OLS for the sample described above.[21] Impulse response functions (IRFs) are obtained by plotting the estimated β_h coefficients for with 90 percent confidence bands

[21] This approach follows that of Gilchrist et al. (2022).

computed using robust standard errors allowing for two way clustering over countries and dates.

The timing, location and intensity of hurricane exposure is unpredictable and stochastic across years, conditional on each country's average climate and trends in climate, whose effects are absorbed by country fixed effects and year effects. Following Hsiang and Jina (2014) this allows us to assume that D is exogenous and uncorrelated with other unobserved factors that influence sovereign risk, permitting the causal effect of hurricanes on sovereign risk at horizon h to be identified by the coefficient β_h.

Second, in order to investigate the role of adaptation in mediating the response of sovereign risk to cyclones, I split the sample and re-estimate equation 1.15. In the 'High Adaptation' sample I include countries for which their average adaptation investment as a proportion of GDP is greater than the median, and in the 'Low Adaptation' sample I include the remaining countries.

Results

Figure 1.6 presents the IRF for a cyclone shock to CDS spreads. There is an increase of CDS spreads on impact which cumulates over time. Six months after the cyclone shock, CDS spreads are around 1.5% higher. In sample this is approximately a 4 basis point increase. The increasing effect over time is consistent with sovereigns increasing borrowing in the process of recovery to the shock. It is also consistent with the prediction of the model that cyclones increase default probabilities.[22]

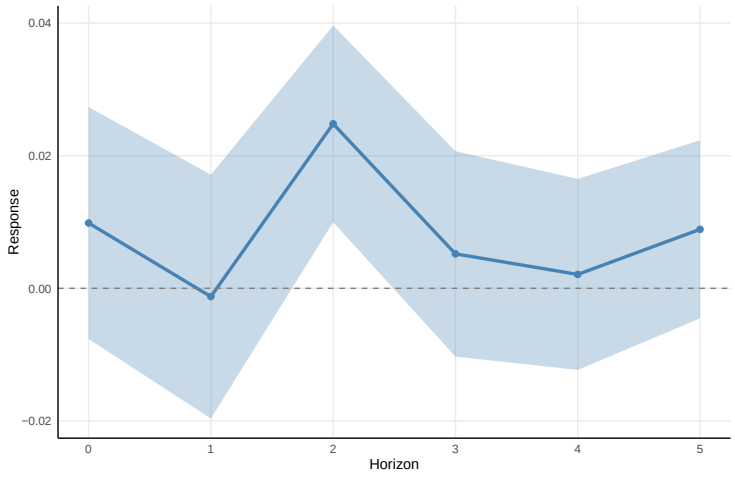


FIGURE 1.7. Impulse Response Function of Sovereign Crisis dummy to a cyclone shock over a horizon of six years. 90% confidence bands are shaded in blue.

Cyclones increase sovereign risk. How is this affected by adaptation? It is not pos-

[22] For the table summarizing these results see Appendix A.1.18

sible to answer this question using the CDS data, as the overlap between countries for whom CDS data is available, and that are included in my Latin American and Caribbean adaptation sample is too small.[23] Therefore, in order to consider the role of adaptation in the relationship between cyclones and sovereign risk I instead use a dependent variable for which there is better coverage: the *SovCrisis* dummy variable from the Global Macro Database.

Figure 1.7 plots the IRF estimates from equation 1.15 with the Sovereign Crisis dummy as the dependent variable. This dummy is available at *yearly* frequency. The probability of a sovereign debt crisis increases slightly on impact. It reaches its peak elevation two years after the cyclone hits. In this period an affected sovereign is about 2.5% more likely to enter a debt crisis. This delayed impact of the storm on sovereign risk is also consistent with the story whereby sovereigns increase borrowing in response to the shock.

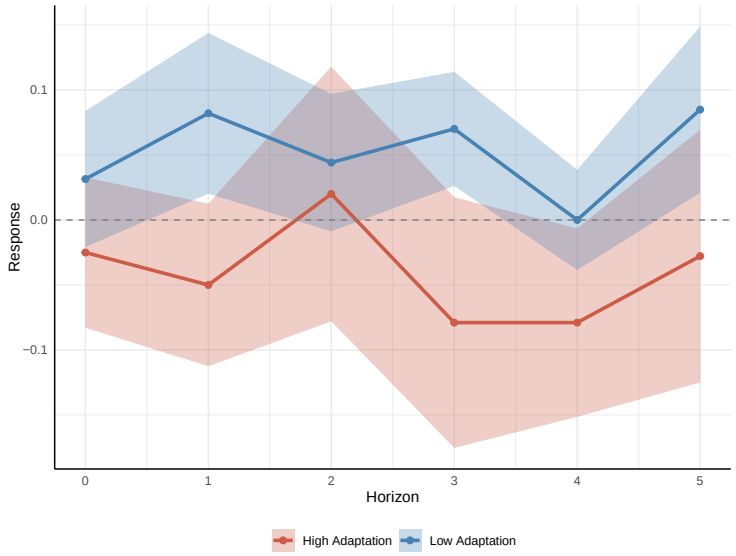


FIGURE 1.8. IRF of Sovereign Crisis dummy to a cyclone shock. 90% confidence bands are shaded. Red IRF shows the subsample of countries with above the median level of adaptation investment as a proportion of GDP. The blue IRF shows the subsample with below the median level of adaptation.

Figure 1.8 shows how this response varies across the two subsamples. The figure shows that the increase in sovereign risk after a cyclone is driven by countries with low levels of adaptation. For countries with higher levels of adaptation there is no statistically significant increase in crisis probabilities. In fact, the probability of a debt crisis actually decreases one year after the shock. However, for countries with low levels of adaptation default probabilities increase on impact and remain elevated. This is consistent with the

[23] However, the result presented in Figure 1.6 that cyclones cause CDS spreads to increase does still hold in the restricted sample of countries also included in the adaptation sample.

prediction from the model that adaptation attenuates the effect of natural disaster shocks on default probabilities. I show that these results are robust to using alternative measures of default in Appendix A.1.19. The difference in the response of default probabilities across high and low adaptation subsamples is statistically significant.

1.4. Quantitative Analysis

I leverage the model to examine the quantitative importance of the sovereign risk - adaptation channel. Additionally the model is used to simulate counterfactuals: outcomes under climate change, and under debt relief scenarios.

1.4.1. Quantification

Output costs of default are given by the function $\phi(y_t)$. As in Chatterjee and Eyigungor (2012) output costs of default are quadratic:

$$\phi(y) = \max\left\{-d_0 y + d_1 y^2, 0\right\}.$$

Therefore it is proportionally more costly to default in good times. Such asymmetric output costs allow the quantitative model to deliver empirically observed historical default probabilities. Output contractions after default are also consistent with empirical observation that sovereign default disrupts the functioning of the private financial market and the assumption that such private credit is an important input to production.

Households' utility takes the standard constant relative risk aversion (CRRA) form:

$$U(c) = \frac{c^{1-\gamma}}{1-\gamma},$$

where the parameter γ determines the degree of risk aversion.

The adaptation function $F(\Lambda)$ takes the following form as in Fried (2022):

$$F(\Lambda_t) = exp\left(-\alpha\Lambda_t^{1/\alpha}\right),$$

where the parameter $\alpha > 1$ determines how effective adaptive capital is at reducing damages from a disaster shock. The marginal benefit of adaptive capital is increasing in α. Crucially, the data on adaptation expenditures will allow me to pin down this parameter.

The model is calibrated at annual frequency.[24] For the baseline calibration I restrict attention to Caribbean economies included in my adaptation expenditure dataset. For these economies, hurricanes are by far the most frequent and severe natural disaster,

[24] As in Mallucci (2022) this is for the reason that GDP series for Caribbean economies at the quarterly frequency are available only sparsely and in recent years. Longer time series are needed to estimate the effects of rare shocks such as hurricanes.

allowing me to calibrate the endowment process using physical data on hurricanes. Three parameters are set to standard values from the literature, five are calibrated externally from the data, and four are estimated internally to match a set of population weighted target moments. Table 1.3 summarizes the calibration.

Parameter		Value	Source/Target statistic
Parameters set Externally:			
Relative risk aversion	γ	2	Standard
Readmission probability	η	0.33	Richmond and Dias (2009)
Depreciation	δ	0.1	Standard
Parameters Estimated Externally:			
Risk free rate	r	0.0451	US T-Bill
Duration	ψ	0.0564	Average Maturity
Hurricane Frequency	p	0.103	NOAA
Endowment autocorr	ρ	0.95	Data
Endowment st dev	σ_ϵ	0.021	Data
Disaster st dev	σ_d	0.031	Data
Parameters Set Internally:			
Discount factor	β	0.92	Debt/GDP
Default cost	d_0	0.621	Mean Spread
Default cost	d_1	0.978	Std. dev Spread
Hurricane intensity	μ_d	0.096	Mean hurricane loss
Adaptation benefit	α	2.496	Adaptation investment/ GDP

TABLE 1.3. Calibrated Parameters: Caribbean.

Externally Set Parameters. The coefficient of relative risk aversion γ is set to a standard value of 2. The readmission probability η is set to 0.33, consistent with the average re-entry rate as estimated by Richmond and Dias (2009). I set the depreciation of adaptation capital δ to 0.1. An additional five parameters are externally calibrated to the data. The risk free rate r is set to the average annual T-Bill rate from 1980 to 2025. The duration ψ is set to match a population weighted average maturity of the countries in my sample. I set the probability of a disaster to the empirical frequency of cyclone strikes of at least category 1 speed between 1980 and 2025. I estimate the endowment process by regressing logged and de-trended GDP for each country on its lag and a cyclone indicator:

$$log(y_t) = \rho log(y_{t-1}) - \beta_1 * x + \epsilon_y.$$

This specification is equivalent to the endowment process in the model with

$$\beta_1 = E[d \cdot F(\lambda)].$$

Therefore, the estimate for β will combine the physical intensity of the disaster, d, and the extent of adaptation, $F(\lambda)$. From this regression I take a population weighted estimate for ρ from the coefficient on lagged de-trended GDP, σ_y from the standard deviation of the residual ϵ_y, and σ_d from the standard deviation of the damages β_1.

Internally set parameters: I set the remaining parameters to jointly target a set of moments. The innovation of the calibration strategy is to pin down the mean disaster losses and adaptation effects separately using the dataset on adaptation expenditures. The most informative moment for α, the parameter governing the effectiveness of adaptation, is the share of adaptation investment in GDP computed from the dataset on adaptation expenditures. Given a level of adaptation investment, the observed losses from a hurricane, β_1 as estimated above, is pinned down by the physical strength of the shock. Therefore the mean hurricane intensity, μ_d is calibrated to match the mean hurricane loss.

The discount factor, β, and the default cost parameters, d_0 and d_1, are set to match the debt to GDP ratio, the mean spread and the standard deviation of the spread. Data on these variables are obtained from the Global Macro Database and the JP Morgan EMBI. All moments are weighted by population.

Solution. The model is solved using state of the art techniques from the quantitative sovereign default literature. The problem is augmented with extreme value taste shocks. For details see Appendix A.3. I also solve a counterfactual no-default benchmark in which the default policy is set to zero in all states.

1.4.2. Model Performance

Model fit is shown in Table 1.4. The first section of the table shows the targeted moments. The second section shows untargeted moments for which data counterparts are available. The third section shows untargeted moments for which empirical counterparts are not readily available. The model matches well the empirical observations of natural disasters, adaptation, and fiscal conditions. Welfare is 5.1% lower than it would be in the absence of hurricanes. [25] Welfare losses are computed in terms of the consumption equivalent welfare changes and correspond to the percentage increases in consumption that an agent

[25] See Appendix A.3.4 for the simulated moments for the economy without hurricane risk.

in the baseline economy should receive in any period and in any state of the world to achieve the same utility as in the economy without cyclones.

	Model	Data
Targeted		
Adaptation Investment/GDP	0.003	0.003
Debt/GDP	0.401	0.414
GDP loss | Cyclone	0.052	0.050
Mean Spread	502	526
Std. dev Spread	352	374
Untargeted		
Default Frequency	0.048	0.051
Median Spread	121	143
Spread Increase | Cyclone	0.015	0.01
Adaptation Capital/GDP	0.029	
Percent Damages Avoided	0.45	
Market Value Debt/GDP	0.37	
Welfare Loss		
	5.1%	

TABLE 1.4. Simulated Moments: Model Fit
The table presents selected moments of the baseline model and corresponding moments from the data. The model is simulated for 9,000 periods. Welfare loss is the consumption equivalent welfare change compared to a counterfactual with no hurricanes.

Additionally, the mechanisms linking climate change, adaptation, and sovereign risk outlined in Section 1.2.2 are visible in the full model. Figure 1.9 shows that the bond price is increasing in the level of adaptation. Adaptation protects the sovereign against hurricane strikes. The price of a bond is lower in states where the bad shock occurs, but the gap between the bond price in the no-hurricane state and the hurricane-state is decreasing in the level of adaptation. As adaptation increases the bond price in the hurricane state converges to that in the non-hurricane state, as the hurricane no longer affects the endowment. The price of the bond in the non-hurricane state is also increasing in adaptation. This is because adaptation reduces future default probabilities. At high levels of debt, default probabilities are already high regardless of adaptation choices and hurricane strikes. Therefore the gap between the bond price curves is smaller.

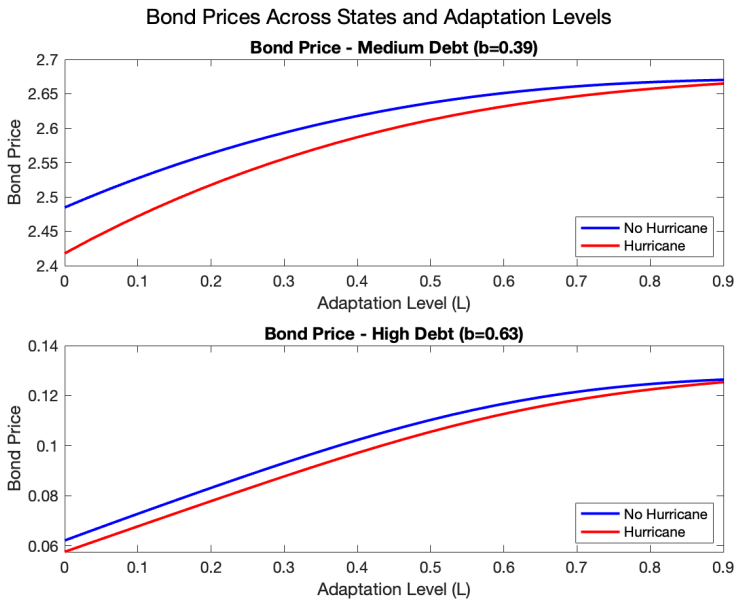


FIGURE 1.9. Sovereign Bond prices for different levels of adaptation. The panes show results for different levels of debt.

1.4.3. Counterfactuals

No Default Risk Benchmark

How does sovereign risk affect adaptation and the welfare costs of natural disasters? I compare the model outcomes to those of a counterfactual where the default policy is set to zero in all periods. In this counterfactual the sovereign can fully commit to repaying debt and so borrows at the risk free rate.[26] Table 1.5 shows the counterfactual moments.

In the absence of default risk adaptation/ GDP is 13% higher than under default risk. The sovereign is able to borrow more cheaply. Its budget constraint slackens and it chooses to invest more in adaptation. This translates to a larger stock of adaptation capital. As a result cyclones are less costly. In the counterfactual without default risk, cyclones are 10% less damaging. These results imply that the sovereign risk-adaptation channel is responsible for a quantitatively important share of total losses from natural disasters.

Table 1.5 shows that default risk is an important driver of adaptation choices. This is also true in the cross section of economies. In Appendix A.3 I split the sample (above and below median spreads) and recalibrate the sovereign default related parameters (β, d_0, d_1) while leaving the climate and adaptation parameters unchanged. Table A.21 shows that differences in default risk account for almost 90% of the differences in adaptation expenditures across these subsamples.

[26] Details: Appendix A.3

	Model	No Default Risk
Adaptation		
Adaptation Investment/GDP	0.003	0.0034
Adaptation Capital/GDP	0.029	0.032
Cyclones		
GDP loss per Cyclone	0.05	0.045
Percent damages avoided	0.45	0.53

TABLE 1.5. Simulated Moments: No Default Counterfactual.
The first column presents simulated moments from the baseline model. The second column presents moments from a no default risk counterfactual. In this counterfactual the default policy is set to zero in all periods.

Climate Change

Climate change is projected to increase the frequency and severity of cyclones. How will this affect the adaptation motive under sovereign risk versus without? I show that climate change increases the wedge between adaptation investments in these two scenarios.

Following Mallucci (2022) I consider projected increases in frequency and severity of cyclones by the end of the century drawing on the scientific literature. In particular I consider a 29.2% increase in frequency, and a 48.5% increase in severity.[27] Table 1.6 presents select simulated moments from these climate change scenarios.

The table shows that climate change increases adaptive investments. Climate change increases the expected benefits from adaptation, increasing the incentives for the sovereign to adapt. The sovereign therefore accumulates a larger stock of adaptive capital. This is the case both when only the probability or severity of a cyclone increases, and when both increase together. As climate change leads to greater adaptation, the fraction of damages avoided under climate change grows. However, this increase in adaptation is not sufficient to offset the increase in the hazard. Therefore, the climate change scenarios are associated with welfare losses.

As well as the direct effect of climate change on cyclone strikes and associated losses, there are indirect effects that operate through the value of debt and default probabilities. Climate change increases default probabilities. This lowers the value of government debt, increasing spreads and tightening the budget constraint. Debt to GDP ratios are therefore also lower under climate change.

The final column presents simulated moments for the model under climate change

[27]The frequency projection comes from Bhatia et al. (2018). The severity projection is the mean from Mejia (2016).

without default risk. In this no default risk counterfactual adaptation investment/GDP is 31% higher. The wedge between adaptation investment under default risk vs without is therefore higher as hazard exposure increases. In the absence of default risk the sovereign is able to respond to the greater threat of cyclones by investing much more in adaptation. Under default risk the sovereign is constrained and under-invests. Due to diminishing returns from adaptation investment, the wedge between GDP losses from cyclones increases by less than the investment wedge. GDP losses from cyclones are 13% greater due to the sovereign risk-adaptation channel under the climate change scenario.

	Baseline	Frequency $1.292 \cdot p$	Severity $1.485 \cdot \mu_d$	Both	No Default Risk
Adaptation					
Adaptation Investment/GDP	0.003	0.0036	0.0039	0.0045	0.0059
Adaptation Capital/GDP	0.029	0.035	0.037	0.044	0.056
Cyclones					
Frequency	0.1	0.1292	0.1	0.1292	0.1292
GDP loss | Cyclone	0.052	0.051	0.076	0.071	0.0632
Percent Damages Avoided	0.45	0.47	0.47	0.50	0.57
Debt					
Debt/GDP	0.40	0.40	0.38	0.38	1.65
Market Value Debt/GDP	0.37	0.33	0.31	0.31	1.65
Mean Spread	502	549	640	646	
Median Spread	121	156	173	181	
Default Frequency	0.048	0.049	0.05	0.05	

TABLE 1.6. Simulated Moments: Climate Change.
This table presents select simulated moments for the baseline model and climate change counterfactuals. In the first column, moments are for the baseline calibration. The second column considers a scenario whereby the probability of a cyclone increases by 29.2%. In the third column mean losses from cyclones are 48.5% larger than in the baseline. The fourth column presents the integrated climate change scenario in which both the frequency and severity of the cyclone shock is elevated. The final column presents results from the scenario with climate change but without default risk.

1.4.4. Debt Relief:

Sovereign risk tightens government budget constraints, limiting investment in adaptation, and so increasing the costs of climate change. Emerging market economies have called for debt relief policies to increase fiscal space for adaptation. For example, the Bridgetown Initiative, a proposal spearheaded by Prime Minister of Barbados Mia Mottley has called for financing solutions to allow fiscal space for climate resilience. In particular, the argument has been that financing for disaster *recovery* is not sufficient: "Liquidity is not enough: these crises have systemic roots. Only investment will change their course... lending should prioritize building climate resilience in climate vulnerable countries."[28].

Debt relief for climate resilience could take many forms: an increase in official lending, coupon suspensions, explicitly adaptation-linked finance. In contrast with existing literature which has focused on policies which limit the effects of natural disaster shocks (Catastrophe Bonds, Insurance), I consider policies which ex-ante aim to increase fiscal space for climate resilience purposes. Could such policies be effective? I consider two such policies, showing that debt-relief can be effective at boosting adaptation and climate resilience.

Interest Free Loan

I model a loan program by introducing an official lender who offers a default free loan of a fixed size to the sovereign.[29] The International Monetary Fund established the Resilience and Sustainability Trust (RST) in 2022. This new lending facility was earmarked to provide long term funding to bolster countries' capacity to address climate change and their pandemic preparedness. The loan program considered in this section is motivated by this facility. I consider the role of a financial assistance entity for easing financial constraints and so increasing adaptation to climate change. As the IMF is the most senior lender very few of its loans are in arrears (Schlegl, Trebesch, and Wright 2019). Therefore I consider such a loan to be default free.

In this counterfactual the sovereign gets F as a lump-sum in period $t = t^*$. A grace period follows in which the sovereign does not have to repay the loan.[30] After g periods of grace, repayment begins. The sovereign repays $\tilde{F}$ each following period in perpetuity. The official lender breaks even at the risk free rate. Therefore the terms of the loan are such that:

$$\tilde{F} = r(1+r)^g F.$$

[28] `https://www.bridgetown-initiative.org/`

[29] This experiment follows Arellano, Bai, and Mihalache (2024).

[30] In the simulations I first simulate the baseline economy for 5000 periods. i.e. this lump sum loan occurs in period 5001. The simulation runs for $10,000$ periods total.

I evaluate a loan with a size of 10% of pre-loan output, with a grace period of 3 years. Table 1.7 presents the outcomes under this loan program. The first column shows simulated moments for the economy in the case where there is no such loan i.e. the baseline results. The second column presents moments for the loan program counterfactual.

	Baseline	Loan Program
Adaptation		
Adaptation Investment/GDP	0.003	0.0031
Adaptation Capital/GDP	0.029	0.030
Cyclones		
GDP loss per Cyclone	0.05	0.048
Percent damages avoided	0.45	0.48

TABLE 1.7. Simulated Moments: Loan Program Counterfactual.
The first column presents simulated moments from the baseline model. The second column presents moments from the interest free loan counterfactual. The loan program consists of a long-term, default-free loan equivalent to 10% of output. The baseline model is simulated for 5000 periods. The loan is introduced in period 5001. Simulated moments are the average over periods 5001 to 10000.

The loan program generates substantial benefits. The sovereign primarily uses the loan to increase adaptive investments. In particular, adaptation investment as a proportion of GDP rises by almost 5%. This is 35% of the gap between adaptation under default risk versus the no-default risk counterfactual. As a result of greater adaptation investment, the stock of adaptive capital increases, reducing the losses from hurricanes. Hurricanes are 4% less costly due to this larger stock of protective capital. The interest free loan therefore reduces hurricane losses by 40% of the total potential reduction from completely frictionless financial markets.

An Adaptation Bond

In this section I modify the baseline model to include a coupon reduction associated with elevated adaptation.[31] Green sovereign bonds have become more popular in recent years. The BIS sustainable bonds database indicates that such bonds outstanding rose more than fourfold from January 2019 to the end of 2022.[32] These bonds typically take one of

[31] I thank Patrick Bolton and Jan Starmans for helpful conversations which prompted this counterfactual exercise.

[32] `https://www.bis.org/publ/qtrpdf/r_qt2209d.pdf`

two types. “Use of proceeds” bonds earmark the proceeds of bond sales for environmental projects. “Outcome-based” bonds have decreased coupon payments if contractually specified environmental performance targets are met.[33] Thus far outcome-based green bonds have largely focused on climate mitigation and/or nature protection. For example, Chile issued a sustainability linked bond in 2022 with two performance targets: reducing the overall level of greenhouse gases produced in Chile, and converting energy usage to renewable energy. Uruguay issued a similar bond with an additional target of maintaining the total area of local forest.

I propose an outcome-based green bond that is instead linked to performance on adaptation.[34] The rationale is that such a bond loosens the sovereign’s budget constraint in high adaptation states. This provides additional incentives to invest in adaptation, opening the possibility for a positive feedback loop between high adaptation investment and lower default risk. Investors value this reduction in default risk.

The value functions are defined as in Section 1.2 with the following adjustments to the resource constraint and bond price function. If adaptation is above some threshold value Λ^* defined in the adaptation bond contract, the investor receives a lower coupon payment where c denotes the discount:

$$c_t|_{D_t=0} = y_t + q_t^{AB}(b_{t+1} - (1-\psi)b_t) - b_t\left(1 - c\mathbb{1}_{\Lambda_t>\Lambda^*}\right) - \lambda_t, \tag{1.16}$$

$$q_t^{AB} = \frac{1}{1+r}\mathbb{E}\left((1-D_{t+1})(1-c*\mathbb{1}_{\Lambda_{t+1}>\Lambda^*}) + (1-D_{t+1})(1-\psi)q_{t+1}^{AB}\right). \tag{1.17}$$

The bond price accounts for the expected value of the coupon reduction in high adaptation states. Appendix A.2.6 outlines the implications of the adaptation bond in the restricted model which permits analytic solutions. The adaptation linked coupon has two countervailing effects on the spread. First, the increased incentive to adapt reduces default probabilities, lowering the spread. Second, the introduction of state-contingency in the coupon demands a premium, increasing the spread.

For low values of c the first channel dominates and the adaptation linked bond reduces spreads. For high values of c the second channel dominates and the contingency increases spreads. In the model I find the spread minimizing level to be $c = 0.022$ given $\Lambda^* = 0.0305$. This implies that the sovereign gets a 2.2% coupon reduction if adaptation capital is 5%

[33] See Cheng et al. (2024) for background. I focus on outcome based or sustainability linked bonds as they are not associated with the loss of control over budget priorities or lack of fungibility of revenue that has created constitutional and other political issues for use of proceeds bonds.

[34] To the best of my knowledge, while the proceeds from ‘use of proceeds’ green bonds have sometimes been used to fund adaptation projects, there has not been an instance of a sovereign issuing an ‘outcome-based’ green bond linked to performance on adaptation targets.

greater than in the no adaptation bond simulation. The introduction of such an adaptation bond is effective in increasing adaptation. Table 1.8 presents simulated moments.

	Baseline	Adaptation Bond
Adaptation		
Adaptation Investment/GDP	0.003	0.0033
Adaptation Capital/GDP	0.029	0.031
Cyclones		
GDP loss per Cyclone	0.05	0.046
Percent damages avoided	0.45	0.52

TABLE 1.8. Simulated Moments: Adaptation Bond Counterfactual.
The first column presents simulated moments from the baseline model. The second column presents moments from the adaptation bond counterfactual.

The introduction of the adaptation contingent bond increases adaptation investment by 10% (compared to 13% for the no default risk counterfactual). As a result the GDP losses per cyclone are on average 4.6% (compared to 4.5% in the absence of default risk). Therefore the adaptation contingent bond is effective at increasing incentives to adapt. Adaptation investment under this counterfactual is almost as large as it would have been absent default risk all together.

1.5. Conclusion

I have studied the costs of climate change for emerging markets in an environment with financial frictions and endogenous adaptation. These economies are subject to the joint challenges of high natural disaster exposure and tight fiscal space. I have shown empirically, theoretically, and quantitatively that the financial friction leading to elevated borrowing costs restricts the ability of emerging markets to adapt to climate change. Comparing my model to an otherwise identical one without the risk of default, I have shown that sovereign risk is responsible for 10% of the GDP losses from cyclones in the Caribbean, with this rising to 13% with climate change. This adaptation trap dynamic is likely to be of concern to policymakers and opens the door to debt relief policies. Both an interest free loan and an adaptation contingent bond are effective in increasing adaptation investment, reducing the likelihood of disastrous cyclone damages and climate related credit events in the future.

CHAPTER 2.

Carbon Border Adjustment and Firm Heterogeneity*

Abstract

Carbon border adjustment mechanisms (CBAMs) are proposed as a solution to the competitive disadvantage faced by firms subject to domestic carbon pricing and to the risk that production shifts to less regulated economies. We develop a heterogeneous-firm trade model following Melitz (2003) in which emissions are a byproduct of production which can be reduced via costly abatement. The CBAM poses a compliance problem: foreign firms may not be aware of their individual emissions intensity, and reporting is costly. In the model, foreign exporters choose between a default tariff and a firm-specific regime that allows firms to pay based on their actual emissions after costly reporting. This compliance choice generates a novel sorting mechanism: more productive exporters self-select into the firm-specific regime, internalising the destination country's carbon price and investing in abatement, while less productive exporters pay the default tariff without changing their emissions intensity. The CBAM therefore affects foreign emissions through a scale channel, a compliance channel, and an abatement channel, the latter two absent from existing models that treat the CBAM as a uniform sectoral levy. We characterise the jointly optimal carbon tax and default tariff, showing the two are complements: a

*This chapter is joint work with Martin Bodenstein, Federico Di Pace, Aydan Dogan, and Marco Garofalo. The views expressed in this paper are those of the authors and not necessarily those of the Bank of England and its committees, or of the Board of Governors of the Federal Reserve System or any person associated with the Federal Reserve System.

higher domestic carbon price raises the optimal default tariff. The welfare-maximising tariff exceeds the carbon-cost-equalising level, reflecting a terms-of-trade motive. In a three-country extension, CBAM generates trade diversion toward cleaner economies, conferring a relative competitive advantage on countries with lower structural emissions intensity.

2.1. Introduction

As governments strengthen climate policies, concerns about carbon leakage have moved to the centre of policy debates. Carbon leakage arises when stricter environmental regulation in one jurisdiction causes production to relocate, or demand to shift, toward countries with less stringent climate policies. In that case, domestic emissions may fall while foreign emissions rise, weakening the effectiveness of unilateral climate action. These concerns are particularly acute in emissions-intensive trade-exposed industries, where international competition can limit the ability of governments to impose ambitious carbon prices without affecting domestic producers' competitiveness.

To address this problem, several jurisdictions have proposed Carbon Border Adjustment Mechanisms (CBAMs). A CBAM imposes a charge on imported goods based on the carbon emissions embodied in their production, with the aim of aligning the carbon cost faced by foreign producers with that faced by domestic firms. The European Union's CBAM is the most prominent example. Its stated objective is to reduce carbon leakage while preserving the incentives created by domestic carbon pricing.

The effectiveness of a CBAM, however, depends critically on how firms respond to the incentives it creates. In practice, implementing a CBAM requires information about the emissions embodied in imported goods. Obtaining and verifying such information is costly. Firms in jurisdictions without a domestic carbon price will often not know the emissions embodied in their products. For this reason, CBAM designs often allow firms to rely on default or benchmark emissions values when firm-specific emissions data are unavailable.[1] This institutional feature creates an important margin of adjustment: exporters may either incur a fixed cost to document their own emissions and pay a levy based on their actual carbon content, or avoid this cost and pay a default charge.

This paper develops a parsimonious heterogeneous-firm trade model to study the effects of carbon border adjustment policies when firms differ in productivity, emissions, and compliance choices. A heterogeneous-firm framework is particularly well suited to analysing CBAMs because these policies affect both the intensive and extensive margins of adjustment. Carbon pricing and border adjustments alter firms' production and abatement decisions by changing marginal costs. At the same time, they affect the profitability of

[1] See, for example, the EU CBAM legislation which includes provision for default values: `https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32023R0956`

exporting and of complying with firm-specific reporting requirements. As a result, firms may enter or exit export markets, and exporters may sort into different compliance regimes. These responses depend critically on firm productivity and cannot be captured in representative-firm models.

Building on Melitz (2003) and Nordhaus (2018), we model emissions as a by-product of production and allow firms to undertake costly abatement. Foreign exporters subject to a CBAM can either incur a fixed cost to report their emissions and pay a levy based on their actual carbon content or avoid the reporting cost and instead pay a default tariff based on benchmark emissions intensity. Relative to the standard Melitz framework, the CBAM introduces an additional policy-induced selection margin: firms must decide not only whether to export, but also whether the benefits of firm-specific reporting outweigh its fixed costs. Relative to much of the existing literature on CBAMs, the emissions intensity of firms is endogenous in the firm-specific regime.

The model highlights a new sorting mechanism: more productive exporters are more likely to incur the fixed cost required to document their emissions, because their revenues are higher and they therefore benefit more from reducing the per-unit carbon charge they face. These firms internalize the destination country's carbon price and adjust their abatement decisions accordingly. Less productive exporters, by contrast, prefer to pay the default tariff and do not change their emissions intensity. The CBAM therefore affects emissions through several channels: it changes the scale of foreign production, induces some firms to exit the export market, and encourages a subset of exporters to reduce emissions through abatement.

This mechanism has important implications for CBAM design. A default tariff that is too low limits the environmental effectiveness of the policy, because few firms choose firm-specific reporting and many exporters do not internalize the carbon price. A default tariff that is too high can reduce trade and consumption by pushing firms out of the export market. The optimal policy therefore involves a trade-off between emissions reductions, trade costs, government revenue, and welfare. In the quantitative version of the model, welfare is shaped by both consumption and global emissions, and CBAM revenues are rebated to households.

The analysis also shows that carbon pricing and CBAM design are closely linked. A higher domestic carbon price increases the cost disadvantage faced by domestic firms and strengthens incentives for carbon leakage. This raises the value of a more stringent CBAM. At the same time, if the default tariff is not adjusted appropriately, a higher carbon price can induce foreign exporters to switch away from firm-specific reporting and toward the default regime, weakening foreign abatement incentives. The model therefore implies that the domestic carbon price and the CBAM default tariff work well as complementary policy tools.

We further use the model to study how firm heterogeneity shapes the incidence of the CBAM across the productivity distribution. The policy has heterogeneous effects on foreign firms' profits, output, and emissions. Some firms stop exporting altogether, some continue exporting under the default regime, and the most productive firms choose firm-specific reporting. These extensive-margin responses are central to the aggregate effects of the policy. They determine not only how much foreign production falls, but also which firms remain active in export markets and whether average emissions intensity declines.

Finally, we extend the framework to a multi-country setting. This extension allows us to analyse how CBAMs affect trade patterns when foreign economies differ in their underlying emissions intensity. The model shows that a CBAM can generate trade diversion away from dirtier trading partners and toward cleaner ones. Countries with lower emissions intensity may lose less market share, or even gain relative to dirtier competitors, when the importing country imposes a border adjustment. This highlights that CBAMs are not only climate policy instruments but also trade policy instruments with distributional consequences across foreign producers and countries.

Related Literature

The paper contributes to the literature on trade and environmental policy in three main ways.

First, we contribute to the heterogeneous-firm trade literature by incorporating emissions, abatement, and climate policy into a Melitz-style framework. Building on Melitz (2003) and Ghironi and Melitz (2005), we model emissions as a by-product of production and allow firms to reduce emissions through costly abatement, following Nordhaus (2018). We then introduce carbon pricing that differs across countries together with a Carbon Border Adjustment Mechanism (CBAM).[2] In addition, our framework is related to Helpman, Melitz, and Yeaple (2004) in that firms choose between alternative export strategies that differ in their fixed and marginal costs. In our setting, exporters choose between a default CBAM regime and a firm-specific reporting regime.

Second, we contribute to the growing literature on carbon border adjustments by allowing CBAMs to affect emissions through firm-level abatement decisions. Most existing analyses model the CBAM as a tariff that depends on sectoral or country-level emissions characteristics. For example, Böhringer, Carbone, and Rutherford (2016), Clausing et al. (2025), and Coster, di Giovanni, and Mejean (2024) model border adjustments as fixed sectoral levies, while Larch and Wanner (2017), Campolmi et al. (2025), and Farrokhi and Lashkaripour (2025) model tariffs that vary across countries or industries but not across

[2] We adopt an abatement-cost specification rather than modelling emissions as a factor of production, as in Copeland and Taylor (1994), Shapiro and Walker (2018), and Berthold et al. (2024). This specification generates more realistic responses of emissions to carbon pricing, particularly at low levels of the tax. Section 2.6 discusses this issue in detail.

firms. In these frameworks, emissions reductions arise through changes in production levels or through the reallocation of activity across sectors and countries. By contrast, we allow exporters to internalize the destination country's carbon price and adjust their emissions intensity through abatement. Consequently, CBAMs affect emissions not only through the scale and composition of production, but also through firms' technology and abatement choices.

Our third contribution concerns CBAM compliance. While the literature has extensively analysed carbon leakage and the rationale for border adjustment policies (e.g. Nordhaus (2015), Clausing and Wolfram (2023)), and has documented leakage empirically (e.g. Aichele and Felbermayr (2015), Coster, di Giovanni, and Mejean (2024), Känzig, Marenz, and Olbert (2024), and Schroeder and Stracca (2024)), the practical issue of firm-level compliance has received relatively little attention. In practice, measuring the carbon content of imports is costly, and many exporters may lack the information required to document their emissions. We explicitly model this institutional feature by allowing firms to choose between paying a default tariff based on benchmark emissions intensity and incurring a fixed cost to report firm-specific emissions.

This compliance decision generates a novel selection mechanism. Firms must decide not only whether to export, but also whether the benefits of firm-specific reporting outweigh its fixed costs. As a result, the CBAM creates an additional productivity cutoff beyond the standard Melitz export cutoff. The most productive firms choose firm-specific reporting and internalize the carbon price, intermediate-productivity firms export under the default regime, and the least productive firms cease exporting altogether. The aggregate effects of the CBAM therefore depend not only on firms' production and abatement decisions, but also on endogenous changes in market participation, market concentration, and the distribution of emissions intensities across firms.

The remainder of the paper is organised as follows. Section 2.3 presents the model. Section 2.4 describes the calibration. Section 2.5 presents the quantitative results and discusses optimal policy. Section 2.6 discusses sensitivity exercises. Section 2.7 extends the analysis to a multi-country setting. Section 2.8 concludes.

2.2. Context

The EU Carbon Border Adjustment Mechanism, introduced by Regulation (EU) 2023/956, entered its transitional phase in October 2023 and takes full effect from 2026. It is designed to prevent carbon leakage by ensuring that foreign producers face a carbon price equivalent to that paid by their EU competitors under the EU Emissions Trading System (EU ETS).

In practice, importers of covered goods must surrender CBAM certificates whose price

tracks the EU ETS allowance price.[3] Imported goods are credited for any foreign carbon price that has already been paid. Therefore, goods produced within the EU and those imported into the EU face the same total carbon price. The carbon charge assessed on each shipment depends on the emissions intensity attributed to the imported goods. Where verified actual emissions are unavailable, the EU Commission publishes sector-specific default values based on estimated average emissions intensities. Under firm-specific disclosure, a firm can instead submit verified measurements of its actual production emissions, paying only for those. Disclosure requires third-party verification and reporting costs.

Our model is designed to capture this compliance choice in a setting with endogenous emissions intensity. Firm heterogeneity is essential: the compliance choice is a fixed-cost investment decision whose return scales with firm size, so it is precisely the largest exporters that self-select into disclosure. Endogenous abatement in the model reflects the fact that firm-specific compliance gives firms a direct incentive to reduce emissions intensity if they verify. The two-tier CBAM structure — a default tariff T on all exporters, with an opt-in firm-specific track available at additional fixed cost f_{xx} — maps onto the EU regulation. Rather than taking the default tariff, T, as given, we will consider the optimal design of the CBAM varying both the domestic carbon tax and the CBAM tariff.

2.3. Model

We extend the model of Melitz (2003) by introducing carbon emissions as a by-product of production, country-specific carbon pricing, and a Carbon Border Adjustment Mechanism (CBAM). Firms are heterogeneous in productivity and decide whether to serve domestic and foreign markets. Production generates emissions, which are subject to carbon pricing and can be reduced through costly abatement activities. The CBAM affects the incentives faced by foreign exporters, and consequently, trade patterns and emissions outcomes. We use the model to study how carbon pricing and border adjustment policies influence firm behaviour, international trade, welfare, and emissions in a general equilibrium setting.

Throughout the paper, variables associated with the foreign country are denoted by an asterisk "$*$", while variables without an asterisk refer to the home country. Given the largely symmetric structure of the model, we focus the exposition on the home economy.

2.3.1. Households

In each country, a representative household derives utility from consuming a continuum of differentiated varieties. Preferences are represented by a constant-elasticity-of-

[3] For expositional purposes, the model will outline the CBAM as a tax or tariff levied instead on the *exporter*. We show this to be equivalent to levying the CBAM on the importer.

substitution (CES) aggregator over individual varieties, indexed by $\omega \in \Omega$:

$$C = \left[\int_{\omega \in \Omega} c(\omega)^{\frac{\theta-1}{\theta}} d\omega \right]^{\frac{\theta}{\theta-1}},$$

where $c(\omega)$ denotes consumption of variety ω, Ω is the set of available varieties, and θ is the elasticity of substitution across varieties. A higher value of θ implies that varieties are closer substitutes, leaving firms with less market power. The CES structure gives rise to the standard aggregate price index,

$$P = \left[\int_{\omega \in \Omega} p(\omega)^{1-\theta} d\omega \right]^{\frac{1}{1-\theta}},$$

which summarizes the cost of purchasing one unit of the composite consumption good. The representative household chooses consumption of individual varieties so as to maximize C subject to its expenditure constraint. Utility maximisation yields the familiar demand schedule for variety ω,

$$c(\omega) = \left(\frac{p(\omega)}{P} \right)^{-\theta} C, \tag{2.1}$$

implying that demand is increasing in aggregate consumption and decreasing in the variety's price relative to the aggregate price index.

2.3.2. Firms

In each country, a continuum of monopolistically competitive firms produces differentiated varieties. Firms draw their productivity z from a common distribution. Firms that remain active must also incur a fixed operating cost f_D if they operate domestically and f_X if operating abroad. These costs are measured in effective labour units. For notational convenience, we henceforth index firms by their productivity draw z rather than by their variety ω. Production requires labour and generates carbon emissions as a by-product. A firm with productivity z that employs $l(z)$ units of labour produces output according to

$$q(z) = zl(z). \tag{2.2}$$

Absent abatement, emissions are proportional to labour input. Firms can reduce emissions by undertaking abatement effort $a \in [0, 1]$, so that emissions are given by

$$e(z) = \mu(1 - a)l(z), \tag{2.3}$$

where μ governs the emissions intensity of production absent abatement. Abatement is costly and requires additional resources,

$$f(a) = \theta_1 a^{\theta_2} l(z), \tag{2.4}$$

where θ_1 and θ_2 determine the level and curvature of abatement costs. Emissions are subject to a carbon price t. Firms therefore choose their level of abatement by balancing the marginal cost of abatement against the reduction in carbon tax payments. The optimal abatement choice satisfies the following condition:

$$t = \frac{\theta_1 \theta_2}{\mu} a^{\theta_2 - 1}. \tag{2.5}$$

Because the optimal abatement decision is common across firms, it does not depend on productivity z. Nevertheless, more productive firms are cleaner in terms of emissions per unit of output because a given quantity of labour generates more output. Emissions intensity is therefore

$$\frac{e(z)}{q(z)} = \frac{\mu(1-a)}{z},$$

which is decreasing in productivity, consistent with the empirical evidence presented in Shapiro and Walker (2018). Taking into account labour costs, carbon tax payments, and abatement expenditures, the firm's marginal cost is

$$mc(z) = \frac{w + t\mu(1-a) + \theta_1 a^{\theta_2}}{z}. \tag{2.6}$$

Substituting the optimal abatement choice yields

$$mc(z) = \frac{1}{z}\left(w + t\mu\left[1 - \frac{\theta_2 - 1}{\theta_2}\left(\frac{t\mu}{\theta_1\theta_2}\right)^{1/(\theta_2 - 1)}\right]\right).$$

Firms may serve the domestic market and, subject to additional fixed and variable trade costs, export to foreign consumers. Specifically, exporting requires the payment of a fixed cost f_X and incurs iceberg trade costs τ. Only firms whose productivity is sufficiently high to generate positive export profits choose to export.

Pricing and Market Participation

Firms can sell their variety either in the domestic market or abroad. Because markets are monopolistically competitive and consumers have CES preferences, firms face downward-sloping demand curves and choose prices to maximize profits. Profits from domestic sales

are given by

$$\begin{aligned}\Pi_D(z) &= \frac{p_D(z)}{P}c_D(z) - mc(z)q_D(z) - wf_D \\ &= \left(\frac{p_D(z)}{P} - mc(z)\right)\left(\frac{p_D(z)}{P}\right)^{-\theta} C - wf_D. \end{aligned} \tag{2.7}$$

Similarly, profits from exporting are

$$\begin{aligned}\Pi_X(z) &= Q\frac{p_X(z)}{P^*}c_X^*(z) - mc(z)q_X(z) - wf_X \\ &= \left(Q\frac{p_X(z)}{P^*} - \tau mc(z)\right)\left(\frac{p_X(z)}{P^*}\right)^{-\theta} C^* - wf_X. \end{aligned} \tag{2.8}$$

Here, $Q = P^*/P$ denotes the real exchange rate, $p_D(z)$ is the domestic price of variety z, and $p_X(z)$ is the export price expressed in foreign consumption units. Exporting is subject to iceberg trade costs τ, implying that τ units must be shipped for one unit to arrive abroad. Consequently, delivered exports satisfy $q_X(z) = \tau c_X^*(z)$. Firms also incur the fixed export cost f_X.

Profit maximization yields the standard CES markup rule,

$$\frac{p_D(z)}{P} = \frac{\theta}{\theta - 1}mc(z),$$

so that all firms charge a constant markup over marginal cost. Substituting the optimal price into the profit function gives

$$\Pi_D(z) = \frac{1}{\theta}\left(\frac{p_D(z)}{P}\right)^{1-\theta} C - wf_D.$$

Since more productive firms have lower marginal costs, they charge lower prices and face higher demand. As a result, profits are increasing in productivity. Only firms whose productivity is sufficiently high to cover the fixed operating cost f_D choose to produce. The productivity cutoff z_D is determined by the zero-profit condition $\Pi_D(z_D) = 0$:

$$z_d = \frac{\theta}{\theta - 1}\left(w + t\mu\left[1 - \frac{\theta_2 - 1}{\theta_2}\left(\frac{t\mu}{\theta_1\theta_2}\right)^{1/(\theta_2 - 1)}\right]\right)\left(\frac{\theta w f_D}{C}\right)^{1/(\theta - 1)}. \tag{2.9}$$

Firms with productivity below z_D exit immediately, while firms with $z \geq z_D$ serve the domestic market. Exporting requires both the payment of the fixed cost f_X and the absorption of iceberg trade costs τ. Consequently, only the most productive firms find it profitable to export. The export cutoff productivity z_X is obtained from the condition

$\Pi_X(z_X) = 0$:

$$z_x = \frac{\theta}{\theta - 1} \frac{\tau\left(w + t\mu\left[1 - \frac{\theta_2 - 1}{\theta_2}\left(\frac{t\mu}{\theta_1\theta_2}\right)^{1/(\theta_2 - 1)}\right]\right)}{Q} \left(\frac{\theta w f_X}{QC^*}\right)^{1/(\theta - 1)}. \tag{2.10}$$

The presence of fixed and variable trade costs implies a selection effect: only firms with productivity above z_X export, while less productive firms serve only the domestic market.

Foreign Exporters and CBAM Compliance

The domestic production problem of foreign firms is identical to that of home firms. The export problem, however, differs because exports to the home market are subject to a Carbon Border Adjustment Mechanism (CBAM). Foreign exporters face iceberg trade costs τ^* and a fixed export cost f_X^*. In addition, they must choose between two CBAM compliance regimes.

Under the default regime, firms do not report their individual emissions and instead pay a levy based on a benchmark emissions intensity. Alternatively, firms may choose a firm-specific regime under which they incur an additional fixed cost to measure and verify their emissions but pay a CBAM levy based on their actual emissions intensity. We assume that the additional reporting cost is given by $f_{XX}^* - f_X^* > 0$. A foreign exporter with productivity z chooses the regime that yields the highest profits:

$$\max\{\Pi_X^*(z), \Pi_{XX}^*(z)\}.$$

Profits under the default regime are given by

$$\Pi_X^*(z) = \frac{p_X^*(z)}{PQ} c_X(z) - (1 + T)\, mc^*(z) q_X^*(z) - w^* f_X^*, \tag{2.11}$$

where T is the CBAM levy. This levy is set by the home regulator to impose the CBAM on firms who do not directly report their emissions.

Profits under the firm-specific regime are

$$\Pi_{XX}^*(z) = \frac{p_{XX}^*(z)}{PQ} c_X(z) - w^* l_{XX}^*(z) - \left(\frac{t}{Q} - t^*\right) e_X^*(z) - t^* e_X^*(z) - w^* f_{XX}^* \tag{2.12}$$

Here, we assume that $f_{XX} > f_X$. The key difference between the two regimes is that the default levy is independent of the firm's own emissions. Consequently, firms choosing the default option have no incentive to undertake additional abatement beyond that induced by the carbon price t^* charged in their country of origin. The marginal cost of these firms

is therefore

$$mc^*(z) = \frac{1}{z}\left(w^* + t^*\mu^*\left[1 - \frac{\theta_2 - 1}{\theta_2}\left(\frac{t^*\mu^*}{\theta_1\theta_2}\right)^{1/(\theta_2-1)}\right]\right).$$

By contrast, firms choosing the firm-specific regime pay a CBAM levy based on their actual emissions. They therefore internalize the carbon price prevailing in the destination market and undertake additional abatement. Marginal costs become

$$mc^*_{XX}(z) = \frac{1}{z}\left(w^* + \frac{t}{Q}\mu^*\left[1 - \frac{\theta_2 - 1}{\theta_2}\left(\frac{t\mu^*}{Q\theta_1\theta_2}\right)^{1/(\theta_2-1)}\right]\right).$$

Only sufficiently productive firms find exporting profitable. Under the default regime, the export cutoff productivity is determined by the zero-profit condition $\Pi_X(z_X) = 0$, yielding

$$z^* \geq z^*_X = \frac{\theta}{\theta - 1} Q\tau^*(1+T)\left(w^* + t^*\mu^*\left[1 - \frac{\theta_2 - 1}{\theta_2}a^*_X\right]\right)\left(\frac{\theta w^* f^*_X Q}{C}\right)^{1/(\theta-1)}. \tag{2.13}$$

Firms with productivity below z^*_X do not export. Among exporting firms, however, the choice of CBAM regime also depends on productivity. More productive firms benefit more from the lower emissions intensity associated with firm-specific reporting and are therefore more willing to incur the additional reporting cost.

The productivity threshold at which firms switch from the default regime to the firm-specific regime is denoted by

(2.14)

$$z^*_{XX} = \frac{\theta}{\theta - 1} Q\tau^*\left(\frac{\theta w^*(f^*_{XX} - f^*_X)Q/C}{\left(w^* + \frac{t}{Q}\mu^*\left[1 - \frac{\theta_2-1}{\theta_2}a^*_{XX}\right]\right)^{1-\theta} - \left((1+T)\left(w^* + t^*\mu^*\left[1 - \frac{\theta_2-1}{\theta_2}a^*_X\right]\right)\right)^{1-\theta}}\right)^{1/(\theta-1)}.$$

Firms with productivity between z^*_X and z^*_{XX} export under the default regime, whereas firms with productivity above z^*_{XX} choose the firm-specific regime.

2.3.3. Firm Aggregation

To aggregate across heterogeneous firms, we assume that productivity draws follow a Pareto distribution with cumulative distribution function $G(z) = 1 - \left(\frac{z_{\min}}{z}\right)^k$. The Pareto assumption yields closed-form expressions for average productivity among active firms. Because revenues and profits are proportional to $z^{\theta-1}$, it is convenient to define produc-

tivity averages that preserve aggregate outcomes

$$\begin{aligned}\tilde{z}_D &\equiv \left[\frac{1}{1-G(z_D)}\int_{z_D}^{\infty} z^{(\theta-1)}dG(z)\right]^{\frac{1}{(\theta-1)}} = \nu z_D,\\ \tilde{z}_X &\equiv \left[\frac{1}{1-G(z_X)}\int_{z_X}^{\infty} z^{(\theta-1)}dG(z)\right]^{\frac{1}{(\theta-1)}} = \nu z_X\end{aligned}$$

where $\nu = \left(\frac{k}{k-(\theta-1)}\right)^{\frac{1}{(\theta-1)}}$. This implies average profits are

$$\tilde{\Pi} = \frac{1}{1-G(z_D)}\left[\int_{z_D}^{\infty}\Pi_D(z)dG(z) + \int_{z_X}^{\infty}\Pi_X(z)dG(z)\right] = \Pi_D\left(\tilde{z}_D\right) + \frac{N_X}{N_D}\Pi_X\left(\tilde{z}_X\right)$$

and revenues

$$\tilde{R} = R_D\left(\tilde{z}_D\right) + \frac{N_X}{N_D}R_X\left(\tilde{z}_X\right).$$

The proportion of firms that export is pinned down by the threshold productivities

$$\frac{N_X}{N_D} = \frac{1-G(z_X)}{1-G(z_D)} = \left(\frac{z_D}{z_X}\right)^k.$$

The average productivities for foreign firms are similarly defined as

$$\begin{aligned}\tilde{z}_X^* &\equiv \left[\frac{1}{G(z_{XX}^*)-G(z_X^*)}\int_{z_X^*}^{z_{XX}^*} z^{\theta-1}\,dG(z)\right]^{\frac{1}{\theta-1}} = \nu\left(\frac{z_{XX}^{*k}\,z_X^{*(\theta-1)} - z_X^{*k}\,z_{XX}^{*(\theta-1)}}{z_{XX}^{*k}-z_X^{*k}}\right)^{\frac{1}{\theta-1}}\\ \tilde{z}_{XX}^* &\equiv \left[\frac{1}{1-G(z_{XX}^*)}\int_{z_{XX}^*}^{\infty} z^{\theta-1}\,dG(z)\right]^{\frac{1}{\theta-1}} = \nu\, z_{XX}^*.\end{aligned}$$

Average foreign profits are

$$\bar{\Pi}^* = \Pi_D^*(\tilde{z}_D^*) + \frac{N_X^*}{N_D^*}\Pi_X^*(\tilde{z}_X^*) + \frac{N_{XX}^*}{N_D^*}\Pi_{XX}^*(\tilde{z}_{XX}^*)$$

with

$$\frac{N_X^*}{N_D^*} = \left(\frac{z_D^*}{z_X^*}\right)^k - \left(\frac{z_D^*}{z_{XX}^*}\right)^k \quad \text{and} \quad \frac{N_{XX}^*}{N_D^*} = \left(\frac{z_D^*}{z_{XX}^*}\right)^k.$$

2.3.4. Market Clearing

We assume that trade is balanced and all government revenues are rebated lump-sum to households. Revenues from domestic carbon pricing are therefore returned to households

in the country where they are collected. In addition, all revenues generated by the CBAM accrue to the home country and are rebated to home households.[4]

Aggregate consumption in the home country is equal to labour income, firm profits, net entry costs, carbon tax revenues, and CBAM revenues:

$$\begin{aligned} C &= wL + N_D\bar{\Pi} - wN_E f_E + t\left(\int_{z_D}^{\infty} e_D(z)dG(z) + \int_{z_X}^{\infty} e_X(z)dG(z)\right) + QT_{CBAM} \\ &= N_D R_D\left(\tilde{z}_D\right) + N_X R_X\left(\tilde{z}_X\right) + QT_{CBAM}. \end{aligned} \tag{2.15}$$

The second line follows from the aggregation results derived above and expresses aggregate expenditure as the sum of revenues generated by domestic producers and exporters, together with CBAM revenues. Similarly, aggregate consumption in the foreign country is given by

$$\begin{aligned} C^* &= w^*L^* + N_D^*\bar{\Pi}^* - w^*N_E^* f_E^* + t^*\left(\int_{z_D^*}^{\infty} e_D^*(z)dG(z) + \int_{z_X^*}^{\infty} e_X^*(z)dG(z)\right) \\ &= N_D^* R_D^*\left(\tilde{z}_D^*\right) + N_X^* R_X^*\left(\tilde{z}_X^*\right) + N_{XX}^* R_{XX}^*\left(\tilde{z}_{XX}^*\right) - T_{CBAM}. \end{aligned} \tag{2.16}$$

Foreign households receive labour income, firm profits, and domestic carbon tax revenues, but transfer CBAM payments to the home country. Consequently, CBAM revenues enter the home resource constraint positively and the foreign resource constraint negatively.

Balanced trade requires that the value of home exports, augmented by CBAM revenues received from foreign exporters, equals the value of imports from abroad:

$$N_X R_X\left(\tilde{z}_X\right) + QT_{CBAM} = Q\left[N_X^* R_X^*\left(\tilde{z}_X^*\right) + N_{XX}^* R_{XX}^*\left(\tilde{z}_{XX}^*\right)\right]. \tag{2.17}$$

2.3.5. Welfare

To evaluate the welfare implications of carbon pricing and border adjustment policies, we assume that aggregate emissions reduce household welfare, following Coster, di Giovanni, and Mejean (2024). Welfare in country i is given by

$$U_i = C_i\left(1 + \eta_i\left(E - E_0\right)\right)^{-1}, \tag{2.18}$$

where C_i denotes aggregate consumption of the representative household in country i, E is total emissions generated by both countries, and E_0 is baseline emissions.[5]

The specification captures the idea that carbon emissions are a global externality. While households derive utility from consumption, they are adversely affected by the

[4] We will also consider the case where the revenues are thrown away.

[5] We define baseline emissions as the level of emissions that would prevail in the absence of a CBAM, i.e. when $T = 0$.

environmental damages associated with aggregate emissions, regardless of where those emissions occur. Consequently, welfare depends not only on domestic economic activity but also on emissions generated abroad.

The parameter η_i governs the sensitivity of welfare to emissions and can be interpreted as a reduced-form measure of the social cost of carbon. A larger value of η_i implies that households place greater weight on environmental quality relative to consumption and therefore experience larger welfare losses from a given increase in emissions.

This welfare criterion highlights the central trade-off generated by carbon pricing and CBAM policies. On the one hand, such policies may reduce consumption by increasing production costs and distorting trade flows. On the other hand, they can improve environmental outcomes by reducing emissions and limiting carbon leakage. The overall welfare effect therefore depends on the extent to which reductions in emissions compensate for any associated decline in economic activity. Because welfare depends on global rather than domestic emissions, the framework is well suited to evaluating whether CBAMs achieve their intended objective of reducing worldwide emissions rather than merely shifting production and emissions across countries.[6]

2.3.6. Equivalence Result

In the baseline model, the CBAM is modelled as a charge levied directly on foreign exporters. In practice, however, the CBAM is typically collected at the border and paid by importers. This distinction raises the question of whether the incidence of the policy affects firms' abatement and pricing decisions.

When the CBAM is levied on importers, exporters recognize that higher emissions increase the effective consumer price of their product and thereby reduce demand. As a result, exporters internalize the effect of emissions on profits through market demand. The incentives to abate emissions are therefore identical to those arising when the CBAM is levied directly on exporters. Consequently, both specifications generate the same equilibrium abatement choices, consumer prices, and trade outcomes.

PROPOSITION 2.1. *The equilibrium allocation is identical whether the CBAM is levied on exporters or on importers.*

Proof. Consider a foreign exporter that chooses the firm-specific CBAM regime and incurs the associated reporting cost. Profits are given by

$$\Pi^*_{XX}(z) = \frac{p^*_{XX}(z)}{PQ} c_X(z) - \left(w^* + \theta_1 a^{\theta_2}\right) l^*_{XX}(z)\,\tau^* - w^* f^*_{XX}. \tag{2.19}$$

[6] We model the rest of the world in a reduced form manner as a single economy: foreign. If the CBAM did not apply to all foreign economies we could include an exogenous rest of the world emissions term: $E^{*,RW}$.

When the CBAM is levied on importers, demand depends on the consumer price inclusive of the CBAM charge:

$$c_X(z) = \left(\frac{p^*_{XX}(z)}{PQ} + T_{imp}\big(a^*(z), z\big) \right)^{-\theta} C, \tag{2.20}$$

where T_{imp} is the CBAM tariff charged to importers:

$$T_{imp}\big(a^*(z),\, z\big) = \frac{t}{Q} \frac{e^*_X(z)}{c_X(z)} = \frac{(t/Q)\, \mu^*(1 - a^*(z))\, \tau^*}{z}.$$

The CBAM therefore enters demand in exactly the same way as any other component of the consumer price. Domestic consumers pay both the producer price and the carbon charge associated with imported emissions:

$$\int_{\omega \in \Omega} \frac{p(\omega)}{PQ}\, c(\omega)\, d\omega \;+\; \frac{t}{Q} \int_{\omega \in \Omega'} e^*_X(\omega)\, d\omega,$$

where Ω' denotes the set of imported varieties. Substituting the demand schedule into the firm's problem yields profits

$$\Pi^*_{XX}(z) = \left\{ \frac{p^*_{XX}(z)}{PQ} - \frac{\left(w^* + \theta_1 a^{\theta_2}\right) \tau^*}{z} \right\} c_X(z) - w^* f^*_{XX}. \tag{2.21}$$

The first-order condition with respect to $p^*_{XX}(z)$ implies

$$\frac{p^*_{XX}}{PQ} = \frac{\theta}{\theta - 1} \frac{\left(w^* + \theta_1 a^{\theta_2}\right) \tau^*}{z} + \frac{1}{\theta - 1}\, T_{imp}\big(a^*(z), z\big)\,. \tag{2.22}$$

The firm therefore absorbs part of the CBAM charge through a lower producer price. Relative to the baseline model, the producer price is reduced because part of the wedge between producer and consumer prices is now generated by the border adjustment itself.

Combining the pricing condition with the first-order condition for abatement yields

$$\theta_1 \theta_2\, a^{\theta_2 - 1} = \frac{t}{Q}\, \mu^*, \tag{2.23}$$

which is identical to the abatement condition obtained when the CBAM is levied directly on exporters. Hence, the firm's optimal emissions intensity is unchanged.

Substituting the optimal abatement choice into the pricing equation gives

$$\frac{p^*_{XX}}{PQ} = \frac{\tau^*}{(\theta - 1)\, z} \left[\theta \left(w^* + \theta_1 a^{*\theta_2}_{XX} \right) + \frac{t}{Q}\, \mu^* \left(1 - a^*_{XX}\right) \right]. \tag{2.24}$$

While the producer price differs from that in the baseline model, the consumer price is

$$\frac{p^*_{XX}}{PQ} + T_{imp}\big(a^*(z), z\big) = \frac{\theta}{\theta - 1} \frac{\tau^* \Big[w^* + (t/Q)\, \mu^* \big(1 - a^*_{XX}\big) + \theta_1 a^{*\,\theta_2}_{XX} \Big]}{z} = \frac{\theta}{\theta - 1} \tau^* mc^*_{XX}, \tag{2.25}$$

which is exactly the same consumer price as in the baseline specification. Since firms choose the same level of abatement and consumers face the same prices, the equilibrium allocation is unchanged. Therefore, modelling the CBAM as a tax on exporters or as a tax on importers is equivalent in this environment.

2.4. Calibration

Table 2.1 summarises the parameter choices for our model. Most parameters are taken from the literature; a small number of parameters are calibrated to match key features of the European economy and its climate policy environment. The home country is taken to be the European Union, while the foreign country is assumed to be symmetric except for differences in carbon policy. We calibrate the benchmark economy in the absence of the CBAM.

We set the elasticity of substitution θ, the Pareto shape parameter k, iceberg trade costs τ, the minimum productivity level $z_{\min}$, the entry cost f_E, and the fixed domestic operating cost f_D to their values in Ghironi and Melitz (2005). Setting the fixed cost of producing domestically to zero implies that all active firms produce domestically, $z_D = z_{min}$. To match the share of exporting firms of 20% we set the fixed export cost f_X equal to 0.37. Each of these parameters are symmetric across countries.

Relative to the benchmark Ghironi-Melitz framework, the model introduces additional parameters governing emissions, abatement, and climate policy. The abatement cost parameters θ_1 and θ_2 are taken from Nordhaus (2018). The remaining parameters — the carbon tax t, the emissions intensity parameter μ, the fixed cost of firm-specific CBAM reporting f_{XX}, and the welfare parameter η — are calibrated to match a set of environmental and policy-related targets.

The carbon tax t and emissions intensity parameter μ are calibrated jointly to match aggregate environmental outcomes in Europe without a CBAM. OECD data indicate that environmental tax revenues amount to approximately 2% of GDP.[7] Although this measure includes taxes beyond carbon pricing, such as fuel and waste-related taxes, we set t so that environmental tax revenues represent approximately 2% of output, an upper bound in the benchmark equilibrium.[8]

To calibrate the emissions intensity parameter μ, we turn to data on aggregate emis-

[7] `https://www.oecd.org/en/data/indicators/environmental-tax.html`

[8] In the baseline we set the carbon tax abroad to 0.

Parameter	Description	Value
θ	Elasticity of substitution	3.8
k	Pareto shape parameter	4
θ_1	Abatement cost	1.0
θ_2	Abatement cost	2.6
τ	Iceberg trade cost	1.3
f_E	Fixed cost of entry	1
f_D	Fixed cost of domestic production	0
f_X	Fixed cost of exporting	0.37
f^*_{XX}	Fixed cost of firm-specific CBAM	0.44
t	Home carbon tax	0.005
μ	Emissions factor	4.65
η	Emissions disutility	0.0067

TABLE 2.1. Calibrated Parameters

sions. The European Union currently emits approximately 3.23 gigatonnes of CO_2 annually; we set μ so that model-generated emissions correspond to this level when interpreted in physical units. Together, the calibrated values of t and μ imply that firms abate approximately 6% of baseline emissions in the benchmark equilibrium.

The welfare parameter η governs the disutility associated with emissions. We calibrate η using a social cost of carbon of €100 per tonne of CO_2. For the welfare loss associated with an additional tonne of emissions to be consistent with this benchmark value, η equals 0.0067.

A key parameter in our setting is the fixed cost of firm-specific CBAM reporting, f_{XX}. Unlike the export cost f_X for which export participation guides the calibration, there are currently no data on firms' sorting into the CBAM regime (default payment or firm-specific reporting) that could provide similar guidance on identifying f_{XX}. Thus, we rely on estimates from the European Commission's CBAM impact assessment (European Commission 2021). The Commission's assessment draws on evidence from emissions reporting requirements and compliance costs associated with the EU Emissions Trading System. Based on this evidence, it estimates that firm-specific CBAM compliance increases administrative and reporting costs by approximately €35,000 per firm relative to reliance on default values.

To map this estimate into model units, we first recover the euro value of the export fixed cost f_X. The export cutoff condition implies

$$R_X(z_x) = \theta f_X.$$

Under the Pareto productivity distribution, this can be rewritten as

$$f_X = \frac{k - (\theta - 1)}{k\theta} \tilde{R}_X,$$

where $\tilde{R}_X$ denotes average export revenue.

Using Eurostat data on total exports from the European Union and the number of exporting firms in 2019, we estimate an average export fixed cost of approximately €182, 000.[9] So the Commission's estimate implies that firm-specific reporting increases fixed costs by roughly 19% relative to standard exporting costs or, applied to our model, total reporting cost of $f_{XX} = 0.44$ — a sizable but not prohibitive cost increase for documenting firm-specific emissions. Consequently, only sufficiently productive exporters choose to incur the additional reporting cost, generating the endogenous sorting mechanism that lies at the heart of the model.

2.5. Quantitative Analysis

With the calibrated model in hand, we turn to analysing the features of the CBAM. First, we examine how the CBAM default tariff T and the domestic carbon price t impact trade pattern and related economic outcomes. In doing so, we highlight the role of firm heterogeneity in determining the extensive-margin adjustments, which shape firms' export and compliance decisions. We then characterise the optimal design of the CBAM, highlighting the trade-off between emissions reductions, trade flows, and consumption.

2.5.1. CBAM and the default value T

Keeping the domestic carbon tax t constant, Figure 2.1 shows the outcomes for selected variables as the default CBAM tariff T increases. Three equilibrium regions emerge that reflect the interplay between two distinct channels: a *trade-reduction channel* that lowers foreign production for any positive tariff and an *abatement channel* that becomes active only when T is sufficiently high for exporters to opt for firm-specific reporting of emissions.

Following Section 2.3.2, a foreign exporter chooses firm-specific reporting when the reduction in variable cost of exporting relative to the default option is large enough to recover the fixed reporting cost. Switching to firm-specific reporting reduces a firm's marginal cost of exporting by the same proportion regardless of productivity. However, because more productive firms operate on a larger scale, this proportional cost reduction translates into a greater absolute gain in variable profit. With the fixed reporting cost being identical across firms, the net gain from switching to firm-specific reporting is

[9] We combine data on extra-EU exports and the number of exporting enterprises from Eurostat's international trade database.

increasing in productivity. For a given parameterization of the CBAM, z^*_{XX} is the threshold productivity level for which the exporter is indifferent between the default and the firm-specific CBAM.

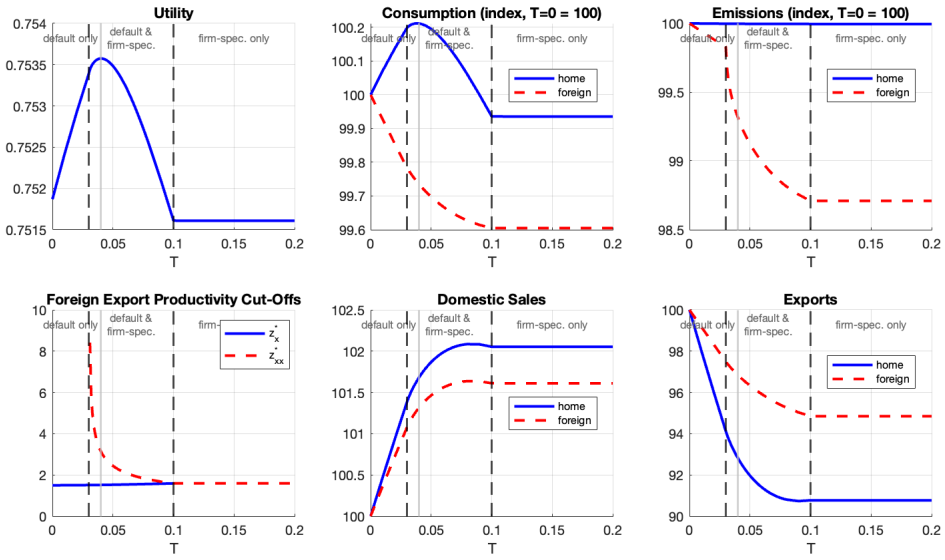


FIGURE 2.1. Economic and environmental effects of changes in the default CBAM tariff T. The domestic carbon tax t is held fixed. Consumption, emissions, domestic sales, and exports are indexed to 100 at $T = 0$.

The position of z^*_{XX} in the productivity distribution depends on T. At low values of T, no exporter finds it profitable to pay the reporting cost and all exporters choose the default regime (*default-only region*). At the limit of $T = 0$, foreign exporters can avoid the border carbon adjustment altogether and the economy corresponds to the no-CBAM benchmark. As T rises, the variable cost disadvantage of the default regime grows and z^*_{XX} falls. When the two thresholds coexist, firms between z^*_X and z^*_{XX} export under the default tariff while firms above z^*_{XX} choose firm-specific reporting (*mixed region*). As T rises further, the default regime is no longer profitable for any exporter and all remaining foreign exporters internalise the home carbon price (*firm-specific-only region*). In this region, the CBAM is equivalent to a system without a default option. The three vertical dashed lines in Figure 2.1 mark these thresholds.

The effect of the CBAM on home welfare is driven by its impact on both consumption and emissions. Consider first the consumption channel. In the absence of revenue recycling, the CBAM acts as a trade barrier, raising the cost of imported goods and reducing consumption (Figure B.1). In the benchmark model, however, all CBAM revenues are rebated lump-sum to households. The overall effect on consumption therefore reflects the balance between the negative effects of reduced trade and the positive effects of higher

transfers.

For low values of T, all foreign exporters remain in the default regime and pay the CBAM tariff. In this region, CBAM revenue increases with T, causing household transfers to rise. The revenue-recycling effect dominates the direct trade-barrier effect, leading home consumption to increase. As T rises further, the composition of exporters begins to change. The most productive firms switch to the firm-specific regime, paying the fixed reporting cost in exchange for a lower emissions-based charge. This endogenous sorting mechanism reduces the amount of revenue collected through the default tariff. Consequently, the increase in transfers slows and eventually reverses, causing home consumption to decline. Once all exporters have adopted firm-specific reporting, further increases in T no longer affect firms' decisions. The economy therefore enters a region in which the allocation is unchanged and all aggregate variables, including consumption, remain constant.

Foreign emissions decline as the default payment T increases, although the underlying mechanism differs across the three regions. In the default-only region, foreign firms do not adjust their abatement decisions. Because the default levy is independent of a firm's own emissions, exporters do not internalise the carbon price and therefore have no incentive to reduce emissions intensity. Emissions nevertheless decline through a scale effect: higher trade costs reduce export sales and output, lowering total emissions even though emissions intensity remains unchanged.

The decline in foreign emissions steepens in the intermediate region. As T increases, an increasing number of exporters switch to firm-specific reporting and begin internalising the home country's carbon price. These firms respond by increasing abatement and reducing emissions intensity. Emissions fall via two channels: a scale effect arising from lower output and an abatement effect arising from lower emissions intensity. As a result, average emissions intensity declines alongside total emissions.

For sufficiently high values of T, all exporters choose firm-specific reporting. At this point, the default payment ceases to be relevant for firms' decisions. Since all firms already internalise the carbon price, further increases in T do not affect abatement incentives, emissions intensity remains unchanged and aggregate emissions are flat.

The welfare path combines the emissions and consumption effects. In the default-only region, consumption rises and emissions fall, which leads to an unambiguous increase in welfare. In the mixed region, consumption declines while emissions continue to fall, generating a trade-off governed by the social cost of carbon η. The welfare-maximising value of T lies within the mixed region, where the abatement channel is active but trade restriction has not yet become severe enough to outweigh the environmental gain. The exact location of this optimum is sensitive to η, as we discuss in Section 2.6: a higher value of η places greater weight on emissions reductions and therefore shifts the welfare-maximising level of T upward.

The welfare gains from the CBAM also depend critically on the treatment of the associated revenues. In the benchmark model, CBAM revenues are rebated lump-sum to households, creating a positive income effect that partly offsets the adverse effects of the policy on trade and consumption. If revenues are not redistributed, however, this channel disappears and welfare declines monotonically with T, as shown in Figure B.1.[10] Similarly, the welfare benefits of the CBAM weaken substantially when an optimal conventional tariff is already imposed.[11] In this case, part of the gains from restricting imports have already been exhausted by the existing tariff, reducing the scope for additional welfare improvements through border carbon adjustment.

Firm Heterogeneity and the Extensive Margin

Figure 2.2 reports the underlying firm-level adjustments behind the aggregate responses in Figure 2.1. The top row shows the export and reporting thresholds together with the number of firms in each compliance regime. This row illustrates that the export productivity cut-off and firm-specific productivity cut-off vary with T as outlined above. The bottom row decomposes emissions into extensive-margin, intensive-margin, and emissions-intensity components, first for all foreign firms and then for exporters only. Total foreign emissions can be expressed as

$$E^* = N^* \tilde{Y}^* \frac{\tilde{E}^*}{\tilde{Y}^*}.$$

where N^* is the number of active firms, $\tilde{Y}^*$ is average output per firm, and $\tilde{E}^*/\tilde{Y}^*$ is average emissions intensity. This decomposition allows us to separate changes in emissions arising from firm entry and exit, changes in production levels, and changes in firms' emissions intensity due to abatement.

For total foreign emissions (Figure 2.2, bottom-left), the extensive margin puts *upward* pressure on emissions. As export demand contracts, the foreign wage falls and additional firms enter the domestic market, raising the number of active firms N^*. This effect is more than offset by the intensive margin: average output per firm declines as export sales contract and lower-productivity firms enter the domestic market. In the mixed region, firm-specific reporters begin internalising the carbon price and reducing emissions intensity through abatement. This additional margin of adjustment causes the decline in total emissions to become noticeably steeper.

The export emissions decomposition (Figure 2.2, bottom-right) applies the same decomposition to emissions embodied in exports. The reduction in export emissions is

[10] In fact, the welfare maximizing level of the tariff is increasing in the share of revenue that is rebated to households, as shown in Figure B.2.

[11] See Appendix B.1 for a discussion of the interaction between a standard tariff and the CBAM. Figure B.4 illustrates the corresponding results.

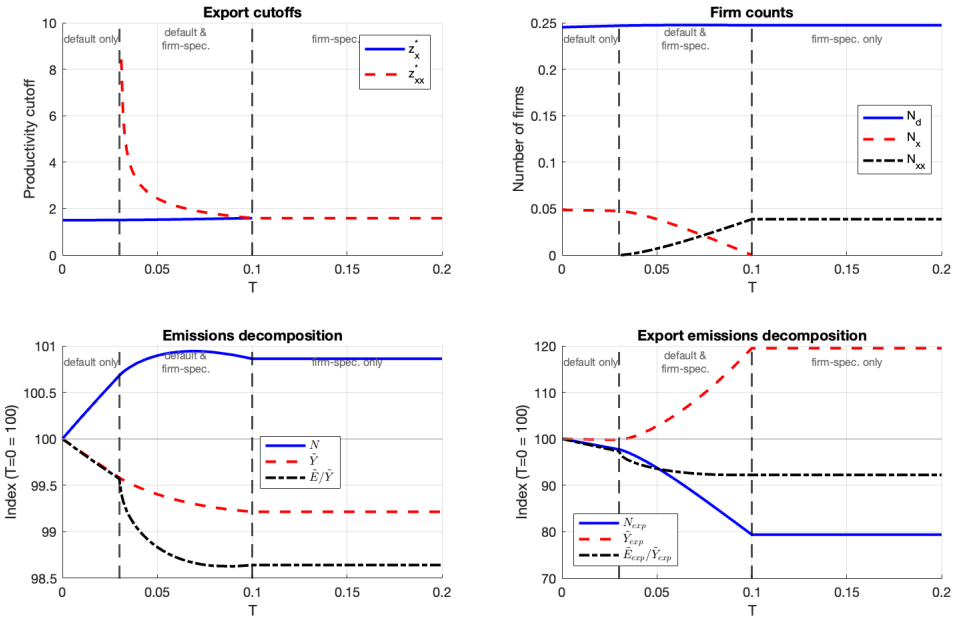


FIGURE 2.2. Model responses to CBAM. The level of the carbon tax t is kept fixed while T varies. Illustrated outcomes are for the foreign country. The third subplot shows the total number of foreign firms, their average output, and their average emissions intensity, all indexed to 100 at $T = 0$. The final subplot shows the total number of exporting firms, their average output, and their average emissions intensity, all indexed to 100 at $T = 0$.

driven primarily by the extensive margin: fewer firms select into exporting, sharply reducing N_{exp}. As less productive exporters exit, the average productivity of the remaining export pool rises, increasing average exports per exporter. Average emissions intensity of the exporting firms falls through two reinforcing forces: the exit of less productive exporters, which raises the average productivity of the remaining export pool and mechanically lowers emissions per unit of output, and the abatement of firm-specific reporters.

Figure 2.3 illustrates how the effects of the CBAM vary across the productivity distribution. The first row reports the percentage change in profits, emissions, and emissions intensity relative to a benchmark without a CBAM. The first dashed vertical line denotes the export cutoff in the absence of a CBAM. The second and third dashed lines denote the productivity thresholds for exporting under the default regime and the firm-specific regime, respectively. These thresholds divide firms into four groups. Firms to the left of the first threshold do not export either with or without a CBAM. Firms between the first and second thresholds export in the benchmark economy but exit the export market once the CBAM is introduced. Firms between the second and third thresholds continue exporting under the default regime. Finally, firms to the right of the third threshold choose

firm-specific reporting and internalize the carbon price.

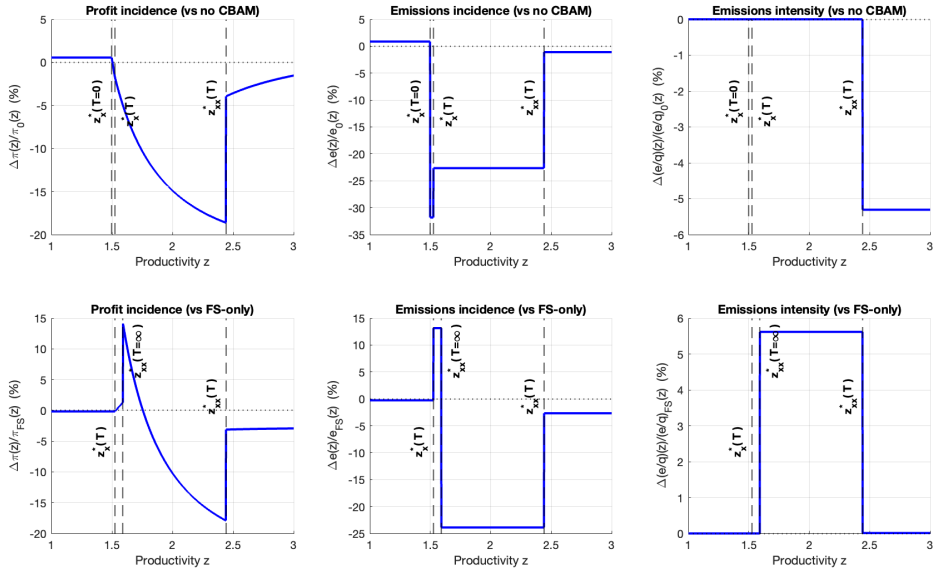


FIGURE 2.3. CBAM impacts on firm profits, emissions, and emissions intensities. The first row shows the effects of CBAM relative to a benchmark with no CBAM at all. The second row shows the effects of CBAM relative to a counterfactual in which there was no default option: all firms had to pay the firm-specific tariff.

The first plot shows that CBAM has heterogeneous effects on profitability of foreign firms. The profits of firms that produce only domestically increase slightly due to the lower wage abroad as a result of lower export demand. Firms above the export threshold, however, earn lower profits than in the no CBAM counterfactual. The greatest decline in profits occurs for firms just below the firm-specific productivity threshold. These firms are the highest revenue default firms and so pay the largest absolute tariff, driving down their profits. Above this threshold, the loss in profits begins to decline as firms are able to invest in abatement in order to reduce their exposure to the carbon tax.

The third plot shows that emissions intensities are constant for all firms apart from those who pay the firm specific tariff. These firms internalize the carbon price and so engage in non-zero abatement which reduces their emissions intensity. The second plot shows the effect of the CBAM on emissions levels which is the product of the change in intensities and the change in output. Domestic firms have an increase in emissions as their intensity is fixed and their production increases. Output falls dramatically for the group between the export threshold absent CBAM and the CBAM default threshold. These firms no longer export and so lose all of their export production which pushes their emissions down. Firms in the default tariff region also produce less due to lower demand for their more expensive goods, and so emit less. Emissions of the firm-specific group

decline due to their abatement, even as their output increases.

The second row shows changes in profits, emissions, and emissions intensities relative to a CBAM without the option to pay a default tariff. The export threshold for this counterfactual is the second dashed vertical line. If instead there is a default value, there are two export thresholds. The threshold for exporting with the default value is the leftmost threshold, while that to export using the firm-specific tariff is the rightmost. The first region of the graph shows firms that don't export under either case, the second region shows those firms that export when there is a default option, but not otherwise. The set of firms that export under both regimes is divided into the group that chooses the default value when offered the option, and the group that always internalises the carbon price.

The figure shows that the profits of firms that do not export under either regime are invariant to the introduction of the default value. Profits increase for those firms who enter the export market when the default value is introduced. This illustrates that without the default value, the CBAM induces a set of firms to exit the export market and lose export profits. Profits also increase for firms just above the export threshold who prefer paying the higher marginal cost and lower fixed cost. However, profits fall as productivity increases. Under the default value option, high productivity firms gain less market share than they otherwise would have. The default value supports lower productivity firms remaining in the export market, limiting the gain to the most productive firms. The third plot shows that emissions intensities change only for the set of firms who opt into the default value once it is offered, but otherwise would have internalized the carbon price. These firms now do not abate and so produce with higher emissions intensities. However, these firms produce lower emissions in absolute terms as they shrink in size. Emissions increase only for the group of firms who did not previously export, but choose to do so when the default option is introduced.

2.5.2. The Domestic Carbon tax

We present a complementary exercise in Figure 2.4, in which the default CBAM tariff is held fixed at $T = 0.05$ while the domestic carbon tax t varies. Relative to Figure 2.1, the sorting mechanism operates in the opposite direction. There, a higher default tariff encouraged firms to switch into the firm-specific regime. Here, a higher carbon tax makes firm-specific reporting less attractive and induces firms to switch back to the default regime.

For low values of t, the carbon price internalised under firm-specific reporting is modest, so the marginal-cost disadvantage associated with that regime is small relative to the fixed default tariff. Many exporters therefore find it profitable to incur the reporting cost and pay a levy based on their actual emissions. The region to the left of the dashed line consequently corresponds to a mixed equilibrium in which some firms choose firm-

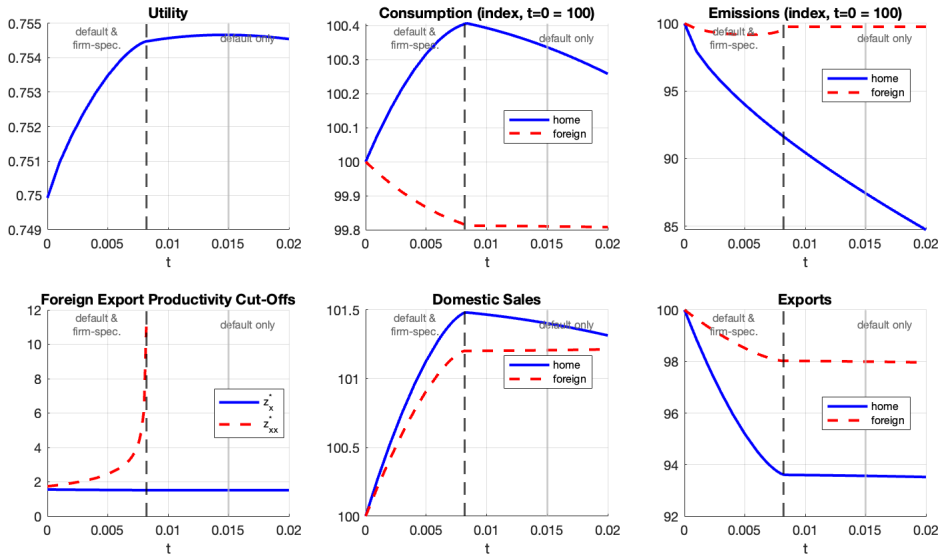


FIGURE 2.4. Economic and environmental effects of changes in the carbon tax t while keeping T fixed at 0.05. Consumption, emissions, domestic sales, and exports are indexed to 100 at $t = 0$.

specific reporting while others rely on the default tariff.

As t rises, however, the effective carbon charge faced by firms in the reporting regime increases. The cost advantage of documenting emissions therefore diminishes, causing exporters to switch back to the default option. For sufficiently high values of t, all exporters choose the default tariff, and the economy transitions into the default-only region.

The emissions response reflects these changing incentives. At low values of t, exporters that choose firm-specific reporting actively abate emissions, so foreign emissions decline through both a scale effect and an abatement channel. As firms switch back to the default regime, the abatement channel progressively disappears. Beyond a threshold, further increases in the carbon tax can even increase foreign emissions. Firms that previously internalised the carbon price and invested in abatement now choose the default tariff and cease reducing their emissions intensity.

Home emissions, by contrast, decline strongly as t increases because all domestic firms are subject to the carbon tax. The contrast between the domestic and foreign responses reflects the asymmetric exposure to carbon pricing. Domestic firms internalise the carbon tax on their entire output, whereas foreign firms are exposed to the home carbon price only on exports and only when they choose firm-specific reporting.

The consumption responses follow a similar logic. Foreign consumption declines monotonically with t because exporters face higher effective costs and reduced access to the home market. Home consumption initially rises as carbon tax revenues increase and

are rebated lump-sum to households. As the carbon tax becomes more stringent, however, the distortionary effects on production begin to dominate the revenue gains. Moreover, the shift of foreign exporters toward the default regime weakens the emissions-reduction benefits generated by the CBAM. Consequently, home consumption eventually declines despite the continued increase in tax revenues. [12]

2.5.3. Optimal Policy

Having examined the effects of carbon pricing and border adjustment policies on aggregate outcomes and firm-level behaviour, we now turn to the optimal (joint) design of these instruments. Specifically, we characterise the welfare-maximising combination of the domestic carbon tax t and the default CBAM tariff T, taking into account their effects on both consumption and emissions.

Each policy instrument involves a trade-off. A higher default tariff T reduces foreign emissions through both the scale and abatement channels. At the same time, however, it raises trade costs, reduces import variety, and encourages exporters to switch from the default regime to firm-specific reporting. While this increases emissions reductions, it also shrinks the CBAM revenue base and thereby reduces the transfers received by domestic households through revenue recycling.

Similarly, a higher domestic carbon tax t lowers domestic emissions by increasing firms' incentives to abate. However, if the default tariff is not adjusted accordingly, a higher carbon tax makes firm-specific reporting less attractive for foreign exporters. Firms then switch into the default regime, weakening foreign abatement incentives and reducing the effectiveness of the CBAM.

The interaction of these forces implies that the two instruments cannot be analysed in isolation. The welfare-maximising policy pair lies in the interior of the policy space, balancing the environmental benefits of lower emissions against the costs of reduced trade and consumption. Figures 2.1 and 2.4 already illustrated this trade-off. Figure 2.5 illustrates the welfare-maximising combination of t and T, with lighter colours corresponding with higher welfare. The upward-sloping shape of this locus reflects the complementarity between domestic carbon pricing and border adjustment: a higher carbon tax increases the value of a more stringent CBAM, while a more stringent CBAM increases the effectiveness of domestic carbon pricing.

The upward slope of the optimal locus reflects the interaction between domestic carbon pricing and border adjustment. As the home carbon tax increases, domestic firms face higher production costs and become less competitive relative to foreign producers that are not subject to the same carbon price. Absent a corresponding increase in the CBAM,

[12] Figure B.9 shows the underlying firm-level adjustments behind the aggregate responses in Figure 2.4. This is the analogue to Figure 2.2.

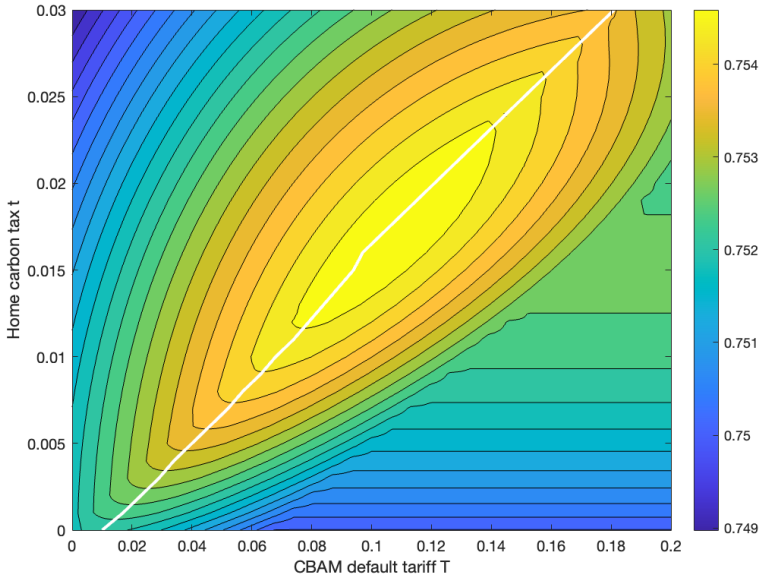


FIGURE 2.5. Heat map showing contours of home welfare for given combinations of the home carbon tax t and the CBAM default tariff T. Baseline emissions E_0 are calculated separately for each level of the home tax t, as the emissions under that tax in the absence of CBAM, or with $T = 0$.

market share shifts toward foreign firms and the scope for carbon leakage increases.

At the same time, a higher domestic carbon tax makes firm-specific reporting less attractive for foreign exporters. Firms that choose the reporting regime internalise the home carbon price on their exports, so an increase in t raises their marginal costs. Unless the default tariff also increases, exporters have an incentive to switch back to the default regime, weakening foreign abatement incentives and reducing the environmental effectiveness of the CBAM.

A more stringent default tariff counteracts both effects. It reduces the competitive advantage of foreign firms in the home market, limits leakage, and encourages exporters to remain in the firm-specific regime where they internalize the carbon price and invest in abatement. In addition, the tariff generates revenue that is rebated to domestic households. Consequently, the welfare-maximising level of T rises with the domestic carbon tax.

The optimal default tariff exceeds the level that would simply equalise carbon costs across domestic and foreign producers, namely the tariff that charges foreign firms on the basis of average emissions intensity. This wedge reflects a terms-of-trade motive. Because CBAM revenues are rebated lump-sum to domestic households, the home country has an incentive to set T above the emissions-correcting level and capture additional revenue from foreign exporters. The resulting increase in household transfers raises domestic welfare, all else equal.

The benefit of a higher tariff must be weighed against its effects on trade. As T increases, fewer foreign firms export to the home market, reducing import variety and lowering the gains from trade. The welfare-maximising tariff therefore balances the revenue gains associated with a higher CBAM against the costs arising from reduced trade and consumption.

An important implication is that a CBAM designed solely to equalise carbon costs across domestic and foreign producers will generally be set below the welfare-maximising level. In our framework, the optimal CBAM reflects not only environmental considerations but also terms-of-trade considerations.

This result also highlights an important interaction between climate policy and conventional trade policy. If an optimal import tariff has already been imposed, the terms-of-trade motive has largely been exhausted. In that case, the CBAM can no longer raise welfare through additional revenue extraction, and its benefits depend entirely on its ability to reduce emissions and limit carbon leakage. Under our baseline calibration, these environmental gains are insufficient to compensate for the associated trade distortions. Consequently, once an optimal tariff has already been set, the CBAM becomes welfare reducing, as shown in Appendix B.1, Figure B.4.

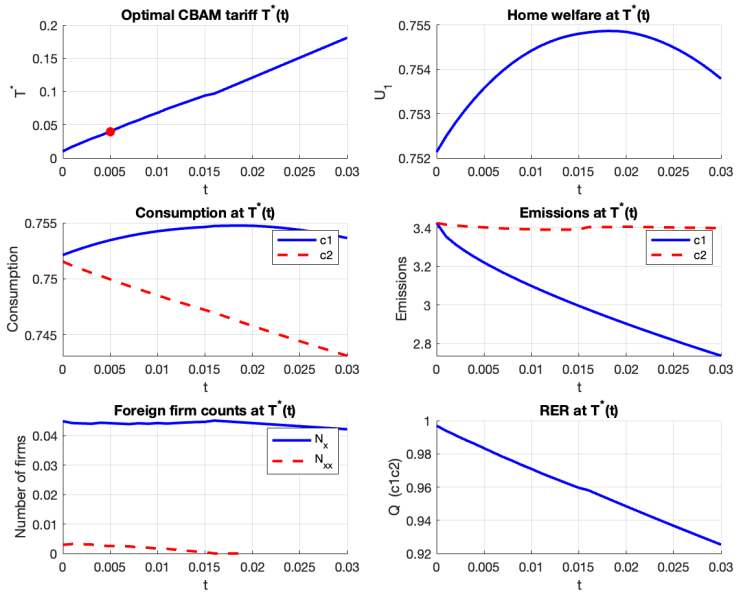


FIGURE 2.6. Model outcomes where each t is paired with its corresponding optimal T.

Figure 2.6 traces model outcomes along the welfare-maximising policy locus, pairing each value of the carbon tax t with its corresponding optimal default tariff T. Two results stand out.

First, the calibrated economy — indicated by the red dot — lies well below the global optimum. Both the carbon tax and the default tariff are substantially lower than their welfare-maximising values, suggesting that the benchmark economy underutilises both instruments and forgoes potentially large welfare gains from more ambitious climate policy.

Second, increasing climate ambition weakens the firm-level abatement channel. Although the optimal default tariff $T^*(t)$ rises with the carbon tax, it does not increase sufficiently to maintain firms' incentives to choose the firm-specific regime. As the domestic carbon price rises, exporters that internalize the carbon tax face increasingly high marginal costs. The benefit of firm-specific reporting therefore declines relative to its fixed reporting cost, causing firms to switch back to the default regime. Consequently, the number of foreign exporters that internalize the carbon price falls as t increases.

This result highlights an important interaction between carbon pricing and CBAM design. A higher carbon tax does not necessarily imply stronger foreign abatement incentives. Unless the default tariff is adjusted sufficiently, more stringent domestic climate policy can induce exporters to abandon firm-specific reporting altogether. Home emissions nevertheless continue to decline because all domestic firms are subject to the carbon tax. Foreign emissions, by contrast, fall much less, since only exporters are exposed to the home carbon price and an increasing fraction of those exporters choose the default regime rather than internalizing the tax.

The precise location of the optimal policy depends on the welfare parameters of the model. In particular, a higher social cost of carbon η increases the value placed on emissions reductions relative to consumption, shifting the welfare-maximising locus upward and to the right. In this case, the home country prefers both a higher carbon tax and a more stringent CBAM. We explore this sensitivity in detail in the following section.

The results also depend on the definition of baseline emissions E_0. In the baseline specification, E_0 is recalculated for each value of t, so that welfare is evaluated relative to the level of emissions that would prevail under that carbon tax in the absence of a CBAM. This approach isolates the contribution of the CBAM from that of domestic carbon pricing. If instead E_0 is held fixed at the level corresponding to the calibrated carbon tax, additional emissions reductions generated by higher values of t receive greater weight in the welfare calculation. As a result, the welfare-maximising policy involves both a higher carbon tax and a higher default tariff, as shown in Appendix B.4, Figure B.10.

2.6. Sensitivity

This section considers the sensitivity of results to two key assumptions. First, our optimal policy results are of course sensitive to our assumption on the social cost of carbon. Second, the emissions reductions from CBAM depend on our specification of the abatement

function.

2.6.1. Social Cost of Carbon

The welfare-maximising pair (t, T) depends on the social cost of carbon η, which governs the weight placed on emissions reductions relative to consumption in the household's utility. A higher η raises the marginal value of the abatement channel, shifting the optimal policy toward a more stringent carbon tax and a higher default tariff. In this section, we examine this sensitivity by varying η.

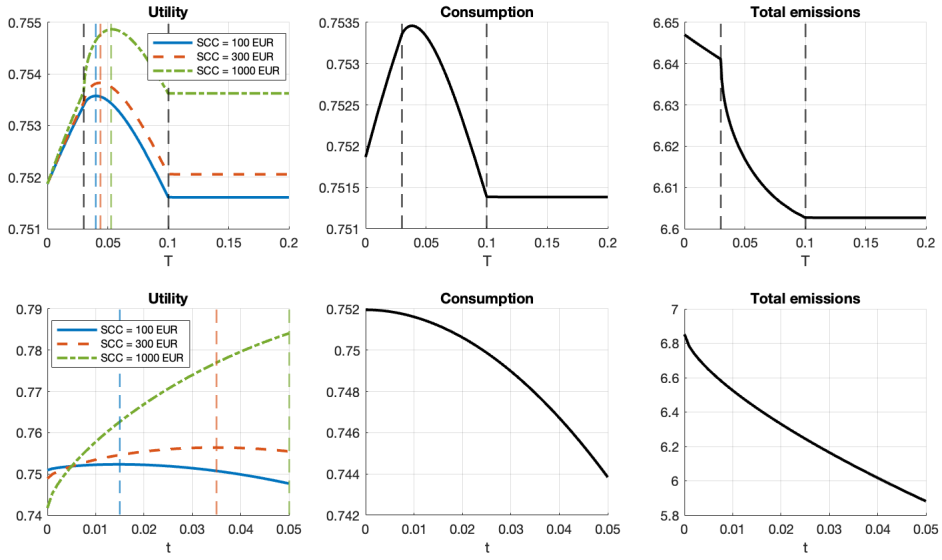


FIGURE 2.7. Model outcomes for three different levels of the social cost of carbon. The blue line shows home utility under a €100 social cost of carbon as in the baseline. The red line shows utility under a €300 social cost of carbon, and the green under a €1000 social cost of carbon. The first row shows outcomes as the CBAM tariff T varies, the second row shows outcomes as the carbon tax t varies.

Figure 2.7 plots home welfare against T (top row, with t fixed) and against t (bottom row, with T fixed) for social costs of carbon of €100, €300, and €1000. In the top row, all three curves originate from the same point at $T = 0$: since baseline emissions E_0 are defined as emissions under $T = 0$ (equation 2.18), the damage term vanishes at that point and η is irrelevant. As T increases and emissions fall below E_0, welfare increases more strongly under higher η, because the marginal value of emissions reductions is larger. As a result, the welfare curves diverge, with higher-η specifications lying above lower-η ones for all $T > 0$. In the bottom row, the curves cross. At low values of t, emissions are high and the welfare loss from environmental damages dominates, so welfare is lowest when η

is high. As t increases, emissions decline and the marginal benefit of further reductions becomes more important. Welfare therefore increases more steeply under higher η, and the high-η curve eventually overtakes the others. Consequently, the welfare-maximising levels of both T and t are increasing in η: a higher social cost of carbon shifts the optimal policy mix toward stronger carbon pricing and a more stringent CBAM, reflecting the greater value of activating the abatement margin.

Figure 2.8 shows welfare contours over the (t, T) space for social costs of carbon of €50 (left panel) and €500 (right panel), with the welfare-maximising schedule $T(t)$ shown by the white line in each panel.[13] The global optimum shifts upward and to the right as η rises, so both the optimal carbon tax and the optimal default tariff are higher under a greater social cost of carbon, consistent with the results in Figure 2.7. Under the higher social cost of carbon, the high-welfare region expands considerably, covering a larger area of the (t, T) space. A wide range of ambitious policy combinations deliver near-optimal welfare when environmental damages are weighted heavily, because activating the abatement channel generates large gains across many (t, T) pairs. The slope of the white line is similar across both panels. The upward-sloping relationship between t and T is robust to the value of η, confirming that the complementarity between the two instruments established in Section 2.5.3 is a general property of the model rather than an artifact of the baseline calibration.

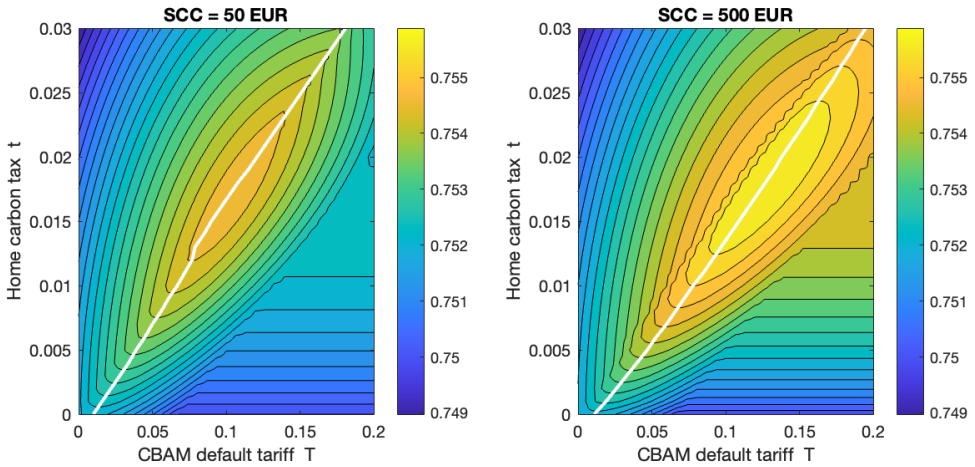


FIGURE 2.8. Heat map showing contours of home welfare for given combinations of the home carbon tax t and the CBAM default tariff T. Baseline emissions E_0 are calculated separately for each level of the home tax t, as the emissions under that tax in the absence of CBAM, or with $T = 0$. In the left panel, η is calibrated to yield a social cost of carbon of €50, while in the right panel it is calibrated to yield a social cost of carbon of €500.

[13] Contour plots for intermediate values of the social cost of carbon are shown in Figure B.14.

2.6.2. Abatement Function

Our results also depend on the specification of the emissions function and abatement costs. Our approach augments the Melitz model with an abatement cost function which we take from Nordhaus (2018). In order to maintain the closed form aggregation of Ghironi and Melitz (2005) we link emissions to labour inputs. Alternatively, we could have adopted a Cobb-Douglas structure in which emissions and labour are both inputs to production as in Shapiro and Walker (2018). We decided against this approach as it implies that emissions are implausibly sensitive to the carbon tax, particularly at low levels of the tax. As we want to study the effect of CBAM on foreign economies with no domestic carbon pricing, this form would therefore imply that emissions are overly sensitive to the CBAM. The equations that govern how this setup differs from our baseline model are included in Section B.4.1. The key difference is that there is no explicit abatement cost ($\theta_1 = 0$), instead abatement reduces emissions which are an input to production:

$$q(z) = e(z)^{\alpha}\big(z\,l(z)\big)^{1-\alpha}, \qquad \alpha \in (0,1). \tag{2.26}$$

$$e(z) = (1 - a(z))^{1/\alpha} z\,l(z). \tag{2.27}$$

Figure 2.9 illustrates this. Emissions fall very steeply at low levels of the carbon tax. A doubling of the carbon tax from the baseline level of 0.005 leads emissions to fall by half. This figure is plotted starting at $t = 0.005$. If we instead started at $t = 0$ the emissions response would be nearly vertical at the beginning. This is problematic in our setting as many economies outside the EU have zero carbon pricing. Therefore this model specification gives implausibly large effects of the CBAM on foreign emissions.[14]

2.7. Three country model

The EU's CBAM will be levied on all imports from the rest of the world. Countries differ greatly in their average emissions intensities. The two country model abstracts from this. This heterogeneity is important as it implies that CBAM will have a differential incidence across source countries. Moreover, the CBAM could potentially lead to trade diversion: reallocating imports towards greener trading partners and away from browner ones. This section considers these effects of the CBAM. Model equations for the three country extension are shown in Appendix B.3.1.

[14] In Figure 2.9 α is calibrated to 0.11 as in Shapiro and Walker (2018). Changing the value for α does not substantially change the emissions sensitivity at low t.

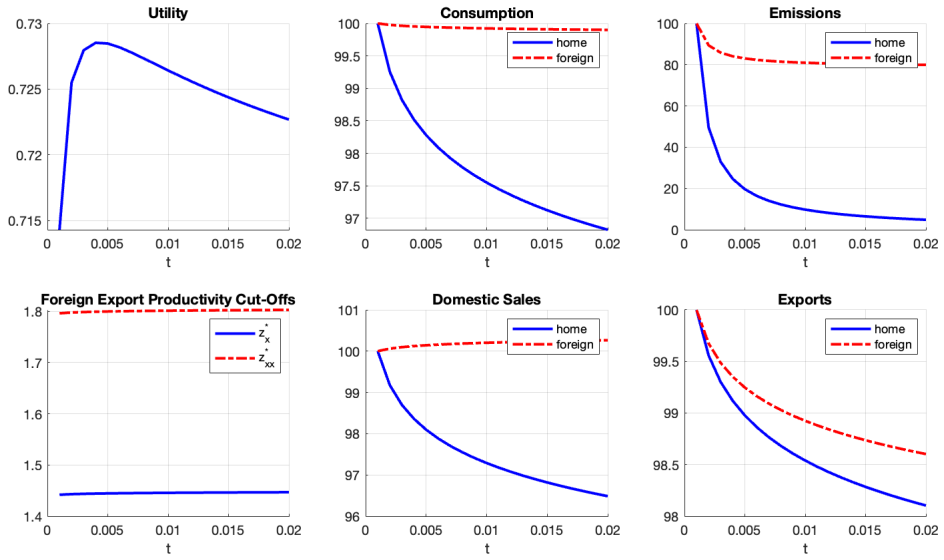


FIGURE 2.9. Outcomes under the alternative model specification in which emissions are an additional input to a Cobb-Douglas production function. The carbon tax varies while the default tariff is kept constant.

Figure 2.10 depicts model responses to a change in the CBAM default tariff in a setting with three countries. We are interested in the heterogeneous incidence of this policy across economies with different emissions intensities. Therefore, we consider a case in which country three has a higher emissions intensity than countries one and two. In particular, we assume that the parameter μ which converts inputs into emissions is twice as high in country three as in the other two economies. There is a positive carbon tax at home and no carbon tax in either of the foreign economies. As a result, the baseline emissions intensity in country two is also greater than at home due to the lack of abatement of firms. This draws out the fact that in our model countries emissions intensities can differ due to i) firm decisions, or ii) the structural emissions factor μ. Even if firms in two countries make identical abatement decisions, emissions can differ across the two economies due to structural factors. For example, one country could have a heavily coal powered grid while another is more reliant on nuclear. Differences in these μ parameters across countries capture these structural differences in emissions intensities.

Figure 2.10 shows that when the two source countries have different emissions intensities, they will have different export productivity cutoffs. For firms in the browner country, the CBAM tariff needs to be higher to induce them to pay the firm-specific tariff. Since they will have greater individual emissions they would prefer to pay the default tariff until it reaches a higher level. Therefore the export productivity cutoffs for firms in country three are shifted rightwards compared to those in country two. This has implications

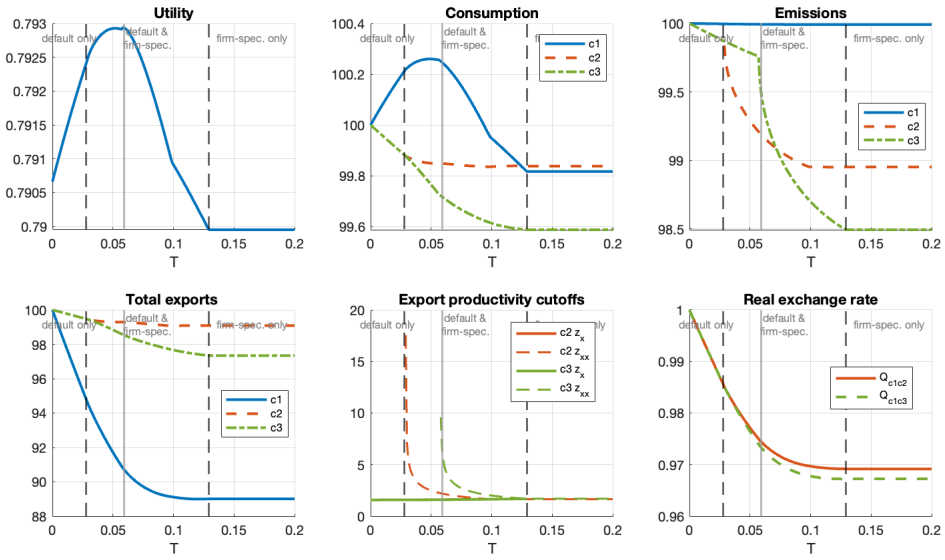


FIGURE 2.10. Model responses to CBAM. The level of the carbon tax t is kept fixed while T varies. Consumption, emissions, domestic sales, and exports are all indexed to 100 at $T = 0$. The underlying emissions intensity of country 3 is set to double that of countries 1 and 2: $\mu_3=2\mu_2=2\mu_1$.

for the effects of CBAM on emissions in these countries. Initially, the CBAM actually reduces emissions by more in the greener country, as firms in this country select into the firm-specific CBAM and so engage in abatement. However, the total effect of CBAM on emissions at high T is much greater for the browner country as emissions start at a higher level and so have further to fall, and because demand for goods from country three falls more due to the larger increase in price caused by the CBAM. This effect is visible by looking at total exports: the exports of country three fall by more than those of country two. As a result, the CBAM is far more detrimental to consumption in country three than in country two. The utility maximizing level of the CBAM tariff is higher in this setting with a browner third country than in the baseline shown in Figure 2.1. In order to induce firms in the browner country to abate, the home country needs to set a higher level of the default tariff.

The CBAM creates trade diversion from country three to country two. Country two has a comparative advantage in producing with low emissions. Therefore, they suffer relatively less than country three when the CBAM is imposed. This is visible first in exports to country one. While country two exports less to country one as the CBAM tariff increases, the effect is larger for country three. This means that the share of home's imports that come from country two increases with T. Country two also benefits from increased exports to country three for low values of T. This increase in exports to country three partly offsets

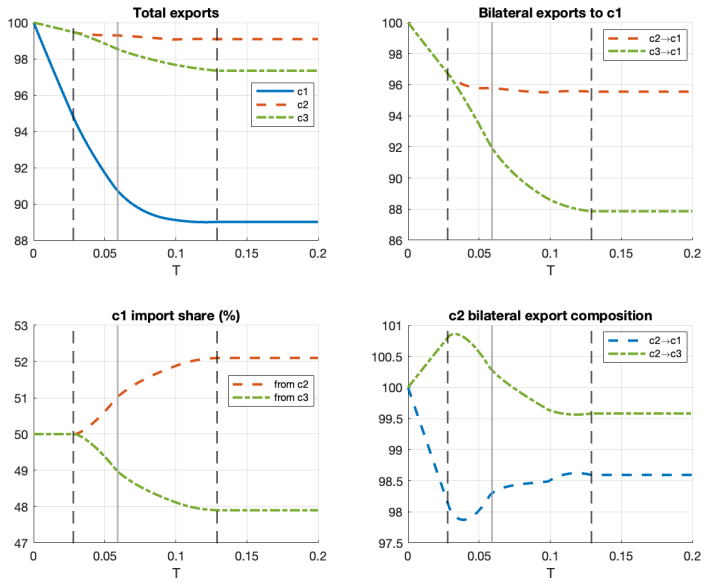


FIGURE 2.11. Model outcomes to CBAM. The level of the carbon tax t is kept fixed while T varies. Total exports, Bilateral exports to country one, and the bilateral export composition of country two are all indexed to 100 at $T = 0$. The underlying emissions intensity of country 3 is set to double that of countries 1 and 2: $\mu_3{=}2\mu_2{=}2\mu_1$.

the decline in exports to country one.

Since structural differences in emissions intensities can have large implications for the effects of CBAM, we may wonder: how much would the browner foreign country be willing to pay to reduce their structural emissions intensity as a result of CBAM? Over and above inducing foreign firms to abate their individual emissions, could the CBAM induce foreign governments to invest in reducing the emissions of their grid?

Figure 2.12 approaches this question. This figure depicts model outcomes as the emissions factor of the third country varies. At the first point, all three countries are as brown as each other. As μ_3 increases, country three becomes browner relative to the other two. The figure shows that as country three becomes browner, countries one and two gain in terms of consumption. Country two increases its exports and gains market share, while country one gains the CBAM revenue. However, utility falls for all of the countries as country three becomes browner. This is due to the utility damages arising from higher emissions. From the figure you can see that country three would be willing to pay to reduce their emissions factor. With a smaller μ, demand for their exports would increase, and emissions damages would fall.

If the baseline emissions were re-calculated for each μ_3 the picture for utility would look different. In this case the increase in baseline emissions due to the higher emissions

of country three is already accounted for and so welfare in countries one and two increase relative to that baseline as country three emissions fall. This scenario is depicted in Figure B.11.

It is also possible that abatement technology could differ across countries i.e. that θ_1 and θ_2 might be heterogeneous. If country three had a higher θ_1 that would imply that abatement was uniformly more costly for them. Therefore emissions would respond less to the CBAM in country three than in country two. This is shown in Figure B.12.

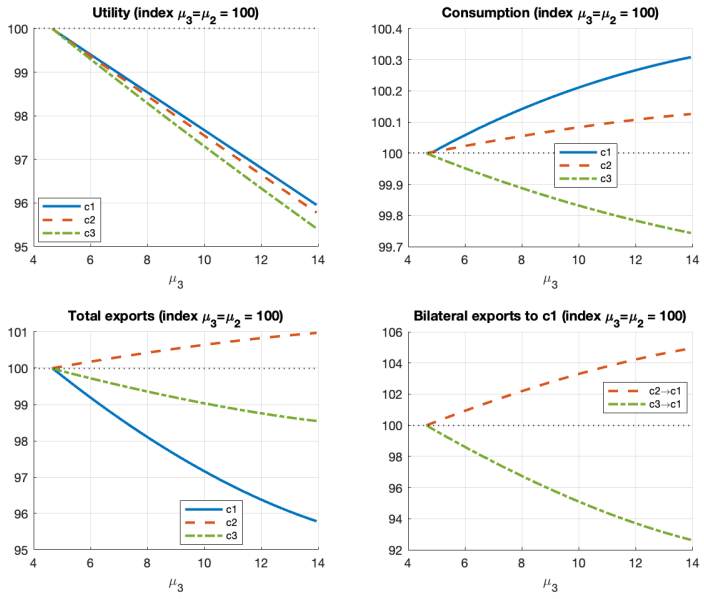


FIGURE 2.12. Model outcomes as the emissions factor of country three varies. Utility, consumption, total exports, and bilateral exports of country one are depicted, all indexed to 100 at $\mu_2 = \mu_3$. Utility is calculated using the same social cost of carbon for each country. The baseline level of emissions E_0 is kept fixed at the level where $\mu_2 = \mu_3$.

2.8. Conclusion

This paper develops a heterogeneous-firm trade model to study the design and effects of carbon border adjustment mechanisms. The central contribution is to introduce endogenous abatement and a compliance choice. Foreign exporters decide whether to incur a fixed verification cost and pay a firm-specific levy based on their actual emissions, or to avoid this cost and pay a default tariff based on benchmark emissions intensity. This choice is absent from the existing CBAM literature, in which border adjustments take the form of uniform sectoral levies and foreign firms have no incentive to reduce their emissions intensity in response.

The compliance choice generates a sorting mechanism with important implications for both aggregate emissions and the distributional incidence of the policy. More productive exporters self-select into the firm-specific regime, internalising the destination country's carbon price and investing in abatement. Less productive exporters remain on the default tariff and do not abate. The CBAM therefore affects foreign emissions through three distinct channels: a scale channel, operating through firm entry and exit, a compliance channel operating through the endogenous decision to report, and an abatement channel, operating through the emissions decisions of firm-specific exporters. The relative importance of these channels depends on the level of the default tariff. At low values of the default tariff, few firms choose firm-specific reporting and the abatement channel is negligible. At high values, trade collapses and the scale effect dominates. These findings imply that the level of the default tariff is a first-order design choice, not a secondary implementation detail.

The model also characterises the jointly optimal domestic carbon tax and default tariff. The two instruments are complements: a higher carbon tax raises the optimal default tariff. The welfare-maximising default tariff exceeds the level that would simply equalise carbon costs across domestic and foreign producers, reflecting a terms-of-trade motive — the importing country has an incentive to set a higher default tariff because CBAM revenues are recycled domestically. This result implies that a CBAM designed purely to level the playing field on emissions costs will be set below its welfare-maximising level.

In the three-country extension, the CBAM generates trade diversion away from countries with higher structural emissions intensity and toward cleaner ones. Countries with an environmental comparative advantage — lower emissions per unit of output — lose less market share, or gain relative to browner competitors, when the importing country imposes a border adjustment. This highlights that CBAMs are not only climate instruments but also trade instruments with distributional consequences across source countries, and that their effects depend critically on the heterogeneity of emissions intensities across trading partners.

CHAPTER 3.

The Carbon Premium and Policy Risk Exposure: A Text-Based Approach

Abstract

Shifts in climate policy have heterogeneous effects on firms' profitability. Does the market price this risk? Theory predicts that exposed firms have negative abnormal returns on policy announcement dates. I build a set of such dates and characterize return responses using *Risk Factors* discussions in 10-K filings. An NLP algorithm uncovers predictors of policy risk exposure in the text. Exposure is correlated with emissions, environmental lobbying, and is predictive out-of-sample. Higher exposure is not associated with a premium. Empirically identified green preference shifts can partly explain this absence of a climate policy risk premium.

3.1. Introduction

Substantial reductions of carbon emissions are required in order to stay below the temperature limits laid out in international climate agreements.[1]. It is widely agreed that such emissions reductions require policy intervention, such as carbon taxes or emissions caps. Climate policy interventions have heterogeneous effects on the profitability of firms depending on their emissions, their ease of substituting to greener technologies, and their positioning in the network of firms who themselves have differential exposure. These factors constitute a risk for firms who will be exposed to these policies: climate policy risk.

Theory predicts that firms with higher exposure to climate policy risk pay higher returns to investors to compensate them for exposure to this risk. This is the climate policy risk premium. In this paper I test for the existence of such a premium. The (non)existence of a climate policy risk premium has important implications. If governments delay in implementing climate policy and this risk is not priced in by markets, a sudden policy shift could in the worst instance lead to fire sales with financial stability implications (Carney 2015).

Motivated by the disagreement in this empirical literature, most of which uses emissions data or ESG scores[2] to proxy for risk exposure (Bolton and Kacperczyk 2021, 2023; Bauer et al. 2022), I build a novel firm-level measure of exposure to climate policy risk utilising equity price movements on climate policy announcement dates and text data from firms' form 10-K. Firm-level emissions data has many limitations: release lags, cross-sectional incompleteness, and instability across vendors and time. Moreover, emissions are an incomplete measure of exposure to climate policy risk. A given firm may have low emissions but may be very vulnerable to climate policy risks due to reliance on inputs from high emissions firms or high emissions associated with the consumption of their products. Exposure to climate policy risk will also be related to how easily a firm can abate their emissions. 'Scope 3' emissions data present a potential solution to the first of these problems by including indirect emissions up and down the value chain as well as direct emissions from production. However, scope 3 emissions are reported only for a small subset of firms and are likely measured with a great deal of error as there is ongoing disagreement on what exactly should (not) be included (Bauer et al. 2022). Therefore,

[1]The UNEP finds that the world is heading for a 2.5-2.9°C temperature rise unless countries deliver more than promised under the Paris Agreement (UNEP 2023). The IPCC states that global warming of 2°C will be exceeded during the 21st century unless deep reductions in CO2 emissions occur in the coming decades (IPCC 2021).

[2]Environmental, social, and governance (ESG) investing is an investing approach that prioritizes environmental issues, social issues, and corporate governance. To aid investors in this approach, vendors of financial data have begun to construct and disseminate ESG scores for listed firms. These scores are designed to summarize the performance of firms along environmental, social, and governance dimensions which are not as easily captured with traditional financial indicators.

rather than relying on emissions data I build a market implied measure of risk using text data from corporate reporting.

I proceed in five steps. First, I outline a simple asset pricing model to motivate the empirical approach. In the model, higher exposure to climate policy risk is associated with i) a larger fall in one period returns in response to the announcement of an increase in climate policy stringency, and ii) a climate policy risk premium in equilibrium. Therefore, I collate a list of salient and unexpected climate policy announcements which are informative for exposure of US-listed firms. I list climate policy announcements by US Presidents, Congressional bill passages related to climate, Supreme Court decisions on climate related legislation, agreements reached at UN Climate Conferences, and major IPCC report releases. Out of these dates I select those that i) are covered in either the New York Times or Wall Street Journal, ii) are associated with detectable movements in stock prices, and iii) aren't confounded by other major non-climate news. Examples of announcement dates included are the signing of the Paris agreement and the passage of the Inflation Reduction Act through the senate. Examples of announcements which are excluded are Executive Orders on climate which are not covered in the news, and Inflation Reduction Act related events which occurred as COVID lockdown measures were also announced.

Second, I use text data from *Risk Factor* discussions in firms' form 10-K to understand in natural language the drivers of firms' exposure to climate policy risk, and to build a firm -level measure of exposure to that risk. In these Risk Factor discussions, firms describe the risks that they are exposed to. The SEC advises that firms should include any item that could impact future earnings. Firms can be sued for omitting material information on risks. Following Davis, Hansen, and Seminario-Amez (2021), the idea is that the language firms use to describe their risks is predictive of their financial performance when these risks materialize. I use this text to predict abnormal returns on the climate policy announcement dates and find that terms associated with fossil fuels are most predictive of negative abnormal return responses, and terms associated with cleaner activities are most predictive of positive abnormal returns.

To implement this procedure I adopt the multinomial inverse regression (MNIR) method introduced by Taddy (2013) and applied by Gentzkow, Shapiro, and Taddy (2019) and Davis, Hansen, and Seminario-Amez (2021). MNIR represents a methodological improvement in this literature as it considers all terms in the *Risk Factor* discussions to be candidate predictors of abnormal returns. Therefore I do not pre-specify a set of terms I believe will be predictive. Instead, terms are selected into the model based on the strength of their association with abnormal returns on climate policy announcement dates. Once predictive terms are found, a sufficient reduction of the text for each firm can be defined as the sum of term counts multiplied by their coefficient in the inverse regression. This is

my climate policy risk exposure score. Therefore, MNIR uncovers both which terms are predictive and how they should be weighted. An additional advantage of this method is its relative simplicity and similarity to econometric models of discrete choice.

Third, the exposure score is validated by its ability to pick out climate policy related terms and its ranking of fossil intensive firms as highly exposed, and green technology firms as negatively exposed. I conduct three further exercises to validate the risk measure. First, I show that it is correlated with firm-level emissions. Second, a higher exposure score is associated with a greater likelihood of lobbying on environmental issues.[3] Third, I re-estimate the exposure score using a subset of the climate policy announcement dates and show it is predictive on the left-out 'test' dates. In this case it also out-performs alternative measures of risk exposure from the literature.

Fourth, with this measure of risk exposure in hand I investigate whether climate policy risk is priced. Both cross sectional regressions following Bolton and Kacperczyk (2021), and portfolio sorts indicate that there is no premium over the sample considered. In fact, the high minus low exposure portfolio earns a negative premium over the period 2012-2020 which turns weakly positive only over the last two years 2021-2022. Markets react to climate policy announcements, however I do not observe a premium associated with this risk.

Finally, I turn to rationalize this empirical result within the framework of the asset pricing model. Green preference shocks which reduce cash-flows for browner firms offer a potential explanation. When a green preference shock hits, abnormal returns fall for brown firms. Therefore, although this also implies a brown premium in equilibrium, persistent preference shocks over the estimation period imply lower realized returns for brown firms. This is plausible given the rise of sustainable investing over the sample period. In order to separate these preference shocks from policy shocks in the data, I draw on a distinction between equities with low policy risk exposure, and equities perceived to be 'sustainable' by ESG investors.

I utilise a sign-restriction SVAR to separate these shocks. van der Beck (2021) constructs a representative ESG portfolio. I compare this portfolio to the low-high risk portfolio constructed using the text-based exposure score and construct an over-under portfolio which goes long in equities over-weight in the ESG portfolio relative to their policy risk exposure score (e.g. a relatively green oil company), and short in equities under-weight in the ESG portfolio relative to their exposure score (e.g. a tobacco company). The idea of the sign restriction is that the over-under portfolio should earn positive returns when a preference shock materializes but not when a policy shock does, whereas the low-high portfolio should increase in both instances. I show that the empirically identified preference shocks explain about as much of the return dynamics of the low-high portfolio

[3] I obtain data on firm-level lobbying from Open Secrets: https://www.opensecrets.org/federal-lobbying/

as the policy shocks do.

Relation to the literature. This paper contributes to an extensive empirical literature that investigates the relationship between environmental and financial performance. The first strand of this literature asks whether stocks of firms with higher carbon emissions earn higher returns. Influential papers by Bolton and Kacperczyk (2021, 2023) provide evidence of a carbon premium: stocks of firms with higher emissions earn higher returns which cannot be explained by differences in other known risk factors. These results are interpreted as evidence of investors seeking compensation for holding stocks which are exposed to 'carbon risks' e.g. from regulation to limit emissions or technology risk from renewable energy. Hsu, Li, and Tsou (2023) similarly find a premium associated with non-carbon industrial pollution. Ilhan, Sautner, and Vilkov (2022) find that climate policy uncertainty is priced in the option market.

Subsequent papers have questioned the existence of such a carbon premium. Aswani, Aneesh, and Shiva (2023) find that the carbon premium result is not robust to restricting the sample to firm-disclosed rather than vendor-imputed emissions data. They also stress the point that returns are not correlated with emissions intensities - emissions scaled by firm size - which may be more informative for climate risk exposure. Bauer et al. (2022) use disclosed emissions data for G7 countries and find a negative premium. Enders et al. (2023) observe a negative carbon premium in Europe. Zhang (2025) argues that after accounting for lags in the release of carbon emissions data, the premium also turns negative. Hong, Weikai Li, and Xu (2019) find that food stock prices under-react to climate change risk. I contribute to this literature by asking a related question: is there a *climate policy* risk premium? In order to answer this question and avoid the problems with emissions data outlined above, I construct a market implied measure of risk using text data from corporate reporting.

Closely related to this paper is a strand of literature which constructs firm-level measures of risk exposure. Hassan et al. (2019) use text data from earnings calls to build firm-level measures of political risk exposure. The share of quarterly earnings conference calls devoted to discussing political risks is used as a measure of exposure. Sautner et al. (2023) extend this approach to the case of climate risks. They provide a list of initial keywords associated with climate change and use a keyword discovery algorithm to construct sets of related terms whose frequency in earnings calls is defined as climate risk exposure. In a later paper Sautner et al. (2024) find that their climate change exposure measure carries a positive and increasing premium since the financial crisis. Li, Tang, and Yao (2024) also use earnings calls to identify climate related risks, in this case using a pre-specified dictionary. Baz, Michaelides, and Zhang (2022) construct another dictionary based measure of exposure to risk using firms form 10-K. They document that

more exposed firms experience positive stock return effects after the 2016 Trump election. Engle et al. (2020) construct a climate news series. Huynh and Xia (2021) find that bonds with a higher climate change news beta earn lower future returns. Faccini, Martin, and Skiadopoulos (2022) construct aggregate measures of climate risk from textual analysis of news coverage. Blasberg, Kiesel, and Taschini (2021) use Credit Default Swap spreads to construct a market-implied carbon risk factor.

I contribute to this strand of the literature using Risk Factor discussions from firms 10-K filings and a supervised machine learning algorithm utilising information from climate policy announcement dates. Davis, Hansen, and Seminario-Amez (2021)construct firm-level exposures to COVID-19 news using this data, showing that the ML approach yields richer characterizations of risk than the dictionary approach and outperforms it in terms of goodness-of-fit. My contribution is to apply this more sophisticated ML method to the climate risk case. Instead of taking pre-specified terms, consistent with the asset pricing model, this algorithm selects terms into the model which are predictive of stock price movements on climate policy announcement dates. Therefore, this paper is also related to empirical literature employing climate policy event studies.

Seltzer, Starks, and Zhu (2022) use the Paris Agreement as a shock to expected climate regulations and show that these risks affect corporate bond risk assessment and pricing. Barnett (2023) uses transition related events to show that shifts in transition risk lead to patterns consistent with a 'run on fossil fuel'. Cassidy (2023) uses tools from natural language processing to construct a set of climate policy announcements from Executive Branch communication. Hengge, Panizza, and Varghese (2023) use EU ETS surprises following Känzig (2023) to show that events resulting in higher carbon prices lead to negative abnormal returns which increase with a firm's carbon intensity. I contribute to this literature by constructing a set of climate policy announcements which are informative for the risk exposure of listed firms.

A final strand of the literature considers 'ESG' investing more broadly. Pástor, Stambaugh, and Taylor (2021) develop an asset pricing model which includes both policy and preference shocks. Green firms outperform brown firms when policy shocks hit, but brown firms earn higher expected returns in equilibrium. Pástor, Stambaugh, and Taylor (2022) provide some evidence that in fact stocks of green firms earn higher realized returns potentially due to increased concerns about climate change. van der Beck (2021) argues that the high realized returns of ESG portfolios can be explained by price pressure from flows towards sustainable funds. Therefore these high realized returns need not reflect high expected returns. In this paper I utilise the theory of Pástor, Stambaugh, and Taylor (2021). By considering stock price movement on climate policy announcement days I can build a measure of risk exposure. I use the ESG portfolios build by van der Beck (2021) to separate policy and preference shocks in a sign restriction SVAR.

Outline. Section 3.2 presents an Organizing Framework to motivate the empirical approach. Section 3.3 outlines the Data and Empirical Approach. Section 3.4 discusses Results, section 3.5 Interprets these results in the context of the Organizing Framework, and section 3.6 concludes.

3.2. Organizing Framework

This section presents a simple theoretical framework useful for understanding climate policy risk and its relation with stock returns. The framework follows closely the model of Giglio et al. (2021) and is similar in structure to models of long run risk a la Bansal and Yaron (2004).

Assume that aggregate consumption follows

$$\Delta c_{t+1} = \mu + x_t - J_{t+1}, \tag{3.1}$$

where

$$x_{t+1} = \mu_x + \rho x_t + \phi J_{t+1}. \tag{3.2}$$

c_t is the log of aggregate consumption which corresponds to aggregate output in equilibrium.[4] The process x_t captures persistent changes in the growth rate of consumption. J_t is a jump process that takes a value of ξ with probability λ in each period and 0 otherwise. I interpret this shock as a climate policy shock i.e. an unexpected shift in climate policy stringency.[5] In line with the empirical evidence, an increase in climate policy stringency depresses consumption (Känzig 2023). A calibration of $\phi > 0$, $\rho > 0$ implies partial mean reversion in consumption after a policy shock.

I specify a separate cash flow process for risky assets which in this setting correspond to equity. There is a cross section of equities in the model indexed by i. The process for equity cash flows is similar to that for consumption:

$$\Delta d_{i,t+1} = \mu_d + y_t - \eta_i J_{t+1} \tag{3.3}$$

$$y_{t+1} = \mu_y + \omega y_t + \psi J_{t+1} \tag{3.4}$$

Equities are differentially exposed to the climate policy shock. This is captured by

[4] The economy is closed and does not feature investment.

[5] Giglio et al. (2021) interpret J_t as a physical climate disaster in their setting.

the η_i coefficients which measure exposure. Equities with larger positive η_i are more negatively exposed to climate policy, equities with larger negative η_i are more positively exposed to climate policy.

I assume the existence of a representative agent who maximizes lifetime utility and faces a complete set of financial instruments. The per period utility function features constant relative-risk aversion (γ):

$$U(C_t) = \delta^t \frac{C_t^{1-\gamma}}{1-\gamma} \tag{3.5}$$

where δ is the rate of time preference. I am interested in one period returns and risk premia. One period returns of equity i are given by:

$$R_{i,t,t+1} = \frac{P_{i,t+1}}{P_{i,t}} \tag{3.6}$$

Therefore log one period returns are:

$$r_{i,t,t+1} = \ln P_{i,t+1} - \ln P_{i,t} = p_{i,t+1} - p_{i,t} + \Delta d_{t+1} \tag{3.7}$$

Assuming that log returns and stochastic discount factor are jointly normally distributed, the risk premium is then given by:

$$E_t\left[R_{i,t,t+1}\right] - R^f_{t,t+1} \simeq \gamma \operatorname{Cov}_t\left[r_{i,t,t+1}, \Delta c_{t+1}\right] \tag{3.8}$$

where $E_t\left[R_{i,t,t+1}\right]$ is the one period expected return of equity i and $R^f_{t,t+1}$ is the risk-free rate.

Solving the model recursively, it can be shown that

$$r_{i,t,t+1} = -\left[a_i + b_i x_{t+1} + e y_{t+1}\right] + \left[\mu_d + y_t\right] - \eta_i J_{t+1} \tag{3.9}$$

$$E_t\left[R_{i,t,t+1}\right] - R^f_{t,t+1} \simeq \gamma \eta_i \xi^2 \lambda(1-\lambda) \tag{3.10}$$

where a_i, b_i, and e solve recursive equations derived analytically by Giglio et al. (2021). The exact expressions are reported in Appendix C.1.

Discussion. A climate policy shock (e.g. an announcement of an increase in a carbon tax or a fall in an emissions cap) leads to a fall in consumption. When the climate policy shock hits, one period returns fall for those firms (equities) which are negatively exposed. One period returns increase for those firms which are positively exposed. Therefore, climate policy exposure constitutes a risk and commands a risk premium: investors demand compensation for holding equity which is negatively exposed to climate policy. The model predicts a risk premium which is increasing in exposure (η_i). This insight will guide the empirical approach of this paper: climate policy jump days will be used to identify equities which are exposed to climate policy risk.

3.3. Data and Empirical Method

3.3.1. Data

Firm-level returns. I consider a sample from 2012-2022 with attention restricted to U.S-incorporated firms with share prices quoted in U.S. Dollars. Financial data is obtained from Compustat. Daily and monthly returns are obtained for 3,894 equity securities for which there is return data on at least three of the jump days listed below and a non-empty part 1a) in form 10-K. See Appendix C.2 for more information about the sample. Abnormal returns are constructed on each climate policy announcement date in the standard way per the Capital Asset Pricing Model (CAPM):

$$\text{Abn}_{i,t} = \log\left(\frac{p_{i,t}}{p_{i,t-1}}\right) - R_{f,t} - \text{ beta }_i \times \left(R_{M,t} - R_{f,t}\right) \tag{3.11}$$

where $p_{i,t}$ denotes the share price for stock i on day t, R_f denotes the four-week treasury bill rate, $beta_i$ is the stock's CAPM beta, and R_M is the value-weighted average market return. Each stock's beta is estimated using an OLS regression of daily excess return on the market excess return in the sample of all trading days for the year prior.

In cross-sectional regressions I use a number of variables following Bolton and Kacperczyk (2021) which are constructed using Compustat. These variables are outlined in Appendix C.2.

Risk Factors Text. The Securities and Exchange Commission (SEC) requires the vast majority of publicly held firms to include a discussion of *Risk Factors* in their annual corporate reporting - their form 10-K. Firms are advised to include any factor which could impact future earnings in these reports. If the firm omits material information or risks, investors can sue for compensation. Machine-readable versions of these reports are available on EDGAR. The raw text is processed into a corpus of words and phrases as

outlined in Appendix C.2. After pre-processing there are 21,876 terms. Following Davis, Hansen, and Seminario-Amez (2021), this large number of terms necessitates some form of dimension reduction. Therefore I employ the MNIR model which operates on all terms (Taddy 2013).

3.3.2. Empirical Approach

Return movements on climate policy announcement dates contain information on firms' relative exposure to climate policy risks. I use a supervised machine learning algorithm to uncover predictors of this risk exposure and build exposure scores for each firm. As the US does not have a national carbon tax, I use a narrative approach to identify dates on which other climate policy announcements have been made.

Jump Days. In order for a candidate date to be useful in this setting, the announcement must lead to movements in abnormal returns which I can be confident are due to the climate policy announcement. Therefore, the announcements must be i) unexpected, ii) reasonably large, and iii) not confounded by other non-climate announcements at the same time. Therefore, I select jump days according to the following steps:

1. Collate a list of climate policy announcements from 2012-2022. These candidate announcements come from a number of sources:
    - Important dates relating to the passage of the Inflation Reduction Act (IRA) from Bistline, Mehrotra, and Wolfram (2023).
    - Important dates relating to the passage and challenge of the Clean Power Plan (CPP).
    - Tabling of other relevant climate legislation e.g. the Green New Deal.
    - Signing of International Agreements and Announcements from UN Conferences.
    - Executive orders relating to climate.
    - Supreme Court decisions on climate legislation.
2. Remove those candidate announcements of which there was no coverage in either the *Wall Street Journal* or the *New York Times*.
3. Remove those candidate announcements which were made at the same time as more salient market news materialized.
4. Remove those candidate announcements which were not associated with negative abnormal returns for especially brown industries: Oil, Coal and Mining.

Step a) results in a list of 53 candidate dates. After step b) 45 dates remain. After step

c) 33 dates remain, and step d) leaves us with the final 15 dates. Details of this process are confined to Appendix C.2. The final set of 15 dates are listed in Table 3.1.

TABLE 3.1. Climate Policy Announcement Dates

Announcement	Date
Loss and damage agreement at COP27	21/11/22
Senate Passage of IRA	08/08/22
Congressional Budget Office Pricing of IRA	03/08/22
Senator Manchin U-turn on IRA	27/07/22
Supreme Court Strikes down CPP	30/06/22
Build Back Better bill passes the house	19/11/21
Glasgow Pact at COP26	13/11/21
IPCC Sixth Assessment Report	09/08/21
Biden Executive Order to rejoin Paris Agreement	20/01/21
Formal notice of intention to withdraw from Paris Agreement	04/11/19
Green New Deal Resolution presented to Congress	07/02/19
Trump's Executive order to begin review of CPP	28/03/17
US and China announce they will sign the Paris Agreement	01/04/16
Paris Agreement Reached	14/12/15
Obama unveils CPP	03/08/15

Note: List of Climate Policy Announcement Dates used. Dates in red are instances of climate policy becoming less stringent.

Multinomial inverse regression. I am interested in what features of the *Risk Factors* text are predictive of abnormal return responses to the climate policy announcements, and in building an exposure score for each firm. I utilise the MNIR method developed by Taddy (2013) and applied by Gentzkow, Shapiro, and Taddy (2019) and Davis, Hansen, and Seminario-Amez (2021). The text for each firm is represented by a bag-of-words i.e. it is a V-dimensional vector $\mathbf{x_i}$ of terms. V is the number of unique terms in the corpus, and $x_{i,v}$ gives the number of instances of term v in firm $i's$ filings. MNIR models the relationship between the term counts and the object of interest - here abnormal returns on climate policy announcement dates - directly. The structure of the model is very similar to econometric models of discrete choice. MNIR posits

$$\mathbf{x}_i \sim \text{MN}(\mathbf{q}_i, N_i) \tag{3.12}$$

where $\mathbf{q}_i$ is a multinomial V-dimensional probability vector and N_i is the total number of terms in firm i's filings. The probabilities of each term for each firm are therefore given by $\mathbf{q}$. The probability of term v for firm i is given by:

$$q_{i,v} = \frac{\exp\left(a_v + \mathbf{y}_i^T \mathbf{b}_v\right)}{\sum_v \exp\left(a_v + \mathbf{y}_i^T \mathbf{b}_v\right)} \tag{3.13}$$

where $\mathbf{y}_i = (\text{Abn}_{i,t}, \mathbf{c}_i)$ contains the firm's abnormal returns on the announcement dates as well as a vector of controls.[6] The baseline frequency of term v is set by the parameter a_v, and b_v is a vector of coefficients describing how firm observables map to the probability of term v appearing in the firm's filings.

Therefore, we have a multinomial logistic regression over V terms where the outcome variable is the probability of a given term appearing in a random draw from the firm's filings. This is a standard econometric model of discrete choice but for the high dimensionality of V. In order to reduce the dimensions of the problem, the model is estimated using Bayesian regularization methods with a Gamma-Laplace prior structure on the regression coefficients. This is a generalization of the standard LASSO penalty with the possibility for term-specific penalties. As shown in Taddy (2013), this prior trades off goodness-of-fit and model complexity via the maximization of an information criterion.

I now have a model of the inverse relationship of term probabilities given returns. To move forward to predictors of abnormal returns I follow Taddy (2013) and Davis, Hansen, and Seminario-Amez (2021) and define a sufficient reduction projection

$$z_i = \sum_v x_{i,v} b_{1,v} \tag{3.14}$$

with the property that

$$\text{Abn}_i \perp \mathbf{x}_i | z_i, N_i, \mathbf{c}_i \tag{3.15}$$

This implies that conditional on the scalar projection z_i - my exposure score - the high-dimensional text data contains no extra predictive information for returns. Therefore, we can model Abn_i as a function of z_i, N_i, $\mathbf{c}_i$ while disregarding $\mathbf{x}_i$. z_i summarizes the predictive information in the text for how abnormal returns respond to climate policy announcements.

Portfolio sorts and cross-sectional regressions. I use the constructed exposure scores to test for a climate policy risk premium. I proceed in two ways. First, I construct quintile portfolios sorted on exposure score. The low portfolio contains firms with the lowest

[6] I control for the number of terms in the part 1a), leverage, NAICS3, and market capitalization.

exposure scores and the high portfolio contains firms with the highest exposure scores. After forming the portfolios I calculate value-weighted monthly returns on these portfolios. I also form a high-minus-low portfolio that takes a long position in the most exposed firms and a short position in the least exposed firms. I calculate the value-weighted return on this long-short portfolio and test whether it earns a positive return over the sample. Such a result would be indicative of a climate policy risk premium.

Following Bolton and Kacperczyk (2021) I also run cross-sectional return regressions to test for a premium. Here, the dependent variable is firm level monthly returns, the independent variable is the exposure score, and I include the same vector of controls as in Bolton and Kacperczyk (2021). In this case a significant positive coefficient on the exposure score would be evidence for a climate policy risk premium.

3.4. Results

3.4.1. Inverse Regression

The MNIR model is fit to the climate policy announcement dates. I control for industry (SIC), market capitalization, and leverage. The model selects 18,054 terms. Of these, it puts positive weight on 9,573 and negative weight on 8,481. 5,946 terms are not selected into the model. Table 3.2 shows the terms with the highest positive and negative coefficients in the inverse regression - the first element of $\mathbf{b_v}$. As is standard I weight the coefficients by their tf-idf. The table indicates the terms which are most predictive of abnormal return responses on the climate policy announcement dates. Therefore it is useful in uncovering factors which contribute to exposure to climate policy risk.

The table shows that terms associated with negative abnormal returns are often related to fossil fuels ("coal mining", "gas price", "natural gas cost"). The model therefore captures that as well as fossil fuel producers, downstream firms who are dependent on fossil energy may be exposed to climate policy. The model also picks up terms directly related to climate policy ("fuel surcharge", "environmental permit", "permit requirement"). Terms associated with positive abnormal returns are related to activities which are less likely to be affected by climate policy. Renewable technologies, healthcare, and financial services all show up in the list of predictive terms.

Table 3.3 shows the coefficients on each of the terms in the Sautner et al. (2023) list of initial keywords which are included in my corpus. They specify a list of initial climate-related keywords and use a keyword-discovery algorithm to build lists of similar terms. I restrict attention to their 'opportunity' and 'regulatory' bigram lists. In cases where the exact bigram is not included in my corpus, I instead take the closest related term. Table 3.3 shows that the MNIR model correctly sorts the terms. Bigrams specified as initial 'regulatory' terms are selected into the model with negative coefficients i.e. the model

TABLE 3.2. Most Predictive Terms

rank	term	rank	term
1	mineable	1	battery
2	regulatory_clearance	2	solar_panel
3	refined	3	prc_foreign_exchange
4	politically	4	electric_transmission
5	mineralize	5	wind
6	fuel_surcharge	6	clinician
7	capital_requirement	7	secondary_trading
8	coal_mining	8	solar
9	mineral_resource	9	financially
10	environmental_permit	10	financial_statement
11	power_shortage	11	fda_approval
12	energy_use	12	variable_interest_rate
13	power_system	13	available_therapy
14	refractory	14	innovator
15	boeing	15	robot
16	gas_exploration	16	department_of_defense
17	gas_price	17	obamas
18	production_from_oil	18	willingness_of_patient
19	permit_requirement	19	solar_energy
20	natural_gas_cost	20	clinical_research

Note: The table shows the terms with the largest coefficients weighted by their tf-idf score in the MNIR model fit to climate policy announcement days. The left hand side of the table shows the 20 terms which have the largest negative tf-idf weighted coefficients. The right hand side of the table shows the 20 terms with the largest positive weighted coefficients. The tf-idf is computed as the count of uses of the term in the whole corpus multiplied by $log(\frac{24{,}000}{df_v})$ where df_v is the number of firms who use term v in their filings. Terms that appear in the filings of more than two-thirds of firms are excluded.

picks up that they are related to negative climate policy risk exposure. Bigrams specified as related to 'opportunity' are selected into the model with positive coefficients. Therefore, by using abnormal return responses on climate policy announcement dates as labels in a supervised machine learning algorithm, I circumvent the need for specifying sets of initial keywords. Instead, I allow the data to tell me which terms are most informative for climate policy risk exposure. The model succeeds in selecting terms which we would imagine a priori would be associated with positive or negative climate-policy risk exposure.

There are two additional advantages of this approach. Firstly, the inverse regression makes clear not only whether a term is positively or negatively related to climate policy risk exposure but also provides an indicator of the strength of this association. Therefore, very

predictive terms will be highly weighted, and less predictive terms less highly weighted when constructing firm-level exposure scores. Secondly, the Risk Factor text by definition only discusses downside risk. Therefore, I do not have to be concerned with performing corrections for sentiment.

TABLE 3.3. Sautner et al initial keywords

coefficient	term	coefficient	term
-25.72	greenhouse_gas	5.46	solar
-19.52	greenhouse_gas_emissions	5.96	solar_energy
-20.41	emission_reduction	5.32	solar_panel
-17.39	pollution	4.61	renewable_energy
-17.01	carbon_dioxide	3.61	renewable
-31.97	emission_of_carbon	6.22	wind
-13.76	environmental_standard	3.81	wave
-12.58	epa	2.69	electric_vehicle
-5.02	dioxide	4.51	geothermal
-22.09	energy		
-5.32	nox		

Note: The table shows the coefficients on terms included in Sautner et al's initial keyword list. Where the exact bigram does not appear in my corpus I instead take the closest term available. The left column shows coefficients on terms in the 'regulatory' category, the right column shows coefficients on terms in the 'opportunity' category. The mean coefficient value in the corpus is −2.39, with a standard deviation of 7.09. The maximum value is 9.1 and the minimum is −31.

3.4.2. Exposure Scores

Having fit the MNIR model to abnormal returns on climate policy announcement dates, I can now construct the sufficient reduction projection:

$$z_i = \sum_v x_{i,v} b_{1,v}$$

This scalar summarizes the information in the text which is relevant for explaining abnormal returns on climate policy announcement dates. This z_i will be my text-based exposure score for each firm. Table 3.4 shows the ten firms with the most negative exposure scores.

These firms discuss risks in their filings which the inverse regression of abnormal returns on term counts has discovered are predictive of negative responses to climate policy. For example, the most predictive paragraph from the filings of the most exposed firm, Peabody Energy Corp, discusses environmental regulation extensively:

TABLE 3.4. Most exposed firms

	name	industry
1	Peabody Energy Corp	Mining
2	Fieldpoint Petroleum Corp	Oil and Gas Extraction
3	Whiting Petroleum Corp	Oil and Gas Extraction
4	Continental Resources Inc	Oil and Gas Extraction
5	Epizyme Inc	Chemical Manufacturing
6	Ring Energy Inc	Mining
7	Chevron Corp	Petroleum and Coal Manufacturing
8	Jones Energy Inc	Oil and Gas Extraction
9	Consol Energy Inc	Oil and Gas Extraction
10	Antrero Resources Corp	Support Activities for Mining

Note: The table shows the 10 firms with the most negative values of z - the sufficient reduction projection from the MNIR model.

"Concerns about the environmental impacts of coal combustion, including perceived impacts on global climate issues, are resulting in increased regulation of coal combustion in many jurisdictions and unfavorable lending policies by government-backed lending institutions and development banks toward the financing of new overseas coal-fueled power plants, and interest in further such regulation and policies, which could significantly affect demand for our products. Global climate issues continue to attract public and scientific attention. Numerous reports, such as the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, have also engendered concern about the impacts of human activity, especially fossil fuel combustion, on global climate issues. In turn, increasing government attention is being paid to global climate issues and to emissions of what are commonly referred to as greenhouse gases, including emissions of carbon dioxide from coal combustion by power plants. Enactment of laws or passage of regulations regarding emissions from the combustion of coal by the U.S., some of its states or other countries, or other actions to limit such emissions, could result in electricity generators switching from coal to other fuel sources. Further, policies limiting available financing for the development of new coal-fueled power plants could adversely impact the global demand for coal in the future."

As well as producers of fossil fuels, the model also identifies firms that rely on fossil fuels, for example airlines, as exposed to climate policy risk. Similarly, the model identifies firms that rely on renewables as positively exposed to climate policy risk. Table 3.5 shows three such examples. Tesla, the electric vehicle company is shown as having one of the lowest exposure scores due to the inclusion of terms related to renewable energy in its filings. Delta airlines on the other hand is quite exposed to the climate policy risk.

TABLE 3.5. Three Example Firms

Firm	Terms	tf-idf x MNIR coeff.
S M ENERGY CO #11 ↗	crude oil gathering	475 · 2
	drill rig	297 · 5
	ngl	136 · 9
	greenhouse gas emissions	99 · 4
	hydraulic fracturing fluid	96 · 1
DELTA AIRLINES INC #76 ↗	airbus	943 · 2
	airline	445 · 6
	crude oil gathering	243 · 5
	passage of legislation	216 · 6
	refined	81 · 9
TESLA INC #30 ↘	electric utility	185 · 7
	alternative energy source	135 · 3
	solar	112 · 0
	batch	95 · 5
	modulator	86 · 8

Note: The table shows the 5 terms with the largest tf-idf weighted coefficients for three example firms.

3.4.3. Exposure Score Validation

The MNIR model is validated by its ability to select climate risk related terms. The subsequent exposure score is validated by its high ranking of firms with known intensity in 'brown' activities. I perform three additional checks on the validity of the exposure score. First, I show that the firm-level exposure score is correlated with emissions intensity.[7] The table in Appendix C.3 shows that a higher exposure score is strongly correlated with higher reported emissions, higher estimated emissions, and higher emissions intensities (emissions scaled by revenues). A one standard deviation increase in exposure score is associated with more than 1 million tonnes of additional CO2 emissions.

Secondly, I show that firms with higher exposure scores are more likely to lobby on environmental issues. Lobbying firms are required to provide a good-faith estimate rounded to the nearest $\$10,000$ of all lobbying-related income from their clients in each quarter. They are also required to report the purpose of the lobbying and the organization being targeted. I obtain data on this lobbying behaviour from OpenSecrets.[8] This dataset

[7] I obtain firm-level emissions data for 2022 from Refinitiv. Summary statistics are included in Appendix C.3.

[8] https://www.opensecrets.org/federal-lobbying/

includes a list of 80 possible topics that firms can lobby on. I designate five of these topics as climate related: "Clean Air and Water", "Environment and Superfund", "Fuel, Gas, and Oil", "Natural Resources", and "Hazardous and Solid Waste". Following Hassan et al. (2019), I generate a dummy variable that equals 1 if a firm lobbies on a climate topic between 2016 and 2019, and 0 otherwise. I run the following regression:

$$\mathbb{1}\left[\text{ Lobbying }_i > 0\right] = \delta_j + \theta z_i + \gamma X_i + \epsilon_i, \tag{3.16}$$

where δ_j is an industry fixed effect at the NAICS 3 digit level. X_i is a vector of controls, and θ measures the association of a firm's climate risk exposure score and its propensity to lobby on climate issues.

TABLE 3.6. Climate related Lobbying

	$1\left[\text{ Lobbying }_i > 0\right]$		
	(1)	(2)	(3)
z_i	0.052***	0.041***	0.039***
	(0.003)	(0.006)	(0.006)
Market Cap			0.000***
			(0.000)
Constant	0.022***	-0.010	-0.015
	(0.004)	(0.043)	(0.041)
Industry Fixed Effects		Yes	Yes
Observations	3,887	3,865	3,982
R^2	0.062	0.161	0.197
Adjusted R^2	0.062	0.142	0.178
F Statistic	256.856***	8.239***	10.711***

Note: This table shows the results from regressions of a dummy variable that equals one if firm i lobbies on climate issues on the firm's climate-risk exposure. z_i is standardized by its standard deviation. ***, **, and * denote statistical significance at the 1, 5, and 10 % level, respectively.

Table 3.6 indicates the results from this regression. The coefficient estimate (0.039, s.e.=0.006) implies that a one-standard-deviation increase exposure to climate policy related risk is associated with a 3.9-percentage-point increase in the probability that a

given firm lobbies on climate related issues. This exercise suggests that the climate policy risk exposure measure is meaningful economically: firms manage their exposure to this risk by lobbying on climate related issues. As discussed in Hassan et al. (2019), this is consistent with theoretical models that predict that exposure to political risks is associated with an increase in active management through lobbying as well as donations (Peltzman 1976).

Thirdly, I test the predictive power of my exposure measure and compare it to that of alternative measures. Figure C.1 shows that on the set of climate policy announcement dates, the R squared of the regression using my exposure score as a predictor is higher than that using the Sautner et al. (2023) exposure score. This is not surprising given that my exposure score is constructed using abnormal return responses on those dates. Therefore, I randomly select half of the climate policy announcement dates as a training set and leave the other half as a test set. I construct my exposure score using only the training set and compare the predictive performance of my exposure score and the Sautner et al. (2023) exposure score on the remaining dates. Again, as shown in figure C.2, the MNIR model provides an exposure score with better predictive performance.

3.4.4. Portfolio Sorts

Armed with this validated exposure score, I test whether higher exposure to climate policy risk is associated with higher returns - whether there exists a climate policy risk premium. Table 3.7 presents the results of the size weighted quintile portfolio sorts on exposure.

For the period 2012-2022, the high-minus-low portfolio generates a significant excess return of −0.39% per month. The pattern is similar for the period 2012-2019. Between 2020 and 2022, the high-minus-low portfolio earns insignificant positive excess returns. Therefore, there is no evidence of a climate policy risk premium. In fact, *less risky* firms have been paying higher returns over this period. Figure 3.1 presents the cumulative return of the return spread between the high and low exposure portfolios. The high-minus-low portfolio loses value between 2012 and 2020, regaining somewhat from 2020 to 2022.

3.4.5. Cross-sectional Regressions

As an additional check I run the following regression:

$$R_{i,t} = \alpha_0 + \beta z_i + \gamma \mathbf{x}_{i,t-1} + \mu_t + \mu_j + \epsilon_{i,t}, \tag{3.17}$$

where $R_{i,t}$ is the return on equity of firm i in month t, z_i is the exposure score and $\mathbf{x}$ is

TABLE 3.7. Portfolio Sorts

	L	2	3	4	H	H-L
2012-2022	1.33***	1.65***	1.29***	1.18***	0.94**	−0.39**
	(0.35)	(0.37)	(0.34)	(0.32)	(0.52)	(0.29)
2012-2019	1.56**	1.42***	1.38***	1.20**	1.00**	−0.564*
	(0.34)	(0.35)	(0.33)	(0.37)	(0.41)	(0.32)
2020-2022	0.37	1.78**	1.31	1.74*	1.1*	0.72
	(0.6)	(0.58)	(0.65)	(0.61)	(0.53)	(0.58)

Note: This table presents the monthly value-weighted returns of the exposure score sorted portfolios. The standard errors are reported in the parentheses below the coefficients. ***, **, and * denote significance at the 1%, 5%, and 10% level, respectively.

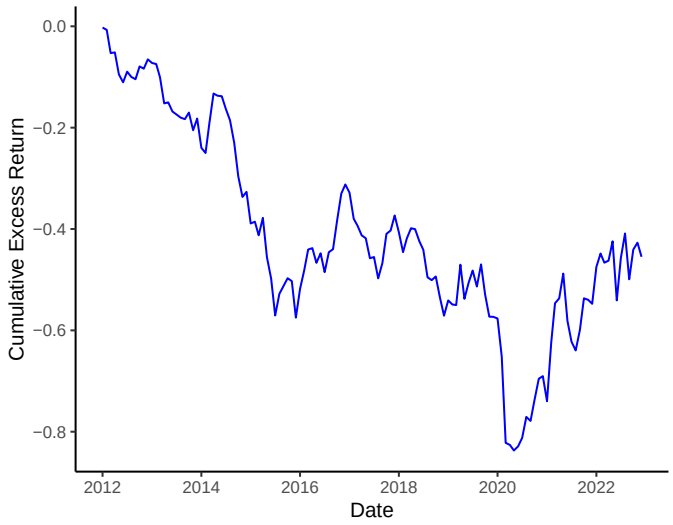


FIGURE 3.1

This figure plots the cumulative return of the return spread between the high and low climate policy risk exposure portfolio.

a vector of controls known to predict returns.[9] The coefficient of interest is β. Standard errors are clustered at the firm and year levels. This specification is identical to that in Bolton and Kacperczyk (2021) but for the use of exposure score rather than emissions as an explanatory variable. Contrary to Bolton and Kacperczyk (2021), however, I find no evidence for a carbon policy risk premium. Table 3.8 presents the results of this regression.

[9]The list of controls along with summary statistics are included in Appendix C.1.

TABLE 3.8. Cross-sectional Regression

Variable	Model 1	Model 2
z	-0.5818**	-0.5786**
	(0.1744)	(0.2259)
Market Cap	0.0000	0.0000
	(0.0000)	(0.0000)
Book to Market	1.5296***	1.7406***
	(0.4304)	(0.4914)
Leverage	0.4643	0.5703
	(0.4716)	(0.4914)
Investa/a	0.2991	0.9567
	(1.6082)	(1.7729)
HHI	-2.3468	-2.7809
	(2.3227)	(3.7085)
PPE	0.0834	-0.1145*
	(0.0599)	(0.0526)
SALESGR	-0.2819	-2.7809
	(0.4599)	(0.4356)
EPSGR	1.8133***	1.8177***
	(0.1296)	(0.1237)
beta	-0.1908*	-0.2712***
	(0.0939)	(0.0551)
ROE	0.3826*	0.3289
	(0.1776)	(0.2399)
MOM	11.3085*	11.1848*
	(5.8725)	(5.7765)
VOL	8.4160**	8.4967**
	(3.2632)	(3.182)
Observations:	177,625	177,625
Year-Month Fixed Effects:	YES	YES
Industry Fixed Effects:	NO	YES
RMSE:	17.5	17.5
Adj. R^2:	0.1388	0.1392

Note: This table presents the results of the cross sectional regression with the dependent variable being firms' monthly returns. The columns present coefficient estimates and standard errors.The sample period is 2012-2022. ***, **, and * denote significance at the 1%, 5%, and 10% level, respectively. Model 1 includes year-month fixed effects. Model 2 additionally includes industry (NAICS4) fixed effects.

A one standard deviation increase in exposure score is associated with a 58 bps decrease in returns. This result is robust to the inclusion of narrow industry fixed effects. The negative premium also remains if the sample is restricted to post 2015, or even post 2019. Therefore, in neither the cross-sectional regressions nor the portfolio sorts do we find evidence for a climate policy risk premium. Rather, it seems that less risky firms from a climate policy perspective are trading at a premium. In section 3.5 I attempt to explain this puzzle.

3.5. Preference Shocks: Rationalizing the Results

The organizing framework presented above predicts that firms with higher exposure to climate policy risk should earn higher returns on their equity. However, the empirical evidence indicates the opposite. I show that empirically identified preference shocks can rationalize this.

In the theory developed by Pástor, Stambaugh, and Taylor (2021), though there is a brown premium in equilibrium, there could be a negative gap between returns on brown and green assets if green preferences strengthen unexpectedly. In this case, a preference shock leads to higher realized returns for green than brown firms. Therefore, persistent strengthening of aggregate demand for green equities over the estimation period could explain the empirical results presented above. A similar mechanism is explored by van der Beck (2021) to explain the high realized returns from ESG investing. Given the rise of ESG investing and increasing salience of climate-related issues over the sample period considered, it is plausible that green aggregate demand could have increased in a persistent manner (Ardia et al. 2023).

The full treatment of consumer and investor preferences for green equity in general equilibrium is considered in Pástor, Stambaugh, and Taylor (2021). In my partial equilibrium framework, green consumer preference shocks can be modelled as entering the dividends process: consumer preferences becoming greener reduces the cashflow for browner firms. Therefore, equations 3.3 and 3.4 from above become:

$$\Delta d_{i,t+1} = \mu_d + y_t - \eta_i J_{t+1} - \upsilon_i V_{t+1}$$

$$y_{t+1} = \mu_y + \omega y_t + \psi J_{t+1} + \zeta V_{t+1}$$

where V is the consumer preference shock and υ_i is the exposure of firm i to the shock. Browner firms will therefore have larger υ_i. As above, the incidence of a preference shock will reduce one period returns of firms with positive υ_i, and those firms will earn higher expected returns in equilibrium. It is clear that such preference shocks could in theory explain the high realized returns of low policy risk equities in my sample as firms with higher υ_i are also likely to have higher η_i. Firms which are more exposed to preference

shocks are likely to also be exposed to policy shocks e.g. an oil company will suffer from an increase in climate policy stringency and from consumer/investor preferences becoming greener.

This similarity in how policy and preference shocks affect returns makes it difficult to separate them empirically to understand their relative effects. I identify preference shocks by considering the different responses of the climate policy risk exposure portfolios and the representative ESG portfolio identified by van der Beck (2021). The idea is that while in general a higher η_i implies a higher υ_i, the rankings of firms by these two parameters need not be the same - some firms which are highly exposed to policy shocks may not be so highly exposed to preference shocks and vice versa.

3.5.1. Data

van der Beck (2021) builds a representative ESG portfolio by identifying a set of 551 ESG mutual funds using a list of sustainability keywords. Using data on these funds' portfolio holdings, he then constructs a representative ESG portfolio that pools their holdings. The deviations of a stock's holdings in the ESG portfolio from the aggregate mutual fund portfolio is therefore a revealed preference measure of how sustainable investors perceive that stock to be. I will consider this as a measure of υ_i: how exposed a firm is to preference shocks.

These deviations are compared to the weightings in my climate policy risk exposure portfolio: the zs or η_i's. I designate a stock to be over-weight in the ESG portfolio if it has a positive deviation in van der Beck's data and has a positive exposure score (z). An overweight stock is one which the supervised machine learning algorithm has picked out as negatively exposed to climate policy risk and is also held in a higher proportion in the ESG portfolio than in the aggregate portfolio. Such a stock is risky from a climate policy perspective however is perceived to be green. Examples of such stocks are fossil fuel companies which are exposed to climate policy risk but are less polluting than their competitors and are therefore included in the ESG portfolio as the 'best in class'. I designate a stock to be under-weight in the ESG portfolio if it has a negative deviation in van der Beck's data and a negative exposure score (z). Such a stock is not risky from a climate policy risk perspective but is perceived not to be sustainable. This category leverages the fact that ESG is a broader category than climate performance. Some stocks which are not negatively exposed to climate policy risk are nonetheless perceived as anti-ESG, for example tobacco companies or firms with poor management practices.

I construct a portfolio that goes long in these overweight stocks and short in those that are underweight (over-under). The performance of this portfolio will be compared to the performance of the portfolio that goes long in the lowest quintile of exposure score stocks and short in the highest quintile. As outlined above, this second portfolio earns a

positive return over the sample. As a shorthand I will call this the green-brown portfolio, though it should be clear that I am discussing exposure to climate policy risk.

3.5.2. Sign-Restriction SVAR

These two portfolios are included in a sign-restriction SVAR in order to separate preference and policy shocks. The intuition is that the over-under portfolio should earn positive returns when there is a preference shock but not a policy shock. The green-brown portfolio should earn positive returns in both cases.

The VAR of the form:

$$Y_t = B(L)Y_{t-1} + U_t \tag{3.18}$$

where the vector Y_t includes monthly returns for the over-under portfolio, monthly returns for the green-brown portfolio, the oil price, and GDP is estimated following the standard sign-restriction methodology (Uhlig 2005; Fry and Pagan 2011), using the efficient algorithm from Arias, Rubio-Ramírez, and Waggoner (2018). The Bayesian estimation procedure uses a Normal-Wishart prior and a constant and 6 lags are included. In order to identify the structural preference and policy shocks I impose a sign restriction on the over-under and green-brown portfolios. The sign restrictions hold for the impact period only.

$$\begin{bmatrix} \\ \text{over-under} \\ \text{green-brown} \\ \text{GDP} \\ \text{Oil price} \end{bmatrix} = \begin{bmatrix} \epsilon_{pref} & \epsilon_{pol} & \epsilon_{y} & \epsilon_{o} \\ + & - & ? & ? \\ + & + & ? & ? \\ ? & ? & ? & ? \\ ? & ? & ? & ? \end{bmatrix}$$

3.5.3. Results

The structural VAR identifies the policy and preference shocks with the sign restrictions. This allows for a historical decomposition of the contribution of the shocks as well as a forecast error variance decomposition. Figure 3.2 shows that over the sample period, preference shocks have contributed to the returns process of the green-brown portfolio. The forecast error variance decomposition in Figure 3.3 shows that, in fact the contribution of preference shocks has been as important to explaining the dynamics of the green-brown portfolio returns as policy shocks.[10] This is indicative evidence that substantial policy

[10]The Structural shocks and IRFS are presented in Appendix C.3

shocks over the estimation period could explain the positive returns of the less risky portfolio in the data. In next steps I plan to calibrate my asset pricing model and input the empirically identified shocks to quantify the contribution of preference shocks to the surprising 'negative premium' result.

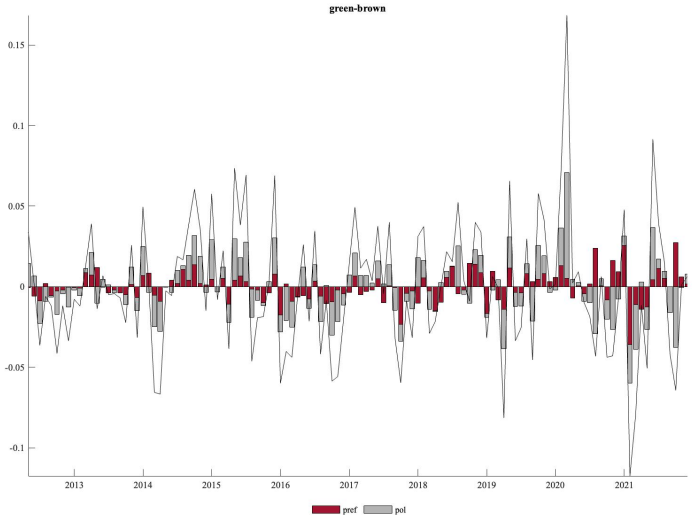


FIGURE 3.2. Historical decomposition of green-brown portfolio. Red bars show the preference shocks, grey bars the policy shocks.

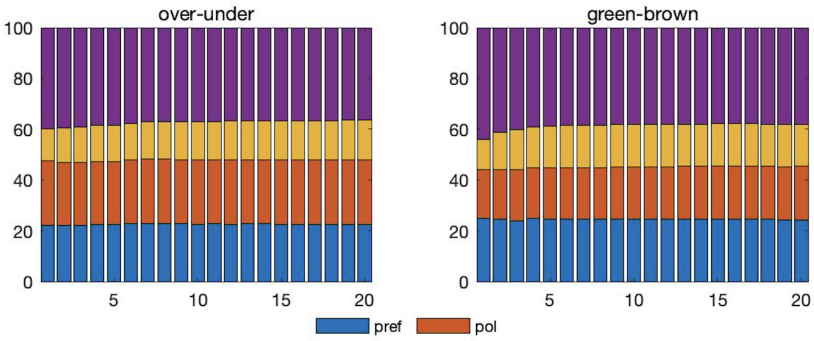


FIGURE 3.3. Forecast Error Variance Decomposition

3.6. Conclusion

This paper exploits text from firms' annual filings and return volatility on climate policy announcement dates to build a firm-level measure of exposure to climate policy risk. The supervised machine learning algorithm employed, MNIR, considers all terms in the text

and selects into the model those with predictive power for returns on the announcement dates. The subsequent exposure score is correlated with firm-level emissions, environmental lobbying behaviour, and is predictive out of sample. Exposure to climate policy risk is not associated with higher returns over the sample. In fact there is evidence for a negative premium on climate policy risk exposure. Preference shocks are considered as a candidate explanation for this discrepancy with theory. Empirically identified preference shocks are shown to have explanatory power for the spread between low and high risk exposure returns, explaining a similar amount of the variation as policy shocks. Further investigation of the consequences of changing aggregate demand for green products and assets is a promising avenue for future research.

APPENDIX A.

Appendices to Chapter 1

A.1. Data

A.1.1. Adaptation Measure: Initial Keywords

- adaptation
- climate_adaptation
- coastal_protection
- seawall
- shoreline_management
- coral_reef_restoration
- stormwater_management
- mangrove_plantation
- coastal_management
- urban_green_area
- air_conditioning_system
- shading
- drainage

- flood_insurance
- agricultural_insurance
- early_warning_system
- irrigation
- water_management
- natural_disaster_management
- national_disaster_management
- drought_management
- flood_management
- hazard_mapping
- cyclone_shelter
- storm_management
- wastewater_management
- managed_retreat
- ecosystem_restoration
- watershed_management
- wetlands_management

A.1.2. Adaptation Corpus

Adaptation discussions comprise of niche language. This generates problems for NLP models trained on general corpora of text. Therefore I train a model on a corpus of adaptation specific text. This enables me to generate more reliable word embeddings and discover adaptation specific keywords related to my initial set of keywords.

Adaptation specific text comes from a number of sources:

- Adaptation sections of Nationally Determined Contributions, as submitted to the UN
- National Adaptation Plans, as submitted to the UN
- UNEP Adaptation Gap Reports
- UNFCCC Adaptation related reports
- Adaptation Communications, as submitted to the UN
- Country Climate and Development Reports, from the World Bank

- Reports from the Global Commission on Climate Adaptation
- Adaptation specific reports from the World Bank and Asian Development Bank

Each of these sources comprise of discussion of adaptation to climate change using specific language.

A.1.3. Text Pre-Processing

I find and replace meaningful phrases in the corpus of adaptation related text with a single term. These phrases are constructed as follows:

1. Initial phrases from the initial set of keywords
2. Additional unigrams and multiword phrases. To identify these I tag all of the words in the corpus using a part-of-speech tagger from the Stanford NLP group. I then tabulate patterns that are likely to correspond to meaningful sequences. The final set of phrases is the resulting unigrams, bigrams and trigrams that appear more than 20 times in the corpus.

I then follow the standard steps to complete the pre-processing:

1. Lowercase all text
2. Tokenize text by breaking it into individual terms
3. Drop common words from a standard stopword list

A.1.4. Final Set of Keywords

coastal_adaptation	waterfront_protection	water_conservation
coastal_protection	gullies	water_storage
coastal_retreat	shore_nourishment	water_saving
coastal_management	shoreline_management	rainwater_harvesting
coastal_infrastructure	integrated_shoreline	water_supply
coastal_zone	coral_reef_restoration	water_quality_management
coastal_restoration	reef_restoration	groundwater
coastal_resilience	coral_reef	aquifers
coastal_degradation	reef_protection	renewable_water
coastal_risk	reef_system	water_levels
coastal_zone_protection	vegetation_restoration	water_efficiency
terrain_raise	sedimentation	water_tank
sea_level	soil_management	water_investment
sea_surge	soil_erosion	water_harvesting
sea_grass	salinization	water_resource_management
salt_marsh	erosion_control	surface_water
sea_defense	sludge_management	watershed_area_management
groyne	storm_surge_protection	adaptation
sea_wall	stormwater_management	climate_adaptation
wetlands_restore	risk_mapping	disaster_risk
wetlands	hazard_risk	disaster_preparedness
wetlands_management	environmental_hazards	post_disaster
wetland_protection	hazard_information	disaster_recovery
mangroves	hazard_data	disaster_prevention
mangrove_conservation	bush_fire	disaster_relief
mangrove_protection	fire_management	disaster_resilience
mangrove_reefs	forest_fire	emergency_management
mangrove_restoration	wildfire	emergency_preparedness
mangrove_planting	shading	national_emergency
mangrove_forests	shade	emergency_shelter

TABLE A.1. List of Final Keywords (Part 1)

river_restoration	agroecology	drought
river_defense	agroecological	drought_management
river_basin_management	agroforestry	drought_preparedness
river_training	retreat	drought_index
basin_management	evacuation	flood
green_space	soil_conservation	flood_management
green_areas	forest_management	flood_mitigation
green_infrastructure	vulnerability_assessment	flood_defense
green_building	remote_sensing	flood_prevention
green_resilience	climate_services	flood_control
air_conditioning	forecasting	flood_infrastructure
cooling	weather_data	weather_observation
cooling_system	weather_forecast	hydrometeorological
evaporative_cooling	meteorological	climate_information
thermal_system	climate_vulnerability	emergency_communication
drainage	climate_assessment	climatological
drainage_infrastructure	disaster_management	green_climate_fund
flood_drainage	hydrological	gcf
urban_drainage	gef	unfccc
storm	flood_forecast	climate_resilience
hurricane	flood_model	resilient_infrastructure
cyclone	flood_risk	climate_response
breakwater	flood_resilience	mitigation_infrastructure
revetment	flood_preparedness	natural_disaster
levee	flood_protection	climate_disaster
culvert	fluvial_flood	disaster_response
beach_nourishment	hazard_mapping	disaster_management
seawall	storm_management	disaster_adaptation
tidal_barrier	stormwater	adaptation_plan
dune_restoration	tropical_storm	climate_resilience

TABLE A.2. List of Final Keywords (Part 2)

A.1.5. Keyword discovery example

	Initial Term: sea wall
Output Term	**Cosine Similarity**
sea defense	0.89
groyne	0.86
tidal barrier	0.81
dune restor	0.79
waterfront protec	0.78
gullies	0.72
breakwater	0.71

A.1.6. Sample Construction

I include country-year observations that have the following characteristics

- In Latin America or the Caribbean
- Budgets in English or Spanish
- Budget is machine readable
- Sovereign is rated in that year

Latin America contains 18 sovereigns, the Caribbean contains 13 sovereigns. I restrict attention to the time frame 2014-2025. I lose observations for the following reasons

1. Due to language I lose two countries: Haiti and Brazil
2. Due to lack of ratings I lose three countries: Saint Lucia, Angtigua and Barbuda, Dominica
3. Due to lack of availability of machine readable budgets I lose seven countries: Trinidad and Tobago, Cuba, Bolivia, El Salvador, Nicaragua, Paraguay, Venezuela
4. I lose a further 65 country-year observations due to lack of budget availability

This leaves a final sample which is an unbalanced panel of 19 economies from 2014-2025. I have 163 country-year observations.

A.1.7. Adaptation Entries: The Bahamas 2023-2024

This section shows screenshots of pages of the budget of the Bahamas 2023-2024. Line items highlighted in yellow are those picked up by the algorithm and included in the final adaptation measure.

SUMMARY OF AGENCIES
RECURRENT EXPENDITURE 2023/2024

HEAD NO.	MINISTRY/DEPARTMENT	PROVISIONAL ACTUAL EXPENDITURE 2021/2022 $	EXPENDITURE (PROVISIONAL) JUL - MAR 2022/2023 $	REVISED APPROVED ESTIMATES 2022/2023 $	ESTIMATES 2023/2024 $	PRELIMINARY FORECAST ESTIMATES 2024/2025 $	PRELIMINARY FORECAST ESTIMATES 2025/2026 $
043	MINISTRY OF SOCIAL SERVICES AND URBAN DEVELOPMENT	11,853,711	9,527,813	13,544,180	15,336,260	14,382,191	14,468,047
044	DEPARTMENT OF SOCIAL SERVICES	53,808,368	35,997,500	52,103,091	46,189,742	46,755,469	47,399,544
045	DEPARTMENT OF HOUSING	1,840,204	2,290,549	2,972,529	3,216,484	3,331,594	3,769,002
047	MINISTRY OF YOUTH, SPORTS AND CULTURE	14,500,725	21,389,325	26,535,786	26,706,494	23,049,794	22,953,164
048	DEPARTMENT OF LABOUR	1,864,454	2,591,935	3,752,923	3,999,277	4,075,117	4,160,387
049	MINISTRY OF ECONOMIC AFFAIRS	5,866,773	8,699,175	12,871,952	11,614,394	11,644,197	11,663,979
051	POST OFFICE DEPARTMENT	6,809,901	6,510,482	9,201,089	9,340,930	9,490,104	9,971,084
053	PORT DEPARTMENT	8,239,794	6,567,442	9,014,970	9,145,089	9,153,700	9,501,326
054	DEPARTMENT OF ROAD TRAFFIC	5,288,088	5,239,486	6,944,828	6,976,416	6,976,416	7,276,416
055	DEPARTMENT OF METEOROLOGY	2,087,999	1,508,292	2,792,064	2,437,303	2,557,564	2,714,632
056	MINISTRY OF AGRICULTURE, MARINE RESOURCES AND FAMILY ISLAND AFFAIRS	21,237,508	20,012,587	28,763,889	28,221,348	28,276,298	29,477,488
057	DEPARTMENT OF AGRICULTURE	4,996,466	3,747,395	5,543,196	5,566,525	5,609,321	6,268,220
058	DEPARTMENT OF MARINE RESOURCES	2,330,771	1,598,106	2,823,060	2,449,563	2,620,779	2,923,668
060	MINISTRY OF HEALTH AND WELLNESS	373,846,036	242,928,786	315,021,918	299,367,187	300,208,287	300,558,537
065	DEPARTMENT OF ENVIRONMENTAL HEALTH SERVICES	50,293,460	48,021,999	61,702,188	59,505,886	60,245,925	60,869,912
066	DEPARTMENT OF PUBLIC HEALTH	45,337,948	38,234,895	56,146,001	48,682,297	48,987,997	48,997,559
067	MINISTRY OF TOURISM, INVESTMENTS AND AVIATION	148,111,959	90,353,548	132,562,117	135,034,206	140,814,071	141,249,711
070	MINISTRY OF LABOUR AND IMMIGRATION	5,002,443	3,049,217	4,244,490	4,974,482	5,273,809	5,301,377
072	MINISTRY OF THE ENVIRONMENT AND NATURAL RESOURCES	17,859,554	10,207,436	16,026,382	13,878,562	13,657,942	13,764,213
073	DEPARTMENT OF INFORMATION AND COMMUNICATIONS TECHNOLOGY	53,251,306	21,783,239	34,143,676	29,230,202	31,485,777	30,349,947
074	MINISTRY FOR GRAND BAHAMA	10,018,186	14,767,945	19,188,189	17,983,328	18,108,654	18,538,774
075	MINISTRY OF DISASTER RISK MANAGEMENT	1,504,339	9,761,377	15,975,932	9,943,301	13,317,965	13,404,278
076	OFFICE OF THE DIRECTOR OF PUBLIC PROSECUTIONS	2,355,847	1,230,775	2,759,729	2,931,230	3,018,761	3,361,449
	GRAND TOTAL	**3,044,069,825**	**2,134,807,682**	**3,073,728,214**	**3,085,536,785**	**3,131,500,001**	**3,154,399,500**

MEMORANDUM
Consistent with Government Finance Statistics (GFS) methodology, Public Debt Redemption is treated as a financing transaction and, therefore, has no impact on the deficit. Public Debt Servicing-Interest & Other Charges is now being shown separately as Head 26.

[Head 013] MINISTRY OF FOREIGN AFFAIRS AND THE PUBLIC SERVICE

ITEM NO.	TITLE OF ITEM	PROVISIONAL ACTUAL EXPENDITURE 2021/2022 $	EXPENDITURE (PROVISIONAL) JUL - MAR 2022/2023 $	REVISED APPROVED ESTIMATES 2022/2023 $	ESTIMATES 2023/2024 $	PRELIMINARY FORECAST ESTIMATES 2024/2025 $	PRELIMINARY FORECAST ESTIMATES 2025/2026 $
22810EE	**Special Financial Transactions**						
2281105	VAT Expenses	157	0	0	0	0	0
	Special Financial Transactions	**157**	**0**	**0**	**0**	**0**	**0**
	Use of Goods & Services	**9,410,520**	**10,860,749**	**16,658,898**	**16,813,202**	**19,264,761**	**19,807,593**
26000EE	**Grants**						
26200EE	**Grants to International Organizations**						
2621101	Operations for IMO (International Maritime Organization)	0	0	0	260,000	260,000	260,000
2621105	Caribbean Regional Drug Testing Lab	0	0	15,360	15,360	15,360	15,360
2621106	Caribbean Regional Secretariat (CARICOM)	2,248,399	2,248,399	2,248,399	2,544,834	2,748,426	2,748,426
2621107	Caribbean Agriculture Research and Development	0	0	150,400	150,400	150,400	150,400
2621108	Caribbean Centre For Development Administration	9,600	9,600	9,600	9,600	9,600	9,600
2621110	Caribbean Environment Health Institute	33,760	0	33,760	33,760	33,760	33,760
2621111	Caribbean Emergency Disaster Preparedness	85,586	85,586	85,586	226,295	226,295	226,295

[Head 072] MINISTRY OF THE ENVIRONMENT AND NATURAL RESOURCES

ITEM NO.	TITLE OF ITEM	PROVISIONAL ACTUAL EXPENDITURE 2021/2022 $	EXPENDITURE (PROVISIONAL) JUL - MAR 2022/2023 $	REVISED APPROVED ESTIMATES 2022/2023 $	ESTIMATES 2023/2024 $	PRELIMINARY FORECAST ESTIMATES 2024/2025 $	PRELIMINARY FORECAST ESTIMATES 2025/2026 $
2241206	Publications	0	1,434	2,450	2,563	2,738	2,738
2241211	Cleaning & Toilet Supplies	4,657	241	1,000	1,000	1,000	1,000
2241212	Computer Software Supplies & Materials	1,655	997	6,156	5,000	5,500	6,000
2241213	Clothing & Clothing Supplies	663	3,034	8,000	8,000	8,250	8,500
2241237	Operation Exp. Botanical Gar.	0	38,764	80,000	60,000	60,000	60,000
2241299	Other Supplies & Materials	3,032	1,808	4,074	4,500	5,120	5,220
	Supplies & Materials	**20,564**	**48,173**	**108,100**	**87,483**	**89,057**	**89,907**
22510EE	**Services**						
2251101	Printing & Duplication Service	7,333	0	0	0	0	0
2251102	Advertising & Public Notices	2,350	15,189	45,000	20,252	20,720	20,820
2251107	Workshops, Conferences, Seminars, Meetings & Exhibits	7,945	1,548	7,380	418,000	7,000	8,000
2251108	Tuition, Training, In-service Awards, Subsistence	5,131	0	14,738	7,000	7,100	7,300
2251109	Licencing & Inspection of Vehicles	1,950	0	0	0	0	0
2251115	Consultancy Services	80,431	101,522	290,000	125,000	135,000	150,000
2251128	Fees & Other Charges	22,829	19,187	29,470	18,280	19,127	19,377
2251129	Staff Engagement	11,384	4,040	12,000	5,387	5,500	5,600
2251201	Local Transportation of Goods	1,196	283	1,520	2,000	2,143	2,143
2251203	Freight & Express	2,159	1,349	4,000	4,300	4,557	4,757
2251306	Computers, Business Machines & Related Equipment	761	2,061	4,500	4,500	5,000	5,000
2251310	Grounds Maintenance	936	0	5,000	0	0	0
2251330	Upkeep & Maintenance of Instruments & Apparatus	270	153	1,107	500	500	500
2251336	Sanitact Maintenance Contract	1,836	0	3,360	3,360	3,360	3,360
2251337	Operation of Facilities or Other Services	36,190	18,499	38,775	29,700	29,700	29,700
	Services	**182,701**	**163,831**	**456,850**	**638,279**	**239,707**	**256,557**
22610EE	**Minor Capital Repairs**						
2261201	Transportation Equipment Upkeep	3,157	887	10,000	10,000	10,000	10,000
	Minor Capital Repairs	**3,157**	**887**	**10,000**	**10,000**	**10,000**	**10,000**
22710EE	**Operational Expenses**						
2271001	Operational Expenses	40,466	25,095	55,000	40,000	40,000	40,000
2271037	Grand Bahama Climate Resilience Master Planning Exercise	0	18,122	80,000	80,000	80,000	80,000
2271038	Development of Marine Protected Area	0	47,221	100,000	50,000	60,000	70,000
	Operational Expenses	**40,466**	**90,438**	**235,000**	**170,000**	**180,000**	**190,000**
22810EE	**Special Financial Transactions**						
2281001	Special Financial Transactions	13,976	10,301	10,500	10,500	10,500	10,500
2281105	VAT Expenses	122	0	0	0	0	0
2281162	International Conferences	9,781	35,506	100,000	50,000	50,000	60,000
	Special Financial Transactions	**23,879**	**45,807**	**110,500**	**60,500**	**60,500**	**70,500**
	Use of Goods & Services	**422,863**	**458,411**	**1,145,441**	**1,192,543**	**808,388**	**848,828**

[Head 021] MINISTRY OF FINANCE

ITEM NO.	TITLE OF ITEM	PROVISIONAL ACTUAL EXPENDITURE 2021/2022 $	EXPENDITURE (PROVISIONAL) JUL - MAR 2022/2023 $	REVISED APPROVED ESTIMATES 2022/2023 $	ESTIMATES 2023/2024 $	PRELIMINARY FORECAST ESTIMATES 2024/2025 $	PRELIMINARY FORECAST ESTIMATES 2025/2026 $
28000EE	**Other Payments**						
28200EE	**Transfers N.E.C.**						
2822007	Energy Restoration & Renewable Energy	15,039,734	9,132,927	23,000,000	23,000,000	23,000,000	0
2822010	Public Private Partnership	3,000,000	2,812,066	9,000,000	27,800,000	26,000,000	25,000,000
2822011	Capital Subscriptions to International Agencies	959,500	4,306,826	2,000,000	2,000,000	2,000,000	2,000,000
2822025	PFR/PFM	4,224,806	1,137,863	3,400,000	3,000,000	3,000,000	2,000,000
2822031	Small and Medium Size Business Support	8,204,923	1,000,000	4,000,000	5,500,000	5,500,000	6,500,000
2822056	National Sports Authority	750,766	0	0	0	0	0
2822063	Capitalization - Bahamas Development Bank	0	500,000	2,000,000	3,000,000	3,000,000	4,000,000
2822065	Capital Budget Reserve Appropriation	5,721,392	31,800	23,444,153	19,256,700	20,106,729	22,424,000
	Transfers N.E.C.	**37,901,121**	**18,921,482**	**66,844,153**	**83,556,700**	**82,606,729**	**61,924,000**
	OTHER CHARGES	**37,901,121**	**18,921,482**	**66,844,153**	**83,556,700**	**82,606,729**	**61,924,000**
31000EE	**Acquisition of Non-Financial Assets**						
31100EE	**Acquisition of Fixed Assets**						
3111116	Rent to Own Housing Programme	0	0	0	3,500,000	3,500,000	3,500,000
3111211	Performing Arts School	0	0	0	1,000,000	1,000,000	1,000,000
3111309	Hurricane Precautions	0	250,000	1,000,000	1,000,000	1,000,000	1,000,000
3111318	Construction of Women Shelter & Support Centre	0	0	0	500,000	500,000	500,000
3111326	National Museum Project	0	0	0	1,000,000	1,000,000	800,000
3111331	Swimming Pool	0	0	0	700,000	1,000,000	2,000,000
3111388	Family Island Capital Development	0	0	2,000,000	13,000,000	13,200,000	16,000,000
3112101	Acquisition of Transportation Equipment (Land)	400,000	1,578,696	2,000,000	2,800,000	2,500,000	2,500,000
3112202	Equipment Maintenance	0	980,000	1,000,000	1,000,000	1,000,000	1,000,000
3112299	Other Machinery & Equipment	278,312	0	0	0	0	0
3113002	Minor Capital Projects	7,600,235	5,429,164	3,500,000	3,000,000	3,000,000	3,700,000
3113003	Acquisition of Assets - Government Ministries and Departments	1,989,985	2,759,250	2,500,000	4,000,000	4,000,000	4,000,000
3113010	Subdivision Infrastructure	70,880	0	0	0	0	0
3113011	Electronic Hansard	1,527,663	367,256	667,256	300,000	0	0
	Acquisition of Fixed Assets	**11,867,075**	**11,364,366**	**12,667,256**	**31,800,000**	**31,700,000**	**36,000,000**
31400EE	**Nonproduced Assets**						
3141101	Purchase of Properties	1,400,000	0	2,000,000	2,000,000	2,000,000	2,000,000
	Nonproduced Assets	**1,400,000**	**0**	**2,000,000**	**2,000,000**	**2,000,000**	**2,000,000**
	Acquisition of Non-Financial Assets	**13,267,075**	**11,364,366**	**14,667,256**	**33,800,000**	**33,700,000**	**38,000,000**
	MINISTRY OF FINANCE TOTAL EXPENSES	**51,168,196**	**30,285,848**	**81,511,409**	**117,356,700**	**116,306,729**	**99,924,000**

The Accounting Officer for this Head is the FINANCIAL SECRETARY

[Head 033] MINISTRY OF WORKS AND UTILITIES

ITEM NO.	TITLE OF ITEM	PROVISIONAL ACTUAL EXPENDITURE 2021/2022 $	EXPENDITURE (PROVISIONAL) JUL - MAR 2022/2023 $	REVISED APPROVED ESTIMATES 2022/2023 $	ESTIMATES 2023/2024 $	PRELIMINARY FORECAST ESTIMATES 2024/2025 $	PRELIMINARY FORECAST ESTIMATES 2025/2026 $
28000EE	**Other Payments**						
28200EE	**Transfers N.E.C.**						
2822007	Energy Restoration & Renewable Energy	0	0	250,000	0	0	0
2822013	National Disaster Recovery Project	11,457,258	2,950,711	6,500,000	4,630,000	5,000,000	5,762,600
2822014	Post National Disaster Recovery Project	392,774	0	0	0	0	0
2822022	Research, Surveys, Studies, Evaluations	1,865,930	561,618	553,831	564,907	576,205	587,729
2822025	PFR/PFM	806,637	2,276,332	5,950,021	5,552,759	5,615,460	5,973,646
	Transfers N.E.C.	**14,522,599**	**5,788,661**	**13,253,852**	**10,747,666**	**11,191,665**	**12,323,975**
	OTHER CHARGES	**14,522,599**	**5,788,661**	**13,253,852**	**10,747,666**	**11,191,665**	**12,323,975**
31000EE	**Acquisition of Non-Financial Assets**						
31100EE	**Acquisition of Fixed Assets**						
3111207	Building Maintenance	10,495,671	12,237,287	12,937,159	12,846,390	17,562,384	16,816,315
3111216	Planning for New Parliament Building (New Providence)	0	0	0	2,000,000	3,000,000	2,000,000
3111268	Construction of Gymnasiums	3,635,025	1,195,394	2,620,159	2,500,000	3,000,000	5,947,862
3111301	Bridge Repair & Maintenance	1,542,647	1,261,248	2,771,402	3,000,000	3,114,026	4,127,889
3111302	Ports & Docks	3,624,863	2,986,593	6,546,512	6,500,000	10,258,863	10,434,047
3111303	Sidewalks	589,156	172,533	1,100,000	700,000	1,144,440	1,167,329
3111307	Road Repairs & Maintenance	19,108,876	12,115,068	22,942,206	20,000,000	27,957,773	28,516,931
3111309	Hurricane Precautions	208,388	198,070	1,500,000	1,500,000	1,589,481	1,607,270
3111310	Water Infrastructure	0	0	1,500,000	0	0	0
3111311	Cemeteries Improvements & Upkeep	377,737	2,036,709	1,201,764	2,000,000	1,250,315	1,275,322
3111313	Maintenance - Standposts/Faucets/Wells/Drains	945,790	1,039,305	1,200,000	1,200,000	1,248,480	1,273,450
3111320	Traffic Study & Systems	3,340,638	800,000	1,346,764	1,373,699	1,401,173	1,429,197
3111321	New Providence Roadworks	9,815,798	12,689,218	11,150,000	11,730,000	11,964,600	12,203,892
3111324	New Bight Airport Redevelopment	0	0	0	6,000,000	6,000,000	2,000,000
3111330	Q.E. Sports Centre Redevelopme	0	0	0	10,000,000	8,000,000	12,000,000
3111338	Construction & Expansion - Buildings & Structures	40,127,114	3,026,239	3,000,000	2,952,000	4,000,000	4,000,000
3111377	Airport Infrastructure Programme	13,341,456	5,747,246	9,154,951	13,141,050	14,660,114	14,953,318
3111389	Road Remediation - Drainage Infrastructure	0	1,367,137	2,290,000	1,500,000	1,500,000	1,500,000
3111399	Other Structures	687,196	0	0	0	0	0
3111403	Improvement of Parks & Grounds	2,017,932	3,848,121	4,000,000	4,000,000	4,369,680	4,457,074
3112101	Acquisition of Transportation Equipment (Land)	0	974,879	1,000,000	0	0	0
3112202	Equipment Maintenance	64,998	313,215	401,353	401,360	417,568	425,919
3112203	Other Office Equip & Furniture	0	18,067	50,000	50,000	50,000	50,000
3112210	Landscape Equipment	0	36,786	150,000	100,000	200,000	200,000
3112211	Machinery & Generators Mainten	355,484	232,958	773,726	500,000	1,196,460	1,220,389
3113005	Software	946,138	357,372	391,933	400,000	0	0
3113006	Hardware	5,799	116,893	117,500	100,000	0	0
	Acquisition of Fixed Assets	**111,230,706**	**62,770,338**	**88,145,429**	**104,494,499**	**123,885,357**	**127,606,204**
	Acquisition of Non-Financial Assets	**111,230,706**	**62,770,338**	**88,145,429**	**104,494,499**	**123,885,357**	**127,606,204**
	MINISTRY OF WORKS AND UTILITIES TOTAL EXPENSES	**125,753,305**	**68,558,999**	**101,399,281**	**115,242,165**	**135,077,022**	**139,930,179**

ANNEX 16 - PUBLIC INVESTMENT PROJECTS (ONGOING)

Code	Project Description	Project Start Date	Total Project Cost	Cumulative Expenditure	Projections 2023/2024	Preliminary 2024/2025	Preliminary 2025/2026
MINISTRY OF WORKS & UTILITIES							
033-0136-0441-011-2822025-15	BNT Consultancy - Climate Resilient Coastal Management And Infrastructure Program	01/31/2021	1,785,714	1,246,429	539,286	0	0
033-0136-0441-220-2822025-15	Baseline Coastal Studies And Engineering Design - Junkanoo Beach-Long Wharf, New Providence	03/31/2022	1,406,209	200,000	1,206,209	0	0
033-0138-0467-011-3111207-15	Repair And Renovations Of Government House, New Providence	10/31/2020	19,982,803	19,671,422	311,381	0	0
033-0138-0467-011-3111207-15	Jack Hayward Senior High School Gymnasium Repairs & Renovations Project	08/31/2022	1,484,807	1,373,568	111,239	0	0
033-0138-0467-011-3111207-15	Renovation And Repair To Eight Mile Rock High School Gymnasium	03/31/2023	2,113,666	1,181,258	932,408	0	0
033-0138-0467-011-3111207-15	Repairs And Renovations Of The Thomas A Robinson Stadium Phase 1	01/31/2023	2,310,000	1,738,501	571,499	0	0
033-0138-0467-011-3111207-15	Fort Fincastle Tower Repairs	06/30/2023	3,000,000	1,500,000	1,500,000	0	0
033-0138-0467-011-3111207-15	Bolam House Completion	06/30/2023	2,000,000	1,500,000	500,000	0	0
033-0138-0467-011-3111207-15	Clifford Park Redevelopment For 50th Independence Celebrations	06/30/2024	3,000,000	2,700,000	300,000	0	0
033-0138-0467-011-3111338-15	Construction Of South Andros All Purpose Gymnasium - Phase 2	12/31/2020	9,930,829	9,423,108	507,721	0	0
033-0137-0465-273-3111301-15	Replacement Of Staniard Creek Bridge	43799	9,604,205	9,393,390	210,815	0	0
033-0137-0465-235-3111302-15	Shoreline Stabilization And Roadworks, Hope Town, Elbow Cay, Abaco	06/30/2019	3,449,701	3,193,524	256,177	0	0
033-0137-0465-372-3111302-15	Replacement Of Main Government Dock And Fisherman's Dock, Rock Sound, Eleuthera	06/30/2020	2,959,367	2,804,401	154,966	0	0
033-0137-0465-295-3111302-15	Refurbishment Of Lisbon Creek Dock And Ramp, Mangrove Cay, Andros	08/31/2022	2,631,314	2,530,788	100,526	0	0
033-0137-0466-387-3111307-15	Exuma Road Repairs And Carriageway Rehabilitation	04/30/2020	7,316,105	6,998,717	317,388	0	0
033-0137-0466-386-3111307-15	Black Point Exuma Road Repairs And Carriageway Rehabilitation	04/30/2020	1,316,910	1,246,710	70,200	0	0
033-0137-0466-413-3111307-15	Long Island Road Repairs & Carriageway Rehabilitation	05/31/2020	3,809,060	3,413,133	395,926	0	0
033-0137-0466-201-3111307-15	Grand Bahama Road Repairs And Carriageway Rehabilitation	09/30/2020	5,534,144	4,500,144	1,034,000	0	0
033-0137-0466-234-3111307-15	Abaco Seawalls & Carriageway Rehabilitation Project	10/31/2020	1,335,993	1,204,023	131,971	0	0
033-0137-0466-362-3111307-15	Harbour Island Road Repairs And Carriageway Rehabilitation	02/28/2021	2,658,667	2,658,667	0	0	0

ANNEX 17 - PUBLIC INVESTMENT PROJECTS (NEW)

Code	Name of Project	Project Description	Total Project Cost	Budget Projections 2023/2024	Preliminary Forecast 2024/2025	Preliminary Forecast 2025/2026
MINISTRY OF WORKS & UTILITIES						
033-0138-0467-011-3111207-15	Thomas A Robinson Stadium Renovations Phase 2 to 5	Building Maintenance	12,000,000	10,000,000	2,000,000	0
033-0138-0467-011-3111207-15	Fort Fincastle Straw Market and Environs	Building Maintenance	10,000,000	2,000,000	4,000,000	4,000,000
033-0137-0465-387-3111301-15	Barratarre Bridge I - Exuma	Bridges	15,000,000	2,000,000	5,000,000	8,000,000
033-0137-0465-387-3111301-15	Ferry Bridge - Exuma	Bridges	15,000,000	2,000,000	5,000,000	8,000,000
033-0137-0465-272-3111301-15	Fresh Creek Bridge - Andros	Bridges	35,000,000	2,000,000	13,000,000	20,000,000
033-0137-0465-355-3111301-15	Glass Window Bridge (Eleuthera)	Bridges	40,000,000	3,000,000	17,000,000	20,000,000
033-0137-0465-280-3111301-15	Stafford Creek Bridge - Andros	Bridges	15,000,000	2,000,000	7,000,000	6,000,000
033-0137-0465-386-3111302-15	Blackpoint Dock	Ports & Docks	6,000,000	2,000,000	2,000,000	2,000,000
033-0137-0465-231-3111302-15	Abaco Docks	Ports & Docks	4,500,000	2,000,000	2,500,000	0
033-0137-0465-280-3111302-15	North Andros Docks	Ports & Docks	2,500,000	1,000,000	1,500,000	0
033-0137-0465-311-3111302-15	Bullock Harbour Dock, Berry Islands	Ports & Docks	2,500,000	1,000,000	1,500,000	0
033-0137-0465-011-3111302-15	Yamacraw Seawall and Road Renovations, NP	Ports & Docks	2,000,000	1,000,000	1,000,000	0
033-0137-0465-355-3111302-15	Gregory Town Seawall in Eleuthera	Ports & Docks	2,500,000	1,000,000	1,500,000	0
033-0137-0465-221-3111302-15	High Rock Construction of Seawall (Grand Bahama)	Ports & Docks	8,000,000	2,000,000	4,000,000	2,000,000
033-0137-0465-212-3111302-15	West End Ramp, Construction of Seawall, Restroom and Fish Fry Amenities (Grand Bahama)	Ports & Docks	2,000,000	1,000,000	1,000,000	0
033-0137-0466-011-3111321-15	Carmichael Road Development (New Providence)	New Providence Road Works	1,400,000	1,400,000	0	0
033-0137-0466-011-3111321-15	Gladsone Road Improvement Project - Construction Phase	New Providence Road Works	20,000,000	5,000,000	8,000,000	7,000,000
033-0137-0466-011-3111321-15	Corridor 41 - Milo Butler Extension from Carmichael to Cowpen	New Providence Road Works	20,000,000	5,000,000	5,000,000	10,000,000
033-0137-0466-011-3111321-15	Development of Killarney Lake Parkway	New Providence Road Works	2,000,000	2,000,000	0	0
033-0138-0467-011-3111338-15	The refurbishment of the former BTC Building on JFK Drive	Construction and Expansion of Buildings and Structures	8,000,000	4,000,000	4,000,000	0

ANNEX 17 - PUBLIC INVESTMENT PROJECTS (NEW)

Code	Name of Project	Project Description	Total Project Cost	Budget Projections 2023/2024	Preliminary Forecast 2024/2025	Preliminary Forecast 2025/2026
033-0137-0466-011-3111389-15	Bay Street Drainage Rehabilitation Project	Drainage	12,000,000	3,000,000	6,000,000	3,000,000
033-0137-0466-011-3111389-15	Coral Harbour Drainage and Road Project	Drainage	3,500,000	1,500,000	2,000,000	0
033-0137-0466-011-3111389-15	Pine Wood Garden Flooding Remediation (New Providence)	Drainage	12,000,000	3,000,000	6,000,000	3,000,000
033-0134-0467-011-3111403-15	Clifford Park Redevelopment	Parks	15,000,000	3,000,000	5,000,000	7,000,000
033-0210-0466-246-3111377-15	North Eleuthera - Landside Construction	Airport Infrastructure Program	25,000,000	5,000,000	6,000,000	14,000,000
033-0210-0466-246-3111377-15	North Eleuthera-Airside Construction	Airport Infrastructure Program	25,000,000	8,000,000	7,000,000	10,000,000
033-0210-0466-387-3111377-15	Exuma-Airside Construction	Airport Infrastructure Program	25,000,000	7,000,000	5,000,000	13,000,000
033-0210-0466-243-3111377-15	Treasure Cay	Airport Infrastructure Program	1,661,000	1,661,000	0	0
033-0136-0441-011-2822025-15	Construction works - JBLW	Beach and dune stabilization in Junkanoo Beach - New Providence	16,490,000	1,649,000	10,000,000	4,841,000
033-0136-0441-220-2822025-15	Construction works - EGB	Sustainable coastal protection infrastructure - East Grand Bahama (EGB)	2,000,000	421,500	1,578,500	0
033-0136-0441-413-2822025-15	Construction works - CLI	Costal flood reduction infrastructure - Central Long Island	2,250,000	450,000	1,800,000	0
		Total	**363,301,000**	**86,081,500**	**135,378,500**	**141,841,000**

A.1.8. Summary Statistics

Country	Observations	Mean T/GDP	Mean M/GDP	Mean D/GDP	SD T/GDP
Argentina	2	0.031	0.002	0.003	
Bahamas	12	0.195	0.021	0.066	0.049
Barbados	12	0.294	0.055	0.020	0.083
Belize	11	0.160	0.029	0.052	0.067
Chile	12	0.260	0.102	0.000	0.059
Colombia	4	0.084	0.007	0.037	0.052
Costa Rica	8	0.060	0.008	0.048	0.057
Dominican Republic	12	0.112	0.005	0.007	0.032
Ecuador	3	0.083	0.003	0.010	0.004
Grenada	11	0.786	0.017	0.078	0.449
Guatemala	10	0.123	0.010	0.070	0.057
Honduras	9	0.492	0.021	0.117	0.147
Jamaica	12	0.253	0.014	0.069	0.301
Mexico	10	0.162	0.002	0.035	0.065
Panama	2	0.138	0.023	0.037	
Peru	6	0.589	0.004	0.431	0.279
SVG	5	0.746	0.043	0.106	0.219
Turks and Caicos	12	0.858	0.099	0.214	0.194
Uruguay	10	0.035	0.027	0.003	0.013

TABLE A.3. Adaptation Expenditure Summary Statistics by Country. Expenditure is given as a percentage of GDP and shown as a percentage.

I also provide descriptive statistics on the number of line items identified by the transfer learning procedure in government budgets.

	N	Mean	St. Dev.	Min	Max
No. Line Items (country x year)	163	17.7	23.3	3	126
No. Line Items (country average)	19	20.33	23.4	4.9	75.4

	N	Corr	p-value
(Line Items, T/GDP)	163	-0.0967	0.2489
(avg Line Items, avg T/GDP)	19	-0.131	0.589

There is no statistically significant correlation between the number of line items identified in a budget and the dollar amount of adaptation expenditure listed.

Regression Controls: Summary Statistics

	Wind Speed	Regulatory Quality (Mean)	Regulatory Quality (SD)	Govt-effect (Mean)	Govt-effect (SD)
Cross-Country Average	0.24	0.148		0.065	
Cross-Country SD	0.45	0.479		0.547	
Argentina	0.0003	-0.483		-0.378	
Bahamas	0.0640	0.070	0.120	0.509	0.147
Barbados	1.1100	0.463	0.077	0.724	0.331
Belize	0.0212	-0.502	0.079	-0.562	0.112
Chile	0.0011	1.174	0.211	0.793	0.153
Colombia	0.0005	0.121	0.028	-0.031	0.063
Costa Rica	0.0098	0.508	0.051	0.239	0.111
Dominican Republic	0.0121	0.029	0.063	-0.249	0.197
Ecuador	0.0018	-0.633	0.150	-0.348	0.131
Grenada	1.1462	0.060	0.244	-0.072	0.083
Guatemala	0.0044	-0.310	0.032	-0.762	0.094
Honduras	0.0052	-0.495	0.038	-0.699	0.126
Jamaica	1.1104	0.100	0.059	0.491	0.110
Mexico	0.0059	-0.013	0.166	-0.216	0.131
Panama	0.0061	0.119		-0.210	
Peru	0.0004	0.333	0.176	-0.322	0.122
SVG	1.2009	0.337	0.017	0.233	0.138
Turks and Caicos	0.9225	0.412	0.082	0.324	0.142
Uruguay	0.0030	0.661	0.046	0.638	0.176

TABLE A.4. Control Variable Summary Statistics by Country. Wind Speed is historical maximum average windspeed scaled by land area from the GeoMet database. Regulatory Quality and Government Effectiveness are indices from the World Bank.

Government Effectiveness and Regulatory Quality are indices from the Worldwide Governance Indicators compiled by the World Bank.[1]

Government Effectiveness captures “perceptions of the quality of public services, the quality of the civil service and the degree of its independence from political pressures, the quality of policy formulation and implementation, and the credibility of the government’s commitment to such policies." Sources used to construct the index include a measure of institutional effectiveness from the Economist Intelligence Unit, the likelihood of infrastructure disruption, state failure or political instability from S&P Global, and quality of financial and revenue management.

Regulatory Quality captures: “perceptions of the ability of the government to formulate

[1] `www.govindicators.org` Kaufmann, Kraay, and Mastruzzi (2010)

and implement sound policies and regulations that permit and promote private sector development." This includes the risk that business operations become more costly due to the regulatory environment, and the risk that fines and penalties will be levied for non-compliance with a tax code that appears disproportionate or manipulated for political ends.

Table A.5 shows results using regulatory quality rather than government effectiveness:

	adapt	
sovrate	198,917,071***	30,901,342***
	(76,413,625)	(8,924,107)
gdp	0.001***	0.0071***
	(0.0001)	(0.0017)
exposure	164,980,764**	
	(82,519,154)	
regulatory quality	19,071,555	
	(54,779,990)	
Country Fixed Effects	No	Yes
Year Fixed Effects	Yes	Yes
Observations	98	151
R-squared	0.95	0.97
Note:	*p<0.1; **p<0.05; ***p<0.01	

TABLE A.5. Regression Results. adapt and gdp are in millions of 2017 US dollars. sovrate is an index from 0-21. Exposure is historical average maximum windspeed scaled by land area, and standardized to have mean 0 and standard deviation 1. Regulatory quality is an index from the World Bank standardized to have mean 0 and standard deviation 1. Standard errors are clustered by country and year.

A.1.9. Adaptation and Exposure

Wind Speed

Hurricanes are responsible for the largest share of damages from natural disasters. Therefore as a proxy for exposure to natural disasters I take a measure of historical average wind speeds scaled by land area. This measure comes from the GeoMet database (Felbermayr and Gröschl 2014). Figure A.1 shows that there is a statistically significant, positive correlation between historical exposure to storms and adaptation expenditures.

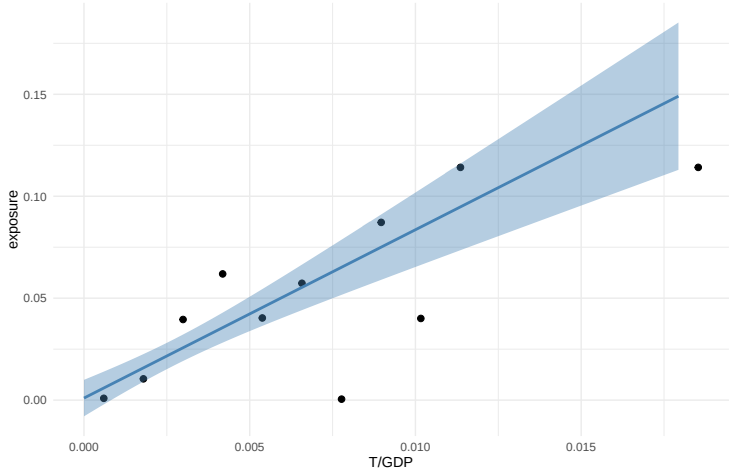


FIGURE A.1. Relationship between adaptation expenditure and natural disaster exposure. The exposure measure is historical average maximum wind speeds scaled by land area. Windspeed data comes from the GeoMet database (Felbermayr and Gröschl 2014)

INFORM Risk

The INFORM Risk index is an open-source risk assessment for different varieties of crises and disasters. The European Commission Joint Research Centre is the scientific lead.[2] In the hazard and exposure dimension the database includes an index of exposure to natural hazards which can be sub-divided by variety. As countries in my sample are most exposed to Tropical storms and droughts I take the aggregate index of exposure to natural hazards as well as the specific tropical cyclone and drought indicators. Table A.6 documents summary statistics.

Table A.16 presents regression results linking adaptation expenditures and natural hazard exposure. From the table we can see that the measure of historical average windspeeds has the greatest explanatory power for the variation in adaptation expenditures.

[2] `https://drmkc.jrc.ec.europa.eu/inform-index`

Statistic	N	Mean	St. Dev.	Min	Max
Natural Disasters	19	4.77	1.49	2.30	6.60
Tropical Cyclone	19	4.58	3.33	0.00	10.00
Drought	19	2.03	1.56	0.30	5.50

TABLE A.6. INFORM Risk: Summary Statistics

	Dependent variable:			
	T/GDP			
Windspeed	0.033***			
	(0.005)			
Natural		0.0002**		
		(0.0001)		
Tropical Cyclone			0.0001	
			(0.0001)	
Drought				0.0002**
				(0.0001)
Constant	0.002***	0.001**	0.002***	0.002***
	(0.0002)	(0.0005)	(0.0004)	(0.0003)
Observations	163	163	163	163
R^2	0.270	0.040	0.006	0.041
Adjusted R^2	0.265	0.031	0.003	0.032

Note: *p<0.1; **p<0.05; ***p<0.01

TABLE A.7. Regression Results: Adaptation and Climate Hazards

Exposure and Spending Disaggregated

Countries spend more to tackle the hazards that they are most exposed to. Figure A.2 shows this. Countries that are more exposed to floods or storms spend a larger share of their adaptation budget on storm/flood protection. Countries more exposed to droughts spend more on drought protections.

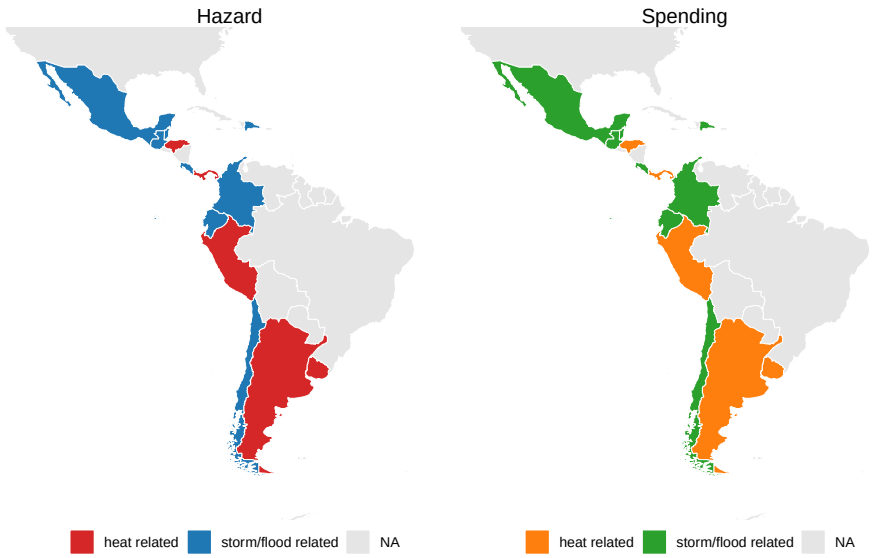


FIGURE A.2. The left map colour codes countries by the type of hazard they are most exposed to. If the country is more exposed to floods or storms they are shown in blue. If they are more exposed to droughts they are shown in red. On the right I categorize countries by the share of adaptation expenditure on heat related hazards or water related hazards.

A.1.10. Adaptation: Cross Sectional Results

This section considers the analysis of the adaptation measure in terms of cross-country differences. In particular I present results for adaptation expenditure across the 19 countries in my sample for the year 2023. I show that similar patterns to those presented in the main text obtain for cross-country comparisons. I find that adaptation expenditure is 0.43% of GDP on average in this year. Disaster preparedness expenditure is 0.11% of GDP on average. Summary statistics are reported in Table A.8.

TABLE A.8. Summary Statistics

Statistic	N	Mean	St. Dev.	Min	Max
Adaptation Total / GDP	19	0.43%	0.0032	0.001	0.0187
Disaster Preparedness / GDP	19	0.11%	0.0022	0.0001	0.0098
Meteorological Services / GDP	19	0.03%	0.0005	0.0000	0.0009

	Adaptation Measure:			
	Total Adaptation	Disaster Preparedness	Meteorological Services	Total Adaptation
sovrate	3,900,370*	1,500,120	477,907	2,601,720*
	(2,081,275)	(1,832,566)	(512,430)	(1,498,012)
GDP	0.003***	0.003***	0.0009	0.003***
	(0.001)	(0.0007)	(0.002)	(0.001)
exposure	11,156,417*	79,546,311**	10,276,532	9,786,053*
	(6,046,099)	(38,546,311)	(22,646,099)	(5,835,924)
Government effectiveness				573,012
				(394,192)
Observations	19	19	19	19
R^2	0.909	0.939	0.382	0.951
Adjusted R^2	0.774	0.848	0.103	0.894
Note:				*p<0.1; **p<0.05; ***p<0.01

TABLE A.9. The first column uses the text based measure of adaptation as the dependent variable. The second column uses disaster preparedness expenditure, and the third uses meteorological expenditure. All values are reported in 2017 US $.

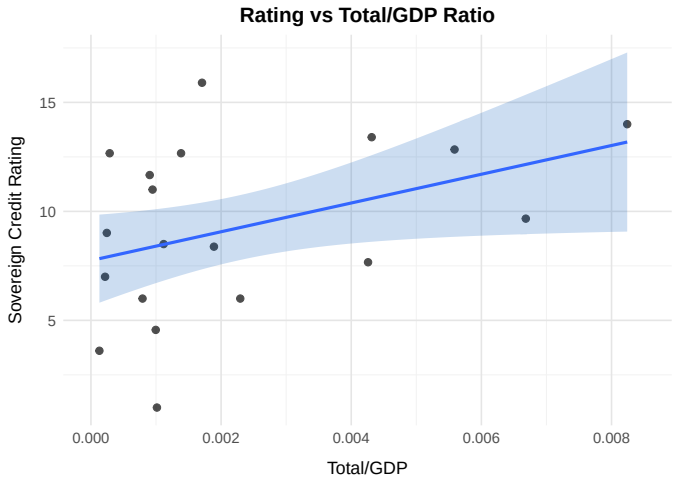


FIGURE A.3. Adaptation Investment and Sovereign Ratings. Sovereign ratings are an average of the previous three years, on a scale from 0-21 from the World Bank fiscal space database (Kose et al. 2022). The adaptation measure is total adaptation spending, shown as a proportion of GDP. The shaded region shows standard errors at the 90% level. The plot includes one observation for each country in the year 2023.

Caribbean Subsample

Figure A.4 shows the wordcloud for commonly used terms from the construction of the adaptation measure restricted to the Caribbean subsample.

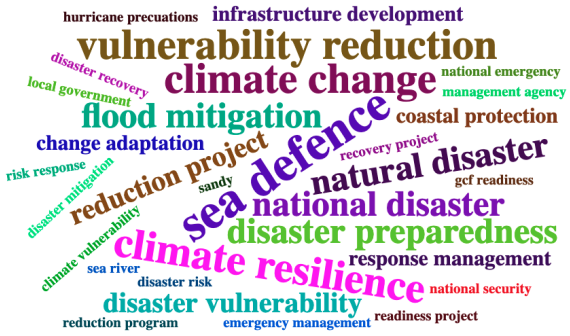


FIGURE A.4. Word Cloud Representing the most frequently used terms in budget entries picked up when building the total adaptation measure: Caribbean subsample.

A.1.11. Disaster Preparedness and Meteorological Expenditure

	Disaster Preparedness	
sovrate	304,152,674	148,507,202
	(254,948,612)	(240,101,032)
gdp	0.0011***	0.0061***
	(0.0004)	(0.0005)
exposure	124,464,182***	
	(12,284,012)	
government effectiveness	140,177,373**	
	(65,775,964)	
Country Fixed Effects	No	Yes
Year Fixed Effects	Yes	Yes
Observations	98	151
R-squared	0.95	0.96

Notes: * p < 0.10, ** p < 0.05, *** p < 0.01

TABLE A.10. Regression Results: Disaster Preparedness and Sovereign Rating

	Meteorological Services	
sovrate	268,014,394***	826,041,817***
	(103,115,274)	(91,630,371)
gdp	0.0061	0.0010**
	(0.0040)	(0.00046)
exposure	129,812,401**	
	(64,190,146)	
government effectiveness	715,689,368***	
	(18,416,559)	
Country Fixed Effects	No	Yes
Year Fixed Effects	Yes	Yes
Observations	98	151
R-squared	0.95	0.96

Notes: * p < 0.10, ** p < 0.05, *** p < 0.01

TABLE A.11. Regression Results: Meteorological Services Expenditure and Sovereign Rating

A.1.12. Exposure Controls

Baseline results with different proxies for exposure to natural disasters.

	adapt			
sovrate	67,554,921***	41,286,883***	38,411,248***	44,220,882***
	(16,647,312)	(9,241,031)	(14,524,916)	(11,551,834)
gdp	0.0022***	0.001***	0.001***	0.001***
	(0.0002)	(0.0001)	(0.0001)	(0.0001)
windspeed	143,757,032**			
	(62,519,154)			
natural		81,436,087*		
		(44,013,869)		
cyclone			37,428,812	
			(45,306,999)	
drought				27,727,914
				(43,063,322)
government effectiveness	121,350,937**	21,131,829	50,668,145	42,115,495
	(48,299,257)	(105,309,509)	(40,124,011)	(39,406,025)
Year Fixed Effects	Yes	Yes	Yes	Yes
Observations	98	98	98	98
R-squared	0.95	0.93	0.92	0.92

Note: *p<0.1; **p<0.05; ***p<0.01

TABLE A.12. Regression Results. adapt and gdp are in millions of 2017 US dollars. sovrate is an index from 0-21. Other exposure measures come from INFORM and are standardized to have mean 0 and standard deviation 1. Government effectiveness is an index from the World Bank standardized to have mean 0 and standard deviation 1. Standard errors are clustered by country and year.

A.1.13. Sovereign Risk Measures

Here I present the baseline results with different measures for capturing sovereign risk.

EMBI

From Global Financial Data, I collect data on emerging market economy's JP Morgan Emerging Market Bond Index (EMBI) spreads. EMBI combines different maturity dollar denominated bonds from a given country into one spread. The composite maturity is typically 2-5 years. I do not use this data for my baseline analysis as it is only available for 38 emerging market economies, 10 of which are in my adaptation dataset. However I show here that the same relationship between sovereign risk and adaptation expenditures is visible using this data. A higher spread is indicative of higher default risk and tighter borrowing constraints, therefore the expected sign of the coefficient flips to negative. The coefficient in the second specification is not statistically significant, potentially due to the lower sample size.

	Adaptation Expenditure	
EMBI	−16,641,818*	−1,725,994
	(1,773,254)	(1,510,511)
gdp	0.001***	0.001***
	(0.0003)	(0.0003)
exposure	109,104,732*	
	(40,190,146)	
government effectiveness	89,042,884	
	(80,729,185)	
Country Fixed Effects	No	Yes
Year Fixed Effects	Yes	Yes
Observations	76	76
R-squared	0.761	0.778

Notes: * p < 0.10, ** p < 0.05, *** p < 0.01

TABLE A.13. Regression Results. EMBI spreads and adaptation services expenditure.

CDS

Here I present the results of the same specification now using CDS spreads from Bloomberg as the measure of sovereign risk as used in section 1.3.2. Again, we find the expected negative coefficient indicating that adaptation is declining with sovereign risk. The CDS also has less coverage than the sovereign rating data used in the baseline analysis. These results cover 8 countries: Argentina, Chile, Colombia, Costa Rica, Ecuador, Mexico, Panama and Peru. With a lower number of observations the coefficient on sovereign risk is no longer significant, but it is of the expected sign.

	Adaptation Expenditure	
CDS Spread	−21,355,235*	−21,412,531*
	(11,963,353)	(11,920,214)
gdp	0.001***	0.001***
	(0.0002)	(0.0002)
exposure	97,521,463***	
	(14,003,729)	
government effectiveness	104,240,907	
	(96,738,648)	
Country Fixed Effects	No	Yes
Year Fixed Effects	Yes	Yes
Observations	71	71
R-squared	0.612	0.646

Notes: * p < 0.10, ** p < 0.05, *** p < 0.01

TABLE A.14. Regression Results. CDS spreads and adaptation services expenditure.

A.1.14. Narrative Evidence

Section 1.3 presents evidence that adaptation is declining in sovereign risk. This is consistent with the model and additional narrative evidence. Rating agency methodologies do not explicitly use adaptation as an input (potentially due to a lack of adaptation related data). Therefore the positive relationship is likely driven in the opposite direction: high borrowing costs restrict adaptation expenditures.

Rating Agency Methodologies

Moody's sovereign rating methodology does not include the term 'adaptation'. The term 'climate' occurs only in conjunction with discussions of vulnerability to climate shocks, and does not discuss resilience or adaptation.[3]

S&P also do not use the term 'adaptation' in their rating methodology. They do note that they consider 'reforms in support of sustainable public-sector finances' which may include 'policies to mitigate the adverse physical effects of climate change'. However this approach is not systematized.[4]

Fitch outline a relatively sophisticated climate modeling component for their rating methodology. Their climate model uses physical inputs only, for example data from EMDAT and INFORM risk, to back out exposure to climate risk. They note that their exposure measures are 'unmitigated' exposures in that they do not incorporate potential mitigation or adaptation capacity. They note that such capacity or policy may be considered instead on an ad hoc basis by screening committees.[5]

Rating Releases

Adaptation is not systematically included in rating agency methodologies. It is also difficult to find instances of rating releases where adaptation was explicitly considered, indicating that the option to include adaptation in an ad hoc way is rarely used. This could be due to i) lack of adaptation data, or ii) lack of sufficient investment in adaptation to warrant material effects on ratings.

For example, Fitch has noted that while a large natural disaster shock could lead to a downgrade for Jamaica, evidence of enhanced resilience to such shocks could lead to an upgrade. At the same time, investment in resilience building is constrained by a 'lack of meaningful fiscal space'.[6]

[3] https://ratings.moodys.com/api/rmc-documents/395819

[4] https://www.spglobal.com/ratings/en/regulatory/article/-/view/sourceId/10221157

[5] https://www.fitchratings.com/research/sovereigns/sovereign-rating-criteria-15-09-2025

[6] https://www.fitchratings.com/research/sovereigns/fitch-upgrades-jamaica-to-bb-outlook-positive-05-03-2024.

In the note released upon Fitch's upgrade of Barbados to B+, the agency notes: "As a small, open tourist economy, Barbados is highly exposed to external shocks, including, economic and natural disaster-related events. The government is working to build resilience to shocks by strengthening its fiscal resources, including reserve funds and insurance policies, and by aiming to improve infrastructure and facilitate greater self-reliance in the private sector. However, given the lack of meaningful fiscal space and limited resources currently available, a severe shock would be difficult to manage. Permanent institutionalization of these reforms is still in progress."[7]

Therefore the narrative evidence on the rating agency side suggests that i) adaptation is not systematically included in methodologies, ii) there is scope to include adaptation in individual rating decisions, but iii) adaptation has not been a driver of rating movements thus far.

Government Statements

Due to this limited narrative support for adaptation affecting sovereign ratings, it is likely that the empirical result may result from constrained sovereigns spending less on adaptation. This is consistent with statements by numerous government officials in climate-exposed economies. Mia Mottley, the Prime Minister of Barbados, has been among the most vocal. In her speech to COP27 she noted:

"Addressing climate impacts is critical for my country and region as frontline states in the climate crisis, which are simultaneously in the world's most disaster-prone, climate vulnerable, debt ridden, and tourism dependent regions."

"As a middle-income country, Barbados' most critical need is capital to address, adapt to, or mitigate climate crisis impacts. Consequently, at the international level, we are seeking new means of financing loss and damage, promoting the five-pronged Bridgetown Initiative". [8]

The Bridgetown Initiative makes this point:

"the level of financing which is made available, to which countries will have access and on what terms, are issues of survival for millions of people and for the well-being of our planet". [9]

[7] https://www.fitchratings.com/research/sovereigns/fitch-upgrades-barbados-to-b-outlook-stable-15-10-2024

[8] https://unfccc.int/sites/default/files/resource/BARBADOS_cop27cmp17cma4_HLS_ENG.pdf

[9] https://www.bridgetown-initiative.org/bridgetown-initiative-3-0/

A.1.15. Composition of Debt

Table A.15 shows that climate vulnerable countries in Latin America and the Caribbean tend to have relatively low shares of official debt out of total. The data comes from Fang, Hardy, and Lewis (2025). This underlies the relevance of sovereign ratings for borrowing costs and investment decisions.

Country	Share of Official Debt (%)
Argentina	7
The Bahamas	3
Barbados	20
Chile	3
Colombia	14
Costa Rica	7
Dominican Republic	16
Ecuador	29
Guatemala	26
Jamaica	22
Mexico	4
Panama	25
Peru	8
Uruguay	7
Average	14

TABLE A.15. Share of Official Debt in Total Public Debt (2018)

Additionally relevant is the point often made by politicians in these countries, that due to their relatively strong fundamentals they are not eligible for concessional finance from organisations such as the IMF. This further restricts their ability to borrow in order to adapt.

A.1.16. Total Government Expenditure and Sovereign Risk

The positive relationship between adaptation expenditure as a proportion of GDP and sovereign ratings can also be found in the more general case of total government expenditure as a proportion of GDP. Using data from the Global Macro Database (Müller et al. 2025) linked with the sovereign rating data from Kose et al. (2022), I document this relationship.

Figure A.5 shows that in 2022 countries with higher sovereign ratings tended to have higher government expenditures as a proportion of GDP. Table A.16 shows regression results to that effect.



FIGURE A.5. Bin scatter plot of government expenditure as a proportion of GDP, against sovereign rating average from the previous three years. The plot uses data on expenditure from the Global Macro Database for the year 2022.

When I restrict attention to the countries in my sample from Section 1.2.2, however, this positive effect is no longer visible. In the matching of the datasets I lose the observation of Turks and Caicos. Figure A.6 shows a scatterplot of government expenditure as a proportion of GDP against sovereign ratings. Here the relationship between the variables is flat.

This could be taken to indicate that the relationship between adaptation investment and sovereign risk is stronger than that between total expenditure and sovereign risk. In both cases it could be argued that higher ratings allow governments to borrow and spend more. However, in the total expenditure case this higher spending may cause markets to lose confidence in the fiscal prudence of the sovereign. In the adaptation case, however, as

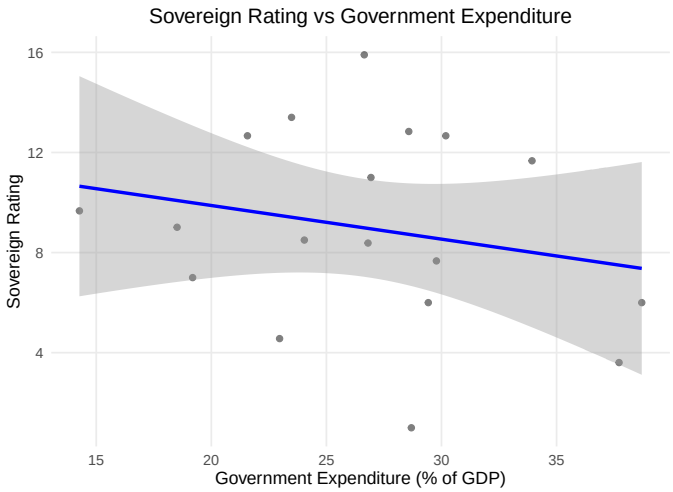


FIGURE A.6. Bin scatter plot of government expenditure as a proportion of GDP, against sovereign rating average from the previous three years. The plot uses data on expenditure from the Global Macro Database for the year 2022. The sample is restricted to the 19 countries included in the main analysis.

the model indicates higher adaptation spending causes spreads to reduce as such spending reduces exposure to future bad shocks, lowering the probability of default.

	Dependent variable:			
	gov expenditure			
sovrate	117,691*	169,315**	486,422***	527,693***
	(67,352)	(69,411)	(91,372)	(102,301)
GDP	0.001***	0.001***	0.001**	0.001**
	(0.00004)	(0.00004)	(0.0004)	(0.0004)
Government Effectiveness			192,201	195,416
			(129,254)	(129,387)
Year Fixed Effect	No	Yes	No	Yes
Observations	3,515	3,515	2,964	2,964
R^2	0.985	0.985	0.986	0.986
Adjusted R^2	0.985	0.985	0.985	0.985
Note:				*p<0.1; **p<0.05; ***p<0.01

TABLE A.16. Regression Results: Total government expenditure and sovereign rating. Global sample.

A.1.17. Summary Statistics

TABLE A.17. CDS spreads by Country

Country	Mean	SD	Country	Mean	SD
Algeria	48.75	15.58	Ireland	129.44	198.08
Australia	36.82	24.50	Japan	36.72	29.23
Belgium	42.54	62.33	Malaysia	88.41	51.11
Brazil	334.14	493.40	Mexico	134.83	66.47
Canada	48.94	9.43	Mongolia	297.15	148.72
China	68.90	37.82	Morocco	158.02	21.00
Colombia	200.23	123.91	Namibia	297.15	148.72
Costa Rica	287.88	145.90	Netherlands	29.50	29.19
El Salvador	307.31	145.84	New Zealand	47.81	11.58
Ethiopia	297.15	148.72	Norway	15.05	10.83
France	39.21	41.10	Oman	131.80	33.81
Germany	21.68	20.71	Pakistan	295.63	147.21
Guatemala	176.31	63.07	Philippines	175.71	142.69
Hong Kong	45.58	12.11	Portugal	163.06	259.91
Iceland	111.97	44.65	South Africa	188.14	78.49
India	48.75	15.58	Spain	101.72	113.58
Indonesia	170.32	106.49	Thailand	82.95	51.33
			Vietnam	129.19	77.54

TABLE A.18. Cyclone Frequency by Country: 1980-2025

Country	Mean	Country	Mean
Algeria	0.02	Mauritius	0.04
Antigua and Barb.	0.15	Mexico	0.96
Australia	0.98	Mongolia	0.02
Bahamas	0.50	Morocco	0.02
Bangladesh	0.72	Mozambique	0.54
Barbados	0.11	Namibia	0.04
Belize	0.37	Nepal	0.02
Bermuda	0.07	Netherlands	0.04
Botswana	0.09	New Zealand	0.33
Brazil	0.04	Nicaragua	0.48
Cabo Verde	0.09	Norway	0.04
Cambodia	0.43	Oman	0.24
Canada	0.70	Pakistan	0.17
China	0.96	Papua New Guinea	0.33
Colombia	0.09	Philippines	0.96
Costa Rica	0.02	Portugal	0.02
Cuba	0.61	Puerto Rico	0.22
Dominica	0.07	Russia	0.74
Dominican Rep.	0.39	Saint Lucia	0.09
El Salvador	0.09	Saudi Arabia	0.04
Ethiopia	0.04	Somalia	0.17
Fiji	0.41	Somaliland	0.09
France	0.41	South Africa	0.09
Greenland	0.04	South Korea	0.78
Grenada	0.09	Sri Lanka	0.26
Guatemala	0.35	St. Vin. and Gren.	0.09
Haiti	0.26	Taiwan	0.85
Honduras	0.37	Tanzania	0.02
Hong Kong	0.11	Thailand	0.80
Iceland	0.04	Timor-Leste	0.07
India	0.89	Tonga	0.04
Indonesia	0.39	Trinidad and Tobago	0.15
Iran	0.02	Turks and Caicos Is.	0.09
Ireland	0.15	United Kingdom	0.20
Jamaica	0.15	United States of America	0.96
Japan	0.96	Vanuatu	0.59
Laos	0.83	Venezuela	0.13
Madagascar	0.85	Vietnam	0.94
Malawi	0.09	Yemen	0.15
Malaysia	0.04	Zimbabwe	0.20

A.1.18. Local Projection Results

Responses	h=0	Year h=1	Year h=2	Year h=3	Year h=4	Year h=5
B_h	0.36	0.86	0.19	0.70	1.14	1.34
	(0.69)	(0.86)	(0.93)	(0.89)	(1.01)	(0.95)

TABLE A.19. Local Projection Results. Dependent variable: log CDS spreads.

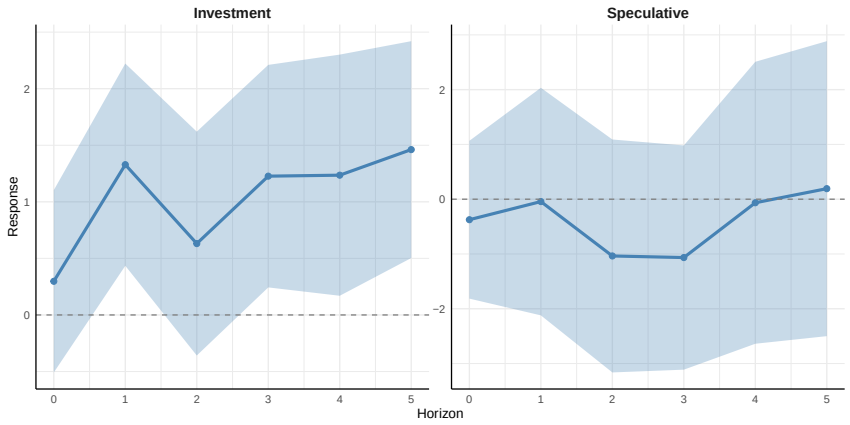


FIGURE A.7. Cyclone shock on CDS spreads. Left panel restricted to only investment grade bonds. Right panel only speculative grade bonds.

A.1.19. Alternative Default Data

In this section I present the results of estimating the local projection presented in Figure 1.7 using alternative measures of default.

Kuvshinov and Zimmermann (2019) database

Kuvshinov and Zimmermann (2019) consolidate a set of different data on default. Two of the most commonly used measures included in the database are that constructed by Reinhart and Rogoff as in Reinhart and Rogoff (2011) and Reinhart and Trebesch (2011), and that constructed from Standard Poors reports as in Beers and Chambers (2006). The data runs from 1980-2010. I show that for this more limited timeframe, and for these alternative measures of default, the results as presented in section 1.3 continue to hold. Due to the more limited coverage, however, I cannot test the adaptation subsamples.

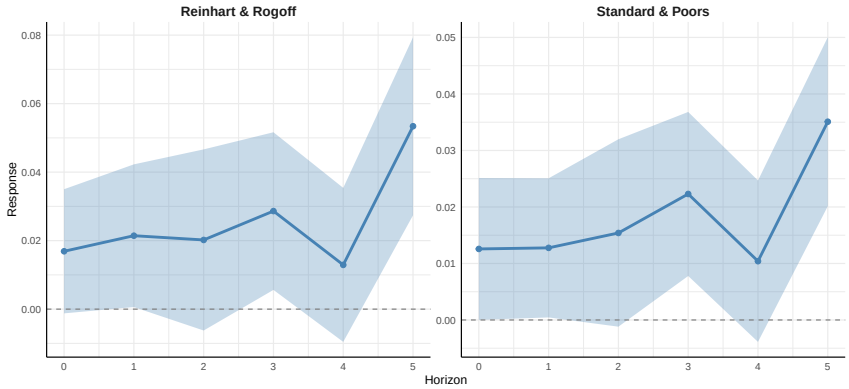


FIGURE A.8. Local Projection of cyclone strike of at least category one speed on default indicators.

In both cases, the cyclone strike causes the probability of default to increase on impact. The magnitude of the increase in default probabilities is comparable in magnitude to that of the baseline results. Both IRFs also show an uptick in default probabilities three years after the cyclone, consistent with the baseline results.

Asonuma and Trebesch database

Asonuma and Trebesch (2016) construct a dataset of defaults and restructurings which is available up until mid 2020. I show that using this dataset, the aggregate pattern of the response of default probabilities is in line with the baseline results and those from the Kuvshinov and Zimmermann (2019) database. When restricted to the countries in my adaptation data sample, the effect on default probabilities is more immediate and more pronounced.

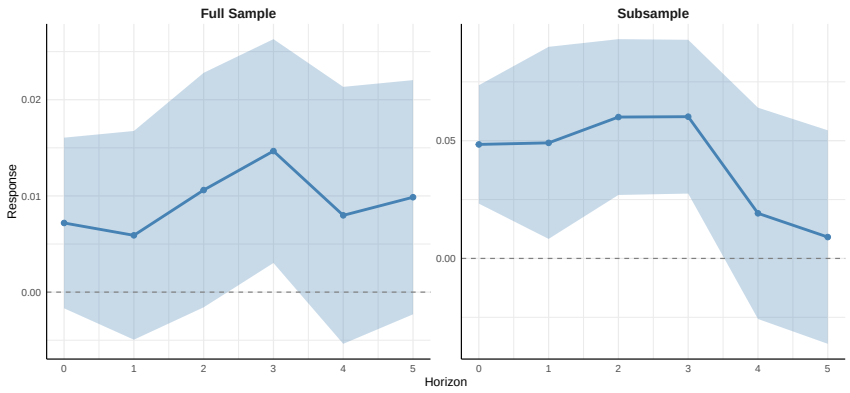


FIGURE A.9. Local Projection of cyclone strike of at least category one speed on default indicator.

Additionally, with this dataset I can examine the heterogeneous effect by adaptation level. Consistent with the baseline results, the effect of cyclones on default risk is driven by the low adaptation subsample. The effect is statistically insignificant for the high adaptation subsample.

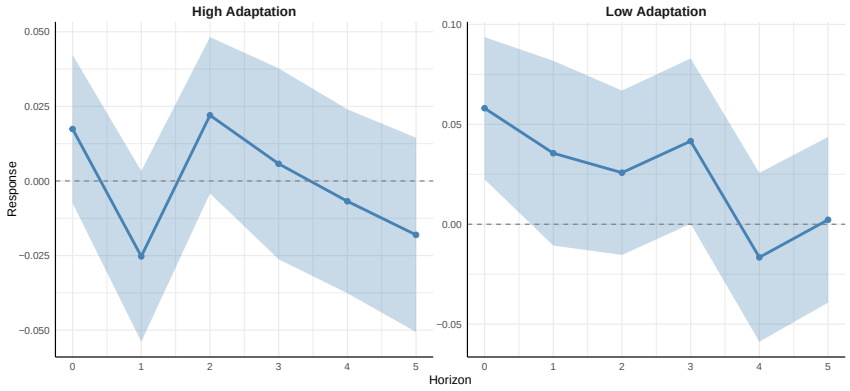


FIGURE A.10. Local Projection of cyclone strike of at least category one speed on default indicator.

A.2. Analytical Model

A.2.1. Proof of Propositions 2 and 3

Proof. Given 1.10, the partial derivative of s with respect to p is:

$$\frac{\partial s}{\partial p} = -\Phi_g(\bar{g}) + \int \Phi_g\Big(\bar{g} - \frac{1}{1+\psi}\ln(1-d(F(\lambda)))\Big)\, d\Phi_d(d')$$

Since the support of Φ_d is $[0,1)$, it follows that $\frac{\partial s}{\partial p} > -\Phi_g(\bar{g}) + \int \Phi_g(\bar{g}) d\Phi_d\left(d'\right) = 0$, i.e., the spread is increasing in the probability of the disaster shock, as desired.

Furthermore, suppose $\hat{\Phi}_d$ first-order stochastic dominates Φ_d. Let $\hat{s}$ denote the spread function associated with the damage distribution $\hat{\Phi}_d$. Since $\Phi_g\left(\bar{g} - \frac{1}{1+\psi}\ln(1-d(F(\lambda)))\right)$ is increasing in d', it follows that

$$E\left[\Phi_g\left(\bar{g} - \frac{1}{1+\psi}\ln(1-d(F(\lambda)))\right)\middle|\ \hat{\Phi}_d\right] \geq E\left[\Phi_g\left(\bar{g} - \frac{1}{1+\psi}\ln(1-d(F(\lambda)))\right)\middle|\ \Phi_d\right].$$

It then immediately follows that $\hat{s} \geq s$, as desired.

A.2.2. Proof of Proposition 4

$$\frac{\partial s}{\partial \lambda} = pE_{d'}\left[\phi_g\left(\bar{g} - \frac{1}{1+\psi}\ln(1-d(F(\lambda)))\right)\cdot \frac{d\cdot F'(\lambda)}{(1+\psi)(1-d\cdot F(\lambda)}\right] < 0$$

This follows as the first term inside the square brackets is positive while the second is negative given the assumption on the domain of d and that $F(\lambda)$ is decreasing in λ. Therefore the derivative is negative.

A.2.3. Cross Partial Derivative

Disasters have less of an effect on the spread the more the sovereign has invested in adaptation. Equivalently, adaptation is more effective at reducing the spread the larger the probability of a disaster. This is seen from the cross partial derivative:

$$\frac{\partial^2 s}{\partial p \partial \lambda} = E_{d'}\left[\phi_g\left(\bar{g} - \frac{1}{1+\psi}\ln(1-d(F(\lambda)))\right)\cdot \frac{d\cdot F'(\lambda)}{(1+\psi)(1-d\cdot F(\lambda)}\right] < 0.$$

This expression is negative by the same logic as given in the proof of Proposition 4.

A.2.4. Borrowing

Borrowing also responds to climate change. Higher probability of a bad shock tomorrow reduces optimal borrowing. However, as the discount rate of the sovereign is below the

inverse of the risk free rate the sovereign will always be a net borrower.

No Default Risk. FOC(B):

$$\frac{1}{C_1(1+r)} = \beta\,\mathbb{E}\Big[\frac{1}{y_2 - b}\Big]$$

therefore borrowing is decreasing with climate change.

Limited Commitment. FOC(B):

$$\frac{(1-s) - s'(b)b}{C_1(1+r)} = \beta\,\mathbb{E}\Big[(1-s(b))\frac{1}{y_2 - b} - s'(b)\,(U(C_D) - U(C_R))\Big],$$

therefore as the spread is increasing in p and in b at a decreasing rate, borrowing is also declining with climate change under default risk. Figure A.11 shows that borrowing is declining in the probability of a cyclone while adaptation is rising. Adaptation is more responsive to the probability of a cyclone than is borrowing: the percentage increase in adaptation is greater.

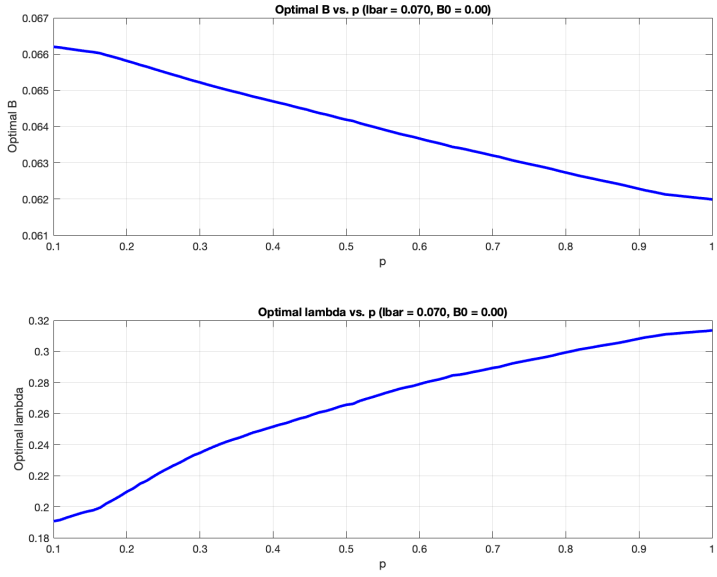


FIGURE A.11. Two period model: borrowing and Adaptation.

A.2.5. Adaptation

Section 1.2.2 outlined that the model prediction on the relative magnitude of adaptation under sovereign risk versus without is ambiguous. Here I outline what governs this tradeoff.

I show that adaptation will be greater under sovereign risk only if spreads are low (default costs are high) while also being very responsive to adaptation (adaptation is very effective, the natural disaster threat is substantial).

The first order condition for adaptation in the absence of default risk is:

$$\frac{1}{c_{1c}} = \beta \mathbb{E}\left(\frac{y_2'(\lambda)}{c_{2c}}\right),$$

where the subscript c to denotes the no default risk or 'commitment' case. The first order condition under limited commitment is:

$$\underbrace{\frac{1}{c_1}}_{MC} = \underbrace{\beta \mathbb{E}\left(\frac{y_2'(\lambda)}{c_R} - s(\lambda)\frac{y_2'(\lambda)b}{y_2 c_R}\right)}_{\text{MB damage reduction}} + \underbrace{\beta \mathbb{E}\left(s'(\lambda)(u(c_D) - u(c_R))\right)}_{\text{MB reduced default prob}} \underbrace{-\frac{\frac{1}{1+r}s'(\lambda)b}{c_1}}_{\text{MB lower spread}}.$$

I first show that the *direct* effects: the marginal cost of adaptation and the marginal benefits of damage reduction, imply that adaptation is greater in the absence of default risk:

$$c_{1c} = y_1 + \frac{1}{1+r}b_c - b_0 - \lambda,$$

$$c_1 = y_1 + \frac{1-s}{1+r}b - b_0 - \lambda.$$

Therefore, for a given λ, the positive spread $s > 0$ reduces c_1 relative to c_{1c}. Additionally, the presence of the spread reduces the optimal debt choice further reducing c_1 relative to c_{1c}. As a result, the marginal cost of adaptation is greater under default risk than without. Next consider the direct marginal benefit: the marginal benefit of damage reduction. This effect in the limited commitment case can be rewritten as:

$$\beta \mathbb{E}\left(\frac{y_2'(\lambda)}{c_R}\frac{y_2 - s(\lambda)b}{y_2}\right),$$

where $c_R = y_2 - b > c_{2c} = y_2 - b_c$, since borrowing is greater in the absence of default risk. Additionally, with positive spreads $y_2 - s(\lambda)b < y_2$. Therefore the marginal benefit of damage reduction is lower under default risk than without. This is due to i) potential lost benefits due to output costs of default, and ii) the lower debt repayment burden.

The marginal cost of adaptation is greater and the marginal benefit of damage reduction is lower under default risk than without. Therefore, adaptation under default risk should be lower than without via these direct effects. However, it is theoretically possible for the two additional indirect marginal benefits to flip the sign. If

$$\beta \mathbb{E}\left(s'(\lambda)(u(c_D) - u(c_R)\right) - \frac{\frac{1}{1+r}s'(\lambda)b}{c_1}$$

is sufficiently large it could dominate the direct effects. These indirect marginal benefits are largest when:

1. The spread is very responsive to adaptation: $s'(\lambda)$ is large. This is likely when:
   - Disasters are a substantial threat (high frequency and/or intensity)
   - Adaptation is very effective in reducing damages
2. Default costs are high.
   - In this case the difference in utility from consumption and repayment is large, and borrowing is high magnifying the effect of reduced spreads from adaptation.

Additionally, the difference in the direct effects of adaptation with vs without default risk is shrinking as the spread declines. Therefore, it will be easier for the indirect effects to overpower the direct effects when the spread is low. For the spread to be low while borrowing is high it must be the case that default costs are high.[10]

Therefore, a calibration in which sovereign risk increases adaptation would feature i) low spreads, ii) high adaptation, and iii) high exposure to natural disasters. Such a calibration is counterfactual for the economies I am considering.

	$p = 0.1$, $\alpha = 2$	$p = 0.1$, $\alpha = 1.1$	$p = 0.5$, $\alpha = 2$	$p = 0.5$, $\alpha = 1.1$
$\bar{l}$ min	NA	0.91	NA	0.87
implied s (bps)	NA	21	NA	28

TABLE A.20. The table shows the minimum value for default costs that imply that adaptation is higher under default risk than without for a set of combinations of the probability of a disaster and adaptation effectiveness. $F(\lambda) = \exp\left(-\alpha\lambda^{1/\alpha}\right)$.

Table A.20 shows that it is not possible to calibrate the model such that the spread is sufficiently large while also having higher adaptation under sovereign risk than without. For the greater indirect marginal benefits to damage the effectiveness of adaptation and the cost of default must be high. For baseline values of the probability of a disaster and the effectiveness of adaptation that correspond to those estimated for the quantitative model, it is not possible to find default costs high enough such that the indirect effect dominates.

[10] High period 0 debt and low discount factors also increase borrowing but simultaneously increase the spread.

A.2.6. Adaptation Bond

Consumption in period 2 is denoted by c_R if the sovereign chooses to repay, and c_D if it defaults. The sovereign defaults if $c_D > c_R$. Consumption in repayment is adjusted by the adaptation bond: the coupon payment is reduced if adaptation is above the threshold level.

$$c_R = y_1^{\rho}(1 - x_t d_t F(\lambda))\epsilon^{y} - b(1 - c\mathbb{1}_{\Lambda>\Lambda^*}), \qquad c_D = \phi(y_2) y_1^{\rho}(1 - x_t d_t F(\lambda))\epsilon^{y}.$$

As in the baseline model this implies that default occurs if the disaster adjusted growth rate $\tilde{g}$ is below an endogenous default threshold $\bar{g}$:

$$\underbrace{g + \frac{1}{1+\psi} ln(1 - x_t d_t F(\lambda)) - \frac{1}{1+\psi} ln(1 - c\mathbb{1}_{\Lambda>\Lambda^*})}_{\tilde{g}} < \underbrace{\frac{1}{1+\psi} ln(\frac{b}{\bar{l} y_1^{\rho}})}_{\bar{g}},$$

where $\tilde{g}$ is adjusted by

$$-\frac{1}{1+\psi} ln(1 - \mathbb{1}_{\Lambda>\Lambda^*})$$

relative to the baseline. This implies that the coupon reduction decreases the probability of default in high adaptation states. In the baseline model the expected payoff from buying the bond was $(1 - \mathbb{P}(D_2 = 1))$. Now the payoff must be adjusted for the potential coupon reduction:

$$\mathbb{E}(\text{payoff}) = \mathbb{P}(\Lambda \leq \Lambda^*)(1 - \mathbb{P}(D_2 = 1|\Lambda \leq \Lambda^*)) + (1 - c)\mathbb{P}(\Lambda > \Lambda^*)(1 - \mathbb{P}(D_2 = 1|\Lambda > \Lambda^*)).$$

$$q = \frac{\mathbb{E}(\text{payoff})}{1 + r}.$$

Therefore the bond price that gives the investor zero expected profit in equilibrium will have to account for the lower expected default probability as well as the lower expected coupon payment.

Rewriting, the spread is:

$$\begin{aligned} s(b, \Lambda) = \\ & (1 - p)\Phi_g(\bar{g} + \mathbb{1}_{(\Lambda>\Lambda^*)} \frac{1}{1+\psi} ln(1 - c)) + \\ & pE_{d'}\left[\Phi_g\left(\bar{g} - \frac{1}{1+\psi} ln(1 - d_t(F(\lambda_t)) + \mathbb{1}_{(\Lambda>\Lambda^*)} \frac{1}{1+\psi} ln(1 - c)\right)\right] + c\mathbb{1}_{\Lambda>\Lambda^*}. \end{aligned}$$

Therefore, the adaptation bond could either tighten the budget constraint by increasing spreads (final term), or loosen it by decreasing spreads via lower default probabilities.

A.3. Quantitative Model

A.3.1. Solution Algorithm

The model is solved numerically, using state-of-the-art techniques developed in the quantitative sovereign default literature. The process for output is discretized on a grid of 61 points. I also define a discrete grid for coupons (80 points) and adaptation (41 points).

The iterative algorithm works as follows:

1. I form initial guesses for the unconditional debt price function and for the value functions
2. Given the initial guesses, I update the value function V_{nd} by solving the maximization problem in the market access case
   - Following Dvorkin et al. (2021), it is assumed that each possible choice of discrete values for debt and adaptation is associated with an additive taste shock.[11]
   - In this nested structure the sovereign chooses b' conditional on having chosen a particular Λ' subject to taste shocks, and that Λ' is chosen subject to taste shocks for a fixed b'.
   - In the presence of the extreme value shocks, the probability of choosing a given discrete value for debt or adaptation is increasing in the value associated with that particular choice and it is given by the multinomial logit formula.
   - Conditional on an arbitrary b', choice probabilities over Λ' are given by:

$$\Pr\left(\Lambda' = \Lambda_i \mid y, b, \Lambda, b'\right) = \frac{\exp \frac{W(y,b,\Lambda,b',\Lambda_i)}{\rho_\Lambda}}{\sum_j \exp \frac{W(y,b,\Lambda,b',\Lambda_j)}{\rho_\Lambda}} \tag{A.1}$$

   with associated ex-ante value:

$$W_\Lambda\left(y, b, \Lambda, b'\right) = \rho_\Lambda \log\left[\sum_j \exp \frac{W\left(y, b, \Lambda, b', \Lambda_j\right)}{\rho_\Lambda}\right]. \tag{A.2}$$

   - The outer choice over b' satisfies:

[11] Extreme value shocks follow a Type-1 Generalized Extreme Value distribution, with scale parameter ρ which is set to 10^{-3} for both borrowing and adaptation capital. The introduction of these shocks facilitates convergence of the solution.

$$\Pr\left(b' = b_i \mid y, b, \Lambda\right) = \frac{\exp \frac{W_\Lambda(y,b,\Lambda,b_i)}{\rho_b}}{\sum_j \exp \frac{W_\Lambda(y,b,\Lambda,b_j)}{\rho_b}}, \tag{A.3}$$

and the ex-ante value of repayment becomes

$$V_{nd}(y, b, \Lambda) = \rho_b \log\left[\sum_j \exp \frac{W_\Lambda\left(y, b, \Lambda, b_j\right)}{\rho_b}\right]. \tag{A.4}$$

- The solution to the maximization problem defines the (average) policy function for borrowing and adaptation and conditional equilibrium price function for government debt.

3. I update the value function V by solving the discrete choice default problem.
   - I introduce extreme value shocks to the default problem in an analogous way to the problem for government borrowing and adaptation choices. The probability of default is therefore given by:

$$\tilde{d}(y, b, \Lambda) = \frac{\exp\left(\frac{1}{\rho_{EV}} V_d(y, \Lambda)\right)}{\exp\left(\frac{1}{\rho_{EV}} V_d(y, \Lambda)\right) + \exp\left(\frac{1}{\rho_{EV}} V_{\text{nd}}\left(y, b, \Lambda\right)\right)}. \tag{A.5}$$

   - The probability of choosing to default increases with the difference between the values of defaulting and repaying.
4. I update the default value function V_d making use of the update values of V and V_{nd}.
5. I repeat (b-d) until value functions have converged.
6. I update the unconditional debt price function by imposing the default policy and the average equilibrium price function.
7. I repeat (b-f) until convergence of the unconditional debt price function.

A.3.2. No Default Counterfactual

I impose the natural debt limit to ensure countries are able to repay without incurring negative consumption. The sovereign still borrows state uncontingently but faces a natural borrowing limit as in Aiyagari (1994). The sovereign cannot borrow more than would be repayable under the worst case exogenous shock. I compute this natural borrowing limit at zero adaptation. This approach is similar to that in Bai and Zhang (2010) and Alessandria, Bai, and Deng (2020).

A.3.3. Default Risk Subsamples

I split the sample of Caribbean economies into those with above median spreads (high default risk), and those with below median spreads (low default risk). In the data the economies with lower spreads spend more on adaptation on average: 0.39% of GDP vs 0.27% of GDP. The model accounts well for this difference, re-calibrating only the default-relevant parameters.

	Low Risk		High Risk	
	Model	Data	Model	Data
Adaptation Investment/GDP	0.38%	0.39%	0.29%	0.27%
Debt/GDP	0.49	0.51	0.37	0.38
Mean Spread	460	442	573	559

TABLE A.21. Data and Simulated Moments
The table presents selected moments of model split across two subsamples. The Low Risk sample is those economies with below median spreads, while the High Risk sample includes those economies with above median spreads. The Simulations run for 9,000 periods.

A.3.4. No Hurricane Counterfactual

	Baseline	No hurricane
Adaptation		
Adaptation Investment/GDP	0.003	
Adaptation Capital/GDP	0.029	
Cyclone		
GDP loss | Cyclone	0.052	
Percent Damages Avoided	0.45	
Debt		
Debt/GDP	0.410	0.481
Market Value Debt/GDP	0.37	0.45
Mean Spread	502	416
Default Frequency	0.048	0.039
Median Spread	121	88
Welfare Loss		
	5.1%	

TABLE A.22. Simulated Moments
The table presents selected moments of the baseline model and corresponding moments from the model without hurricane risk. Simulations run for 9,000 periods. Welfare loss is the consumption equivalent welfare change compared to the case with no hurricanes.

APPENDIX B.

Appendices to Chapter 2

B.1. CBAM and the default value

B.1.1. Revenue Rebate

Figure 2.1 shows an optimal CBAM tariff of 4.5% however if the revenue from CBAM is not redistributed to households, but rather thrown away, the CBAM is uniformly welfare reducing. Figure B.1 shows this: utility is declining in T.

Figure B.2 shows how the optimal level of the tariff T varies with the share of revenue rebated. The leftmost point corresponds to the outcome in Figure B.1 while the rightmost point corresponds to the outcome in Figure 2.1.

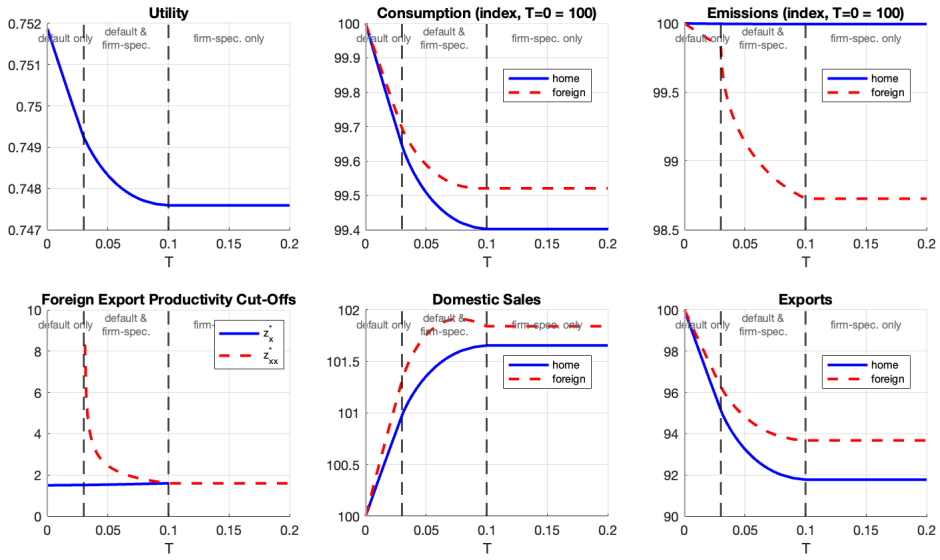


FIGURE B.1. Model outcomes as T varies with t fixed. Revenue is not redistributed to households.

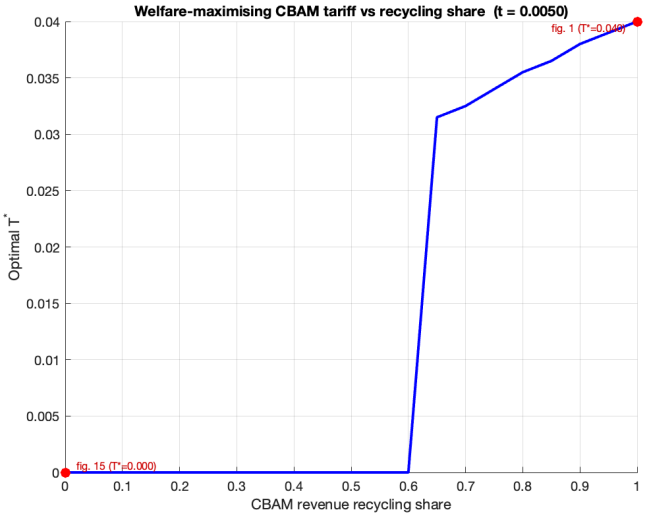


FIGURE B.2. Utility maximizing level of the tariff T as the share of revenue that is rebated lump sum to households varies.

B.1.2. Regular Tariff

We allow for a traditional import tariff levied on foreign goods:

$$c_X(z) = \left(\frac{(1+\tau_q)\,p_X^*(z)}{PQ}\right)^{-\theta} C \tag{B.1}$$

This implies the altered export thresholds:

$$z_X^* = \frac{\theta}{\theta-1} Q\tau^*(1+T)\left(w^* + t^*\mu*\left[1 - \frac{\theta_2-1}{\theta_2}a_X^*\right]\right)\left(\frac{(1+\tau_q)^{\theta}, \theta w^{f_X^*} Q}{C}\right)^{1/(\theta-1)} \tag{B.2}$$

$$z_{XX}^* = \frac{\theta}{\theta-1} Q\tau^* \left(\frac{(1+\tau_q)^{\theta}\theta w^*(f_{XX}-f_X)Q/C}{\left(w^* + \frac{t}{Q}\mu*\left[1-\frac{\theta_2-1}{\theta_2}a_{XX}^*\right]\right)^{1-\theta} - \left((1+T)\left(w^* + t^*\mu^*\left[1-\frac{\theta_2-1}{\theta_2}a_X^*\right]\right)\right)^{1-\theta}}\right)^{1/(\theta-1)}$$

We assume that the tariff revenue is redistributed to households lump-sum:

$$C = N_D R_D(\tilde{z}_D) + N_X R_X(\tilde{z}X) + QT\text{CBAM} + \tau_q Q\left[N_X^* R_X^*(\tilde{z}_X^*) + N_{XX}^* R_{XX}^*(\tilde{z}_{XX}^*)\right] \tag{B.3}$$

The level of the regular tariff, τ_q matters for the welfare effects of the CBAM. Similar to the CBAM, there is a positive optimal tariff when the revenue is redistributed to households. Figure B.3 illustrates this. The tariff decreases imports, increases domestic sales, and increases home consumption. Emissions decrease very slightly due to the aggregate fall in production. The regular tariff is also welfare reducing if the revenues are thrown away.

Once the optimal tariff τ_q is implemented, CBAM is also welfare reducing. Figure B.4 shows that in this case consumption is declining in the CBAM tariff. The emissions reductions are not enough to counteract this at a social cost of carbon of €100 and so utility falls. This result is sensitive to the level of the social cost of carbon. However, a very large social cost of carbon is required for there to be a positive utility maximizing T conditional on the optimal tariff τ_q being set. Figure B.5 shows that there is a positive utility maximizing T under a social cost of carbon of €1500.

Figure B.6 shows how the utility maximising level of the default tariff varies with the regular tariff τ_q under the baseline calibration (social cost of carbon of €100).

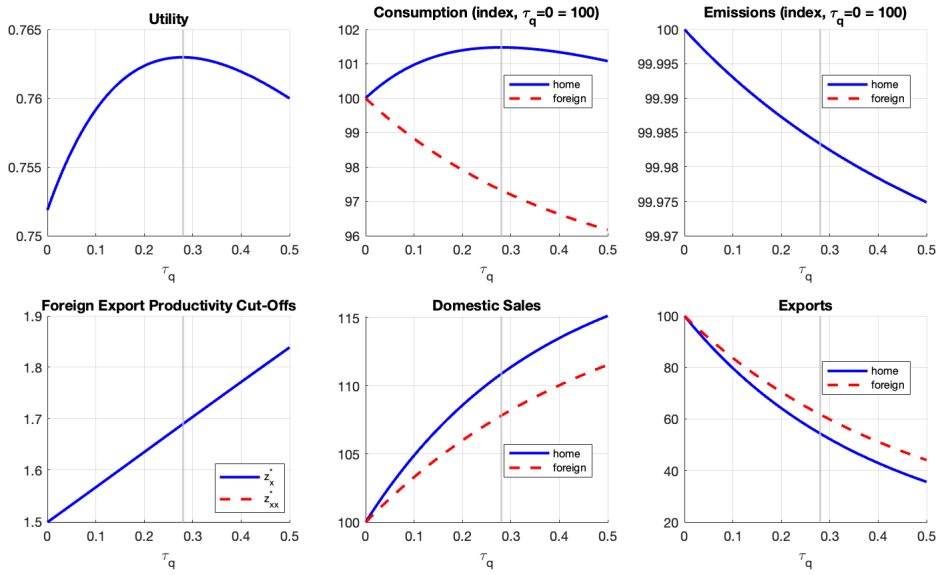


FIGURE B.3. Model outcomes as τ_q varies with t fixed and $T = 0$. Revenue is redistributed to households.

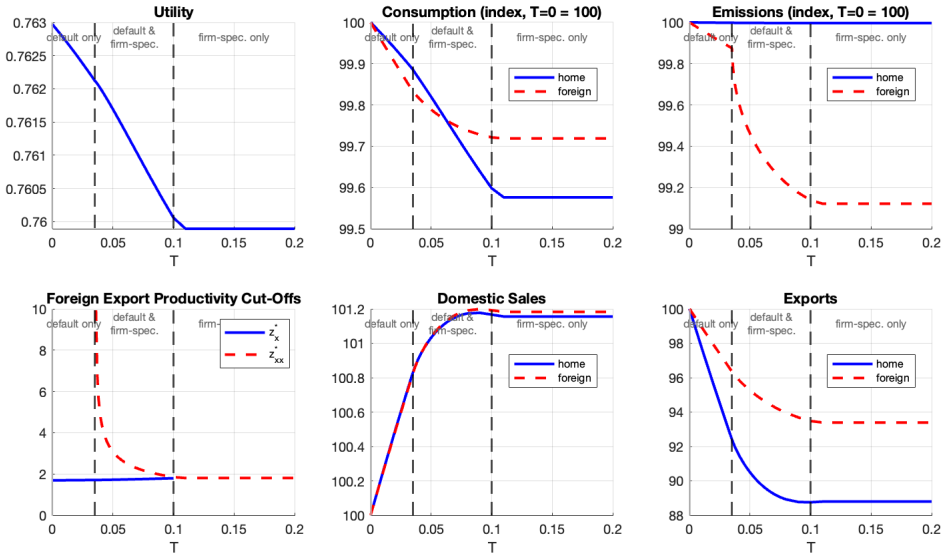


FIGURE B.4. Model outcomes as T varies with t fixed and $\tau_q = \tau_q^*$. Revenue is redistributed to households.

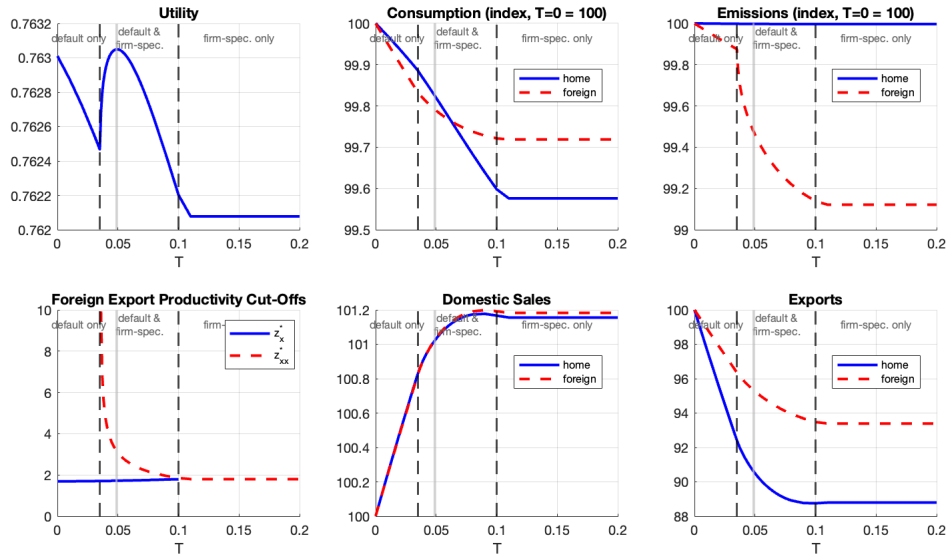


FIGURE B.5. Model outcomes as T varies with t fixed and $\tau_q = \tau_q^*$. Revenue is redistributed to households. Social cost of carbon is €1500.

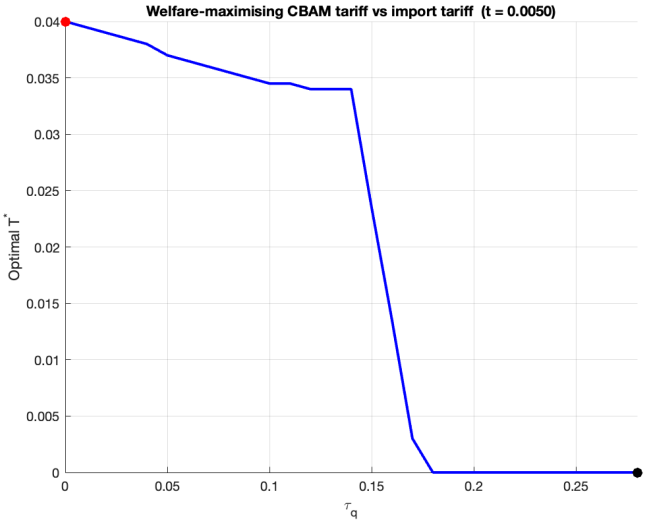


FIGURE B.6. Welfare maximising level of the default tariff for each value of τ_q under the baseline calibration.

B.1.3. Carbon Tax

The optimal value of the carbon tax shown in the text varies under different regimes. In particular, if the carbon tax is set jointly by both countries, the utility maximizing level of the tax is greater. In this case there is no leakage. Figure B.7 illustrates this. On the other hand, if the carbon tax is set unilaterally by the home country while the foreign economy has no carbon tax, and there is no CBAM, the home country would prefer a lower level of the tax. This is shown in Figure B.8.

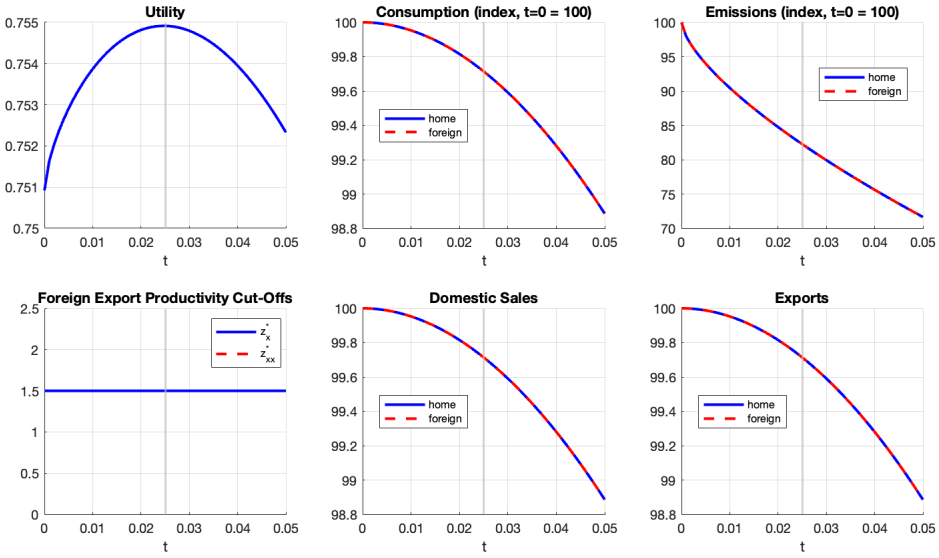


FIGURE B.7. Model outcomes as the carbon tax changes. The carbon tax is set to apply to both countries.

The carbon tax response shown in Figure 2.4 can explained by the underlying firm adjustments which are shown in Figure B.9.

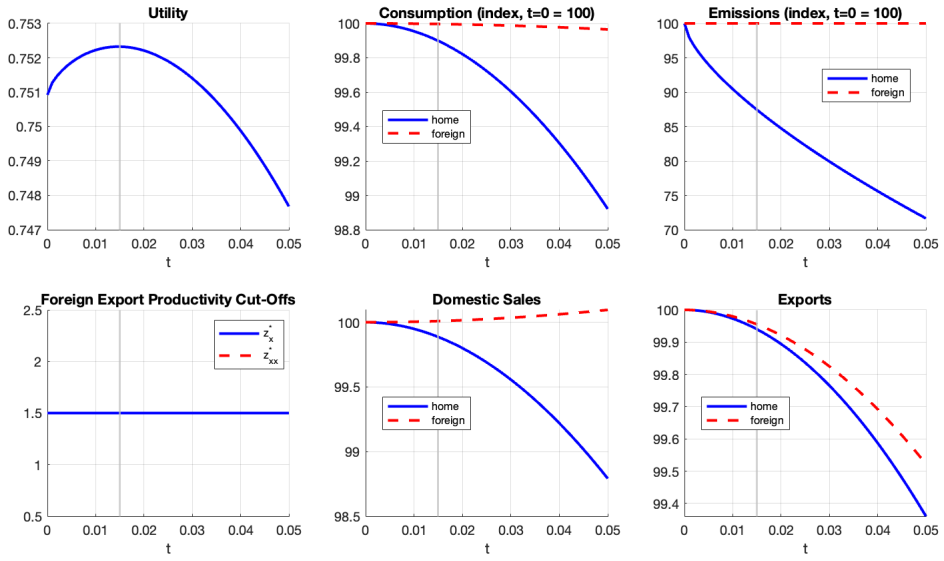


FIGURE B.8. Model outcomes as the carbon tax changes. The carbon tax is set to apply only at home and there is no CBAM (T=0).

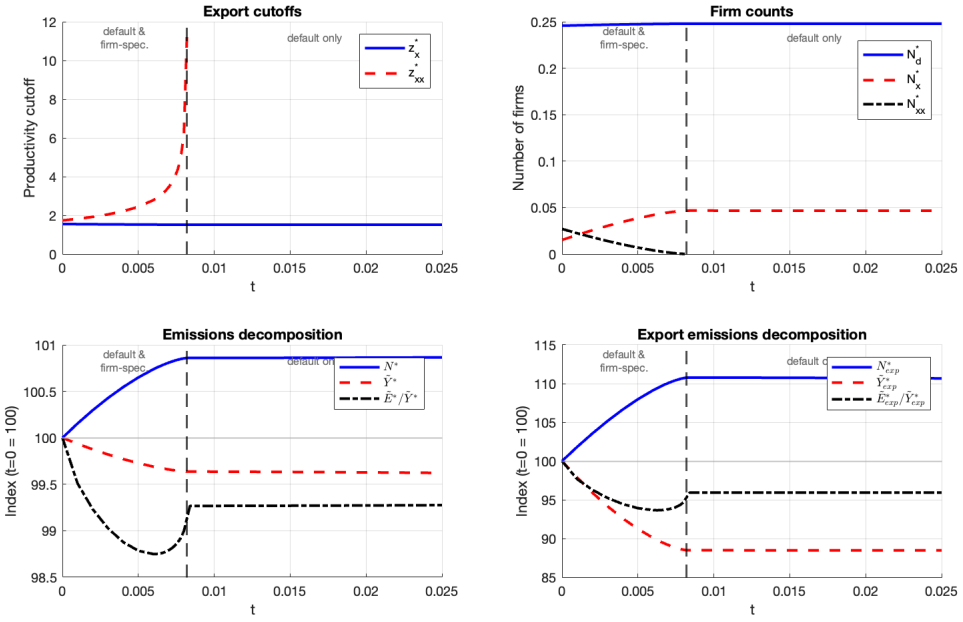


FIGURE B.9. Model outcomes as the carbon tax changes. The carbon tax is set to apply only at home and the CBAM is fixed (T=0.05). Illustrated outcomes are for the foreign country. The third subplot shows the total number of foreign firms, their average output, and their average emissions intensity, all indexed to 100 at $t = 0$. The final subplot shows the total number of exporting firms, their average output, and their average emissions intensity, all indexed to 100 at $t = 0$.

B.2. Optimal Policy

Figure B.10 shows the home utility contours computed relative to a fixed baseline emissions. Baseline emissions are computed as those when the carbon tax takes the calibrated value and there is no CBAM.

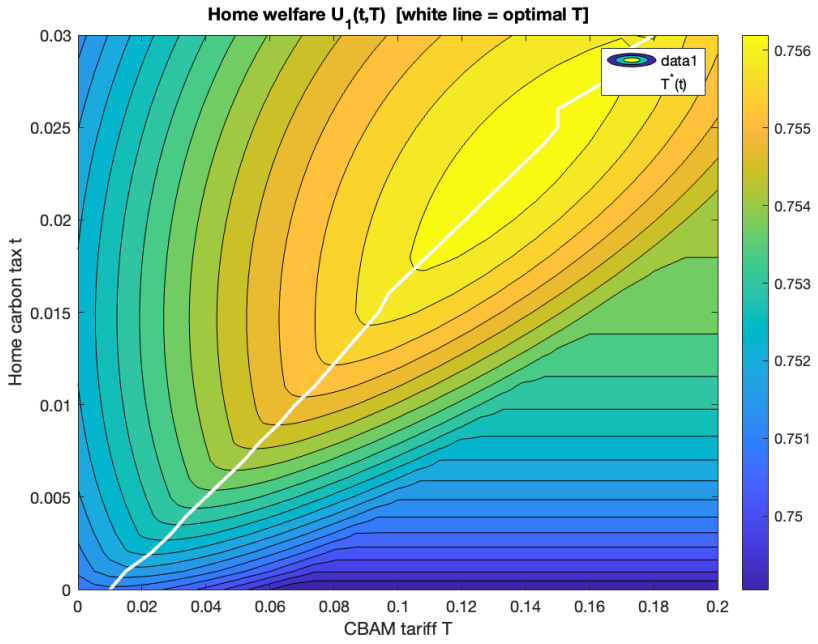


FIGURE B.10. Heat map showing contours of home welfare for given combinations of the home carbon tax t and the CBAM default tariff T. Baseline emissions E_0 are kept fixed at the level with the calibrated home carbon tax and no CBAM.

B.3. Three Country Model

B.3.1. Model Equations

We extend the model to three countries: Home (H), Foreign (F), and the Rest of the World (R), all of equal size. Home is the only country with a domestic carbon tax t and a CBAM; countries F and R have no domestic carbon pricing ($t^F = t^R = 0$). The CBAM applies to imports arriving in H from both F and R; bilateral trade between F and R is not subject to border adjustment. Countries may differ in their emissions intensity parameter μ^i. We define $Q^{ij} \equiv P^j/P^i$ as the bilateral real exchange rate between countries i and j.

Preferences are identical across countries. Households in country $i \in H, F, R$ maximise a CES consumption aggregate over differentiated varieties, yielding the demand schedule

$$c^i(\omega) = \left(\frac{p^i(\omega)}{P^i}\right)^{-\theta} C^i. \tag{B.4}$$

Firms

A firm in country i with productivity z produces output $q^i(z) = zl^i(z)$ and generates emissions

$$e^i(z) = \mu^i(1 - a^i)l^i(z), \tag{B.5}$$

where $a^i \in [0, 1]$ is abatement effort. Abatement requires resources

$$f(a^i) = \theta_1(a^i)^{\theta_2} l^i(z). \tag{B.6}$$

Since $t^F = t^R = 0$, firms in F and R do not abate when serving domestic markets or non-Home export destinations ($a^F = a^R = 0$), so their marginal cost is simply

$$mc^i(z) = \frac{w^i}{z}, \qquad i \in F, R. \tag{B.7}$$

Home firms face the carbon tax t and choose abatement optimally:

$$a^H = \left(\frac{t\mu^H}{\theta_1\theta_2}\right)^{1/(\theta_2-1)}, \tag{B.8}$$

with marginal cost $mc^H(z) = mc_0^H/z$, where

$$mc_0^H \equiv w^H + t\mu^H\left[1 - \frac{\theta_2 - 1}{\theta_2}\left(\frac{t\mu^H}{\theta_1\theta_2}\right)^{1/(\theta_2-1)}\right]. \tag{B.9}$$

The home firm's problem is identical to Section 2.3. Home exports to $j \in F, R$ with iceberg costs τ^{Hj}, fixed costs f_X^j, and real exchange rate $Q^{Hj} = P^j/P^H$.

Domestic production and trade between F and R. For $i \in F, R$, domestic profits are

$$\Pi_D^i(z) = \frac{1}{\theta}\left(\frac{p_D^i(z)}{P^i}\right)^{1-\theta} C^i - w^i f_D, \tag{B.10}$$

with optimal price $p_D^i(z)/P^i = \frac{\theta}{\theta-1}\frac{w^i}{z}$ and domestic cutoff

$$z_d^i = \frac{\theta}{\theta-1}, w^i\left(\frac{\theta w^i f_D}{C^i}\right)^{1/(\theta-1)}. \tag{B.11}$$

For bilateral trade between F and R — neither of which levies a CBAM — export profits and cutoffs take the standard form:

$$\Pi_x^{ij}(z) = \frac{1}{\theta}, Q^{ij}\left(\frac{p_x^{ij}(z)}{P^j}\right)^{1-\theta} C^j - w^i f_X^j, \; z_x^{ij} = \frac{\theta}{\theta-1}, \frac{\tau^{ij}}{Q^{ij}}, w^i\left(\frac{\theta w^i f_X^j}{Q^{ij} C^j}\right)^{1/(\theta-1)}, \tag{B.12}$$

for $(i, j) \in (F, R), (R, F)$.

Exports to Home: the CBAM.. Firms in $i \in F, R$ exporting to H face the CBAM and choose between the default and firm specific options as in Section 2.3.

Default option. Since the levy is independent of the firm's decisions, it does not abate ($a^i = 0$), and the CBAM tariff enters as a multiplicative cost on the variable cost of exporting. Profits are

$$\Pi_x^{iH}(z) = \frac{1}{\theta}, Q^{iH}\left(\frac{p_x^{iH}(z)}{P^H}\right)^{1-\theta} C^H - w^i f_X^H, \tag{B.13}$$

with optimal price $p_x^{iH}(z)/P^H = \frac{\theta}{\theta-1}\frac{(1+T)\tau^{iH} w^i}{Q^{iH}, z}$.

Firm-specific option. The optimal abatement rate is

$$a_{xx}^i = \left(\frac{t\mu^i}{Q^{Hi}\theta_1\theta_2}\right)^{1/(\theta_2-1)}, \tag{B.14}$$

which, as in the two-country model, is independent of z. The marginal cost is $mc_{xx}^i(z) =$

$mc^i_{xx,0}/z$, where

$$mc^i_{xx,0} \equiv w^i + \frac{t}{Q^{Hi}}\mu^i \left[1 - \frac{\theta_2 - 1}{\theta_2}\left(\frac{t\mu^i}{Q^{Hi}\theta_1\theta_2}\right)^{1/(\theta_2-1)}\right]. \tag{B.15}$$

Profits are

$$\Pi^{iH}_{xx}(z) = \frac{1}{\theta}, Q^{iH}\left(\frac{p^{iH}_{xx}(z)}{P^H}\right)^{1-\theta} C^H - w^i f_{XX}, \tag{B.16}$$

with optimal price $p^{iH}_{xx}(z)/P^H = \frac{\theta}{\theta-1}\frac{\tau^{iH} mc^i_{xx,0}}{Q^{iH},z}$.

The export entry cutoff z^{iH}_x, at which default export profits are zero, is:

$$z^{iH}_x = \frac{\theta}{\theta - 1}, \frac{(1+T)\tau^{iH} w^i}{Q^{iH}}\left(\frac{\theta w^i f^H_X}{Q^{iH} C^H}\right)^{1/(\theta-1)}. \tag{B.17}$$

The firm-specific cutoff z^{iH}_{xx}, at which profits under both options are equal, satisfies $\Pi^{iH}_{xx}(z^{iH}_{xx}) = \Pi^{iH}_x(z^{iH}_{xx})$:

$$z^{iH}_{xx} = \frac{\theta}{\theta - 1}, \frac{\tau^{iH}}{Q^{iH}}\left(\frac{\theta w^i\left(f_{XX} - f^H_X\right)}{Q^{iH} C^H\left[\left(mc^i_{xx,0}\right)^{1-\theta} - \left((1+T)w^i\right)^{1-\theta}\right]}\right)^{1/(\theta-1)}. \tag{B.18}$$

Firms with $z < z^{iH}_x$ do not export to H; firms with $z \in [z^{iH}_x, z^{iH}_{xx})$ use the default tariff; firms with $z \geq z^{iH}_{xx}$ opt for firm-specific assessment.

Firm Averages

Productivity is drawn from a Pareto distribution $G(z) = 1 - (z_{\min}/z)^k$ with $k > \theta - 1$. Letting $\nu \equiv (k/(k - (\theta - 1)))^{1/(\theta-1)}$, average productivity satisfies $\tilde{z}^i_D = \nu z^i_d$ for all countries and $\tilde{z}^{ij}_x = \nu z^{ij}_x$ for all bilateral pairs without CBAM.

For exports from $i \in F, R$ to H, there are two thresholds. Default exporters (with productivity between z^{iH}_x and z^{iH}_{xx}) have average productivity

$$\tilde{z}x^{iH} = \nu\left(\frac{(zxx^{iH})^k (z^{iH}_x)^{\theta-1} - (z^{iH}_x)^k (z^{iH}_{xx})^{\theta-1}}{(z^{iH}_{xx})^k - (z^{iH}_x)^k}\right)^{1/(\theta-1)}, \tag{B.19}$$

while firm-specific exporters (with productivity above z^{iH}_{xx}) have $\tilde{z}xx^{iH} = \nu, zxx^{iH}$. The

fractions of firms in each export category are

$$\frac{N_x^{iH}}{N_D^i} = \left(\frac{z_d^i}{z_x^{iH}}\right)^{!k} - \left(\frac{z_d^i}{z_{xx}^{iH}}\right)^{!k}, \qquad \frac{N_{xx}^{iH}}{N_D^i} = \left(\frac{z_d^i}{z_{xx}^{iH}}\right)^{!k}. \tag{B.20}$$

B.3.2. Market Clearing

Let T_C^i denote the CBAM revenue collected by H on imports from country i, expressed in country i's consumption units. All government revenues are rebated to domestic households. Aggregate consumption in each country is:

$$C^H = N_D^H R_D^H(\tilde{z}_D^H) + \sum_{j\in\{F,R\}} N_x^{Hj} R_x^{Hj}(\tilde{z}_x^{Hj}) + \sum_{i\in\{F,R\}} Q^{Hi} T_{\text{CBAM}}^i, \tag{B.21}$$

$$\begin{aligned} C^i = {} & N_D^i R_D^i(\tilde{z}_D^i) + N_x^{iH} R_x^{iH}(\tilde{z}_x^{iH}) + N_{xx}^{iH} R_{xx}^{iH}(\tilde{z}_{xx}^{iH}) \\ & + N_x^{ij} R_x^{ij}(\tilde{z}_x^{ij}) - T_{\text{CBAM}}^i, \quad i \in \{F, R\}. \end{aligned} \tag{B.22}$$

where $j \in F, R \setminus i$. We assume bilateral balanced trade. For each pair (H, i) with $i \in F, R$:

$$N_x^{Hi} R_x^{Hi}(\tilde{z}x^{Hi}) + Q^{Hi} T^i \text{CBAM} = Q^{Hi}! \left(N_x^{iH} R_x^{iH}(\tilde{z}x^{iH}) + Nxx^{iH} Rxx^{iH}(\tilde{z}_{xx}^{iH})\right), \tag{B.23}$$

and for the F-R pair:

$$N_x^{FR} R_x^{FR}(\tilde{z}_x^{FR}) = Q^{FR}, N_x^{RF} R_x^{RF}(\tilde{z}_x^{RF}). \tag{B.24}$$

B.3.3. Welfare

Home welfare is

$$U^H = \frac{C^H}{1 + \eta\left(E^H + E^F + E^R - E_0\right)}, \tag{B.25}$$

where E^i denotes total emissions in country i and E_0 is total global emissions at the no-policy baseline.

B.3.4. Model outcomes

Additionally to heterogeneity in μ across countries we could also consider heterogeneity in abatement technology, or in θ_1 and θ_2.

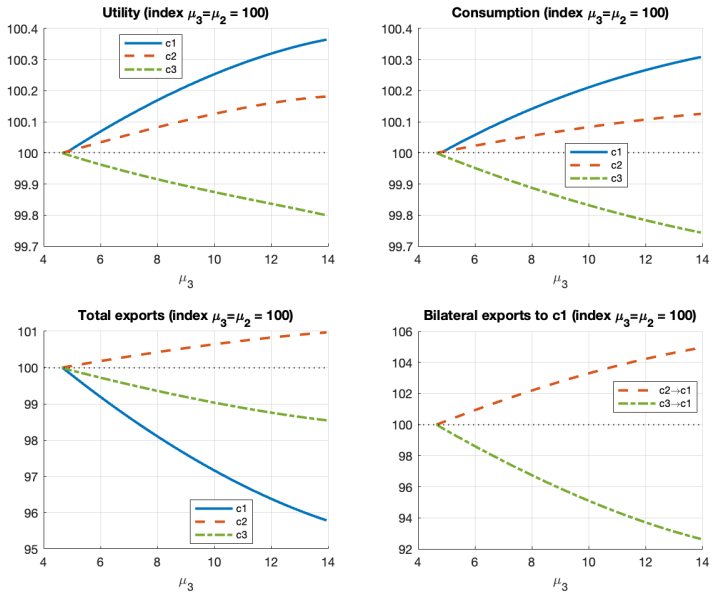


FIGURE B.11. Model outcomes as the emissions factor of country three varies. Utility, consumption, total exports, and bilateral exports of country one are depicted, all indexed to 100 at $\mu_2 = \mu_3$. Utility is calculated using the same social cost of carbon for each country. The baseline level of emissions E_0 is recalculated for each mu_3 without CBAM (T=0).

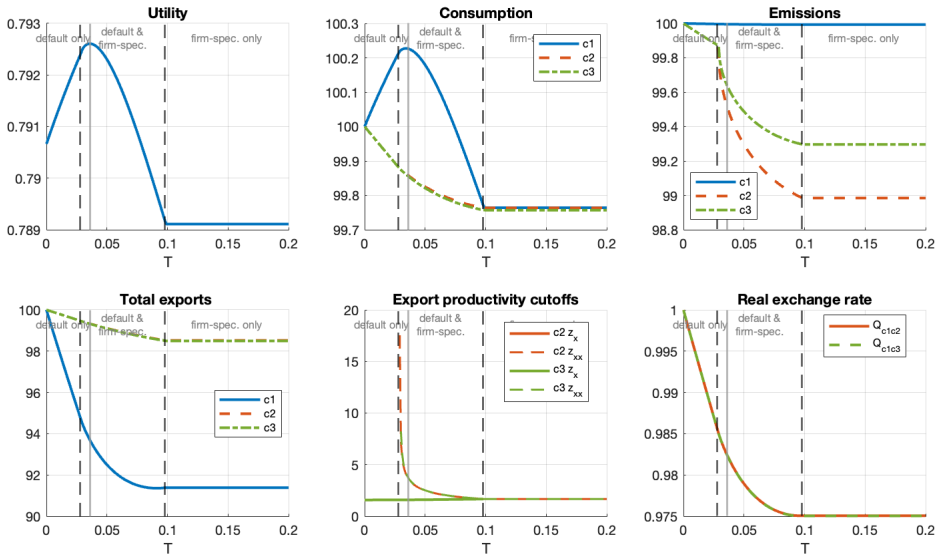


FIGURE B.12. CBAM model outcomes as T varies. Country three has a θ_1 twice as large as countries one and two.

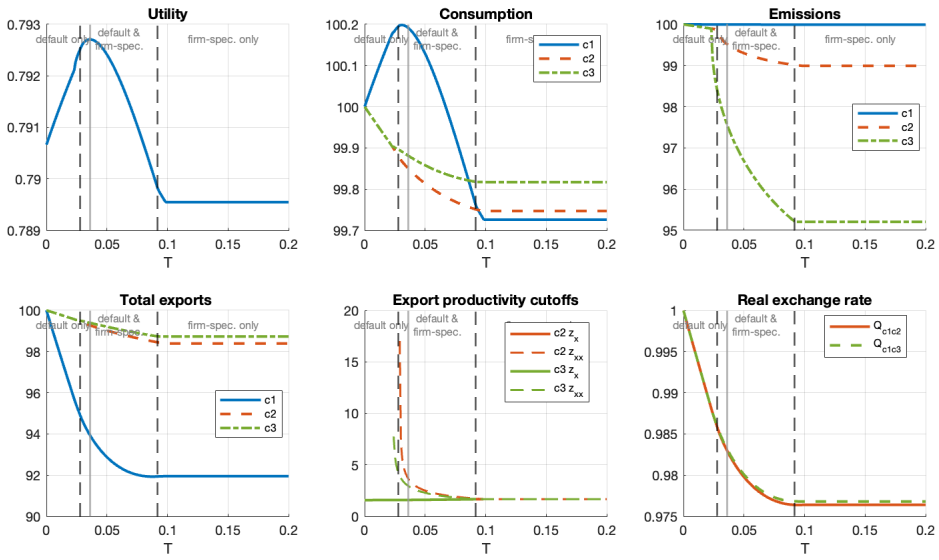


FIGURE B.13. CBAM model outcomes as T varies. Country three has a θ_2 twice as large as countries one and two.

B.4. Sensitivity

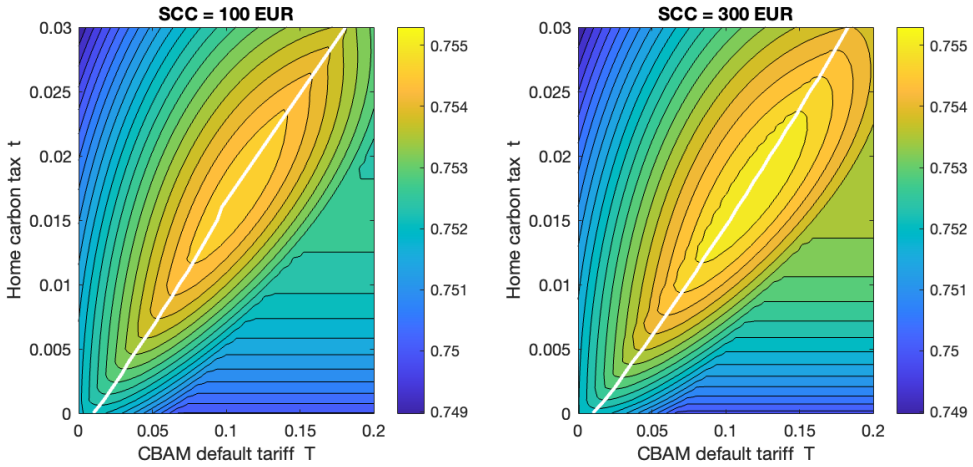


FIGURE B.14. Heat map showing contours of home welfare for given combinations of the home carbon tax t and the CBAM default tariff T. Baseline emissions E_0 are calculated separately for each level of the home tax t, as the emissions under that tax in the absence of CBAM, or with $T = 0$. In the left panel, η is calibrated to yield a social cost of carbon of €100, while in the right panel it is calibrated to yield a social cost of carbon of €300.

B.4.1. Model Equations: Cobb-Douglas Production Function

This appendix describes an alternative model specification in which abatement arises from cost-minimising factor substitution within a Cobb-Douglas technology, rather than from the explicit abatement cost function of the baseline model. The demand structure, entry and exit conditions, CBAM architecture, and welfare specification are identical to those in the main text; only the firm-level technology and its implications differ.

Technology

A firm with productivity z produces output by combining labour l and emissions e as a Cobb-Douglas composite:

$$q(z) = e(z)^{\alpha}\big(z\,l(z)\big)^{1-\alpha}, \qquad \alpha \in (0,1). \tag{B.26}$$

Equivalently, one can write $e(z) = (1 - a(z))^{1/\alpha} z\,l(z)$, so that output reduces to $q(z) = (1 - a(z))z\,l(z)$, paralleling the LMAC specification. The key difference is that the abatement rate $a(z)$ is not chosen via a separate cost function but is determined by the firm's optimal factor mix.

Marginal cost and abatement

Cost minimisation subject to output gives marginal cost

$$\mathrm{mc}(z) = \frac{c}{z^{1-\alpha}}, \qquad c \equiv \frac{t^{\alpha} w^{1-\alpha}}{\alpha^{\alpha}(1-\alpha)^{1-\alpha}}, \tag{B.27}$$

and the optimal emission rate

$$1 - a(z) = \left(\frac{\alpha}{1-\alpha} \frac{w}{z\,t} \right)^{\alpha}. \tag{B.28}$$

Unlike the baseline model, abatement is *firm-specific*: more productive firms face a higher shadow value of the emissions input and therefore abate more. The marginal cost also scales as $z^{-(1-\alpha)}$ rather than z^{-1}, which propagates through all cutoff and revenue expressions.

For foreign firms subject to firm-specific CBAM (the *xx* regime), the effective carbon price is t/Q (in foreign units), so their marginal cost and abatement rate are obtained by replacing t with t/Q and w with $w^{*}\tau$ in the expressions above:

$$1 - a^{*}_{xx}(z) = \left(\frac{\alpha}{1-\alpha} \frac{w^{*}\tau Q}{z\,t} \right)^{\alpha}. \tag{B.29}$$

Foreign firms that do not pay the CBAM compliance cost face no carbon price and set $a^{*} = 0$, so $e^{*}(z) = z\,l^{*}(z)$.

Prices

Because $\mathrm{mc}(z) \propto z^{-(1-\alpha)}$, the CES optimal price for home domestic sales is

$$\frac{p_D(z)}{P} = \frac{\theta}{\theta - 1} \frac{t^{\alpha} w^{1-\alpha}}{\alpha^{\alpha}(1-\alpha)^{1-\alpha}\, z^{1-\alpha}}, \tag{B.30}$$

and analogously for export and *xx*-regime prices (substituting w^{*}, τ, and the effective carbon price as appropriate).

Aggregation and average productivity

Because price is proportional to $z^{-(1-\alpha)}$, firm revenue scales as $z^{(1-\alpha)(\theta-1)}$ rather than $z^{\theta-1}$. The relevant average productivity is therefore

$$\tilde{z} \equiv \left[\int_{z_{\min}}^{\infty} z^{(1-\alpha)(\theta-1)}\, \mathrm{d}G(z) \right]^{\frac{1}{(1-\alpha)(\theta-1)}}, \tag{B.31}$$

and under a Pareto distribution the scale factor becomes

$$\nu \equiv \left(\frac{k}{k - (1-\alpha)(\theta - 1)} \right)^{\frac{1}{(1-\alpha)(\theta-1)}}, \tag{B.32}$$

replacing the LMAC value $\nu = (k/(k-(\theta-1)))^{1/(\theta-1)}$. For foreign default exporters (no abatement), revenue scales as $z^{\theta-1}$ and the standard LMAC value of ν applies to that mass of firms.

The cutoff productivity for home exporters satisfies the same zero-profit condition as in the main text, with $c/z^{1-\alpha}$ in place of the LMAC marginal cost; the foreign xx-regime cutoff z^*_{xx} is defined analogously.

APPENDIX C.

Appendices to Chapter 3

C.1. Model Solutions

The return on an equity is given by by:

$$R_{i,t,t+1} = \frac{P_{i,t+1}}{P_{i,t}}.$$

Consequently, the log return is simply:

$$r_{i,t,t+1} = \ln P_{i,t+1} - \ln P_{i,t} = p_{i,t+1} - p_{i,t} + \Delta d_{t+1}$$

The adjustment for Δd_{t+1} is necessary as p denotes the log price-dividend ratio, not just the log price. The model is solved to find the log price-dividend ratio:

$$p_{i,t} = a_i + b_i x_t + e_i y_t$$

Where the expressions of the coefficients in terms of primitives are as follows:

$$\begin{aligned} a_i &= \ln \delta - \gamma\mu + \mu_d + \ln\left[1 + \bar{\lambda}\left(\exp\left\{(\gamma - \eta_i)\,\xi\right\} - 1\right)\right] \\ b_i &= -\gamma \\ e_i &= 1 \end{aligned}$$

Therefore, substituting for the log price-dividend ratio and for dividend growth in

returns:

$$r_{i,t,t+1} = -\left[a_i + b_i x_t + e_i y_t\right] + \left[\mu_d + y_t - \eta_i J_{t+1}\right].$$

For the expected return of the stock, we have:

$$E_t\left[R_{i,t,t+1}\right] = E_t\left[\exp\left\{r_{i,t,t+1}\right\}\right]$$
$$= \exp\{-\left[a_i + b_i x_t + e_i y_t + \left[\mu_d + y_t\right]\right\} \times \left[1 + \lambda\left(\exp\left\{-\eta_i\right)\xi\right\} - 1)\right],$$

where the last line follows from J_{t+1} only taking value $\xi \in (0,1)$ with probability λ and zero otherwise.

$$E_t\left[R_{i,t,t+1}\right] - R^f_{t,t+1} \simeq \gamma\,\mathrm{Cov}_t\left[r_{i,t,t+1}, \Delta c_{t+1}\right].$$

Substituting for consumption growth and the log return and dropping constant terms:

$$\gamma\,\mathrm{Cov}_t\left[r_{i,t,t+1}, \Delta c_{t+1}\right] = \gamma\,\mathrm{Cov}_t[-\eta_i J_{t+1}, -J_{t+1}].$$

Since $\mathrm{Var}_t\left[J_{t+1}\right] = \xi^2\lambda\left(1-\lambda\right)$, we obtain:

$$\gamma\,\mathrm{Cov}_t[-\eta_i J_{t+1}, -J_{t+1}] = \gamma\left[\eta_i\right]\xi^2\lambda\left(1-\lambda\right),$$

and therefore:

$$E_t\left[R_{i,t,t+1}\right] - R^f_{t,t+1} \simeq \gamma\eta_i\xi^2\lambda(1-\lambda)$$

C.2. Data

C.2.1. Sample

The following are the details on how we construct our analysis sample:

- 5,239 firms are identified with return data on at least three of the climate policy announcement dates
- 23 firms with no leverage information are removed
- In order to compute abnormal returns, I first need to get estimates of stock- level betas.I keep stocks for which there are at least 125 daily return observations for the year prior to at least three of the jump days. I lose 18 firms in this step.
- I remove 7 firms with no available NAICS2 code in the dataset.
- Finally, I link these firms with the text data from form 10-K. I end up with a sample of 3,894 stocks with a non-empty 10-K.

C.2.2. Cross-sectional Controls

Financial data for cross-sectional regressions are obtained from Compustat.

The control variables are as follows:

- Market Cap is the natural logarithm of market capitalization (price times shares outstanding) at the end of year.
- Book to Market is the book value divided by market cap and the end of the year.
- Leverage is the book leverage of the company.
- Invest/a represents the firm's capital expenditures divided by the book value of its assets.
- HHI is the Herfindahl concentration index of firms with respect to industry.
- PPE is the natural logarithm of the firm's property, plant and equipment
- SALESGR is the dollar change in annual firm revenues normalized by last month's market capitalization.
- EPSGR is the dollar change in annual earnings per share normalized by the firm's equity price.
- beta is the market beta of the firm calculated over the one year period using daily data.
- ROE is the firm's earnings performance, given by the ratio of its net yearly income divided by the value of its equity.
- MOM is the average of the most recent 12 months' returns on the stock.
- VOL is the standard deviation of returns based on past 12 months of monthly returns.

Following Bolton and Kacperczyk (2021), to eliminate the impact of outliers, I winsorize Book to Market, Leverage and Invest/a at the 2.5% level and MOM, VOL, SALESGR and EPSGR at the 0.5% level. Summary statistics for the variables are in Table A1.

C.2.3. Text preprocessing

I follow Davis, Hansen, and Seminario-Amez (2021) in processing the text from the 10Ks. First, 10Ks from 2011-2022 are scraped from EDGAR. Terms are created as follows:

- 4,237 phrases correspond to named entities that appear more than 25 times in the corpus. These are identified with the named entity recognizer (NER) from the Stanford NLP group.
- 26,729 additional multi-word expressions (MWE) are identified. In order to identify these, all words in the corpus are tagged using a part-of-speech tagger from the Stan-

	Mean	Median	sd
Market Cap	6.7	6.65	10.8
Book to Market	0.633	0.489	0.541
Leverage	0.371	0.342	0.316
Invest/a	0.034	0.018	0.052
HHI	0.0	0.342	0.316
PPE	6.612	5.598	8.236
SALESGR	-0.021	0.0176	0.448
EPSGR	-0.016	0.004	0.583
beta	1.048	1.026	0.821
ROE	-0.061	0.073	0.585
MOM	0.014	0.011	0.065
VOL	0.137	0.102	0.133

TABLE C.1. Summary Statistics

ford NLP group. Tag patterns likely to correspond to meaningful sentences are then tabulated. The final set of MWE is the set of resulting trigrams that appear more than 150 times in the corpus, and bigrams that appear more than 500 times.

The following standard steps complete the preprocessing:

- Lowercase all text (case-folding)
- Tokenize text by breaking it into individual terms
- Drop common words from a standard stop word list
- Drop any terms that appear in the Risk Factors text over fewer than 25 firms over the sample

After preprocessing there are 21,876 unique terms.

C.2.4. Climate Policy Announcement Dates

This table shows the 38 candidate climate policy dates from the initial 53 which are not included in the final set. The third column specifies the reason for which the candidate date was removed. The options are: no news coverage, confounded by other announcements, insignificant return response from brown industries.

TABLE C.2. Candidate Climate Policy Announcement Dates Removed

Announcement	Date	Reason Removed
Biden Executive Order to reduce ghg from power plants	11/05/23	No Coverage
Green New Deal reintroduced	20/04/23	Insignificant
Biden Executive Order to reduce air pollution	12/04/23	No Coverage
IPCC sixth assessment report	20/03/23	Insignificant
Biden Executive order to require federal contractors to disclose climate impact	14/11/22	No Coverage
House passage of IRA	12/8/22	Insignificant
Announcement of end of Manchin-Schumer negotiation	14/7/22	Cofounded
Manchin announces decision to vote against BBB	19/12/21	Confounded
Biden revokes Keystone Pipeline permit	09/06/21	Insignificant
Moratorium on new oil leases on federal land	27/01/21	Insignificant
Actual withdrawal from Paris agreement	04/11/20	Cofounded
Wheeler confirmed as EPA head	12/04/18	Insignificant
Trump plans to cut Obama's coal emissions standards	21/08/18	Confounded
Trump weakens fuel economy standards	24/08/18	Confounded
IPCC special report on 1.5 degrees	08/10/18	Insignificant
Trump announces US will leave Paris	01/06/17	Insignificant
Trump executive order reviving pipeline plans	24/01/17	Insignificant
EPA budget cut	01/03/17	Insignificant
Trump proposes Wheeler to EPA	26/07/17	Insignificant
Pruitt begins CPP appeal	09/10/17	Cofounded
US and China agree to ratify Paris	03/09/16	No Coverage
Trump nomination of Pruitt to EPA	07/12/16	Insignificant
Supreme Court blocks CPP	09/02/16	Insignificant
House rejects Obama's climate regulations	01/12/15	Insignificant
Senate blocks Obama's climate regulations	17/11/15	Cofounded
Obama vetoes push to kill climate regulations	24/02/15	Insignificant
Obama vetoes Keystone XL pipeline	24/02/15	Insignificant
Obama rejects Keystone XL pipeline	06/11/15	Cofounded
Bilateral climate agreement with Brazil	30/06/15	Cofounded
EPA announces rules on power plants	02/06/14	No Coverage
Obama announces CPP	18/06/14	Insignificant
US-China deal on carbon cuts	11/11/24	Cofounded
Third national climate assessment	06/05/14	Insignificant
Obama announcement of Climate Action Plan	25/06/13	Insignificant
Warsaw COP walkouts	20/11/13	Cofounded
IPCC report	27/09/13	Insignificant
Obama executive order for stricter fuel economy standards	15/10/12	Insignificant
Doha COP	08/12/12	Insignificant

C.3. Results

C.3.1. Emissions

TABLE C.3. Emissions Regression Results

	Dependent Variable: Emissions		
	Emissions in Tonnes	Emissions Intensities	Reported Emissions
	(1)	(2)	(3)
z	1,163,635.000***	124.047***	1,533,491.000***
	(144,015.300)	(32.851)	(336,516.500)
Constant	1,061,955.000***	174.999***	2,323,302.000***
	(132,421.900)	(31.582)	(367,936.300)
Observations	2,149	1,878	797
R^2	0.030	0.008	0.025
Adjusted R^2	0.029	0.007	0.024
Residual Std. Error	6,121,662.000 (df = 2147)	1,359.725 (df = 1876)	9,756,542.000 (df = 795)
F Statistic	65.285*** (df = 1; 2147)	14.259*** (df = 1; 1876)	20.766*** (df = 1; 795)

Note: This table presents the results of the cross sectional regression with the dependent variable being emissions and the independent variable emissions. Column 1 presents the case where the dependent variable is Refinitiv's estimate of each firm's total emissions in Tonnes. Column 2 instead takes emissions divided by revenue (in millions of dollars). Column 3 restricts the sample to only those firms who directly report their emissions. ***, **, and * denote significance at the 1%, 5%, and 10% level, respectively.

	Mean	Median	sd
Emissions In Tonnes (Estimated)	1,141,675	17,392	6,212,592
Emissions scaled by Revenue (In Millions)	188.58	17.83	1364.52
Reported Emissions	2,898,664	164,018	9,876,934

This table presents summary statistics for the emissions data from Refinitiv employed in the cross sectional regressions.

TABLE C.4. Summary Statistics

C.3.2. Predictive Power

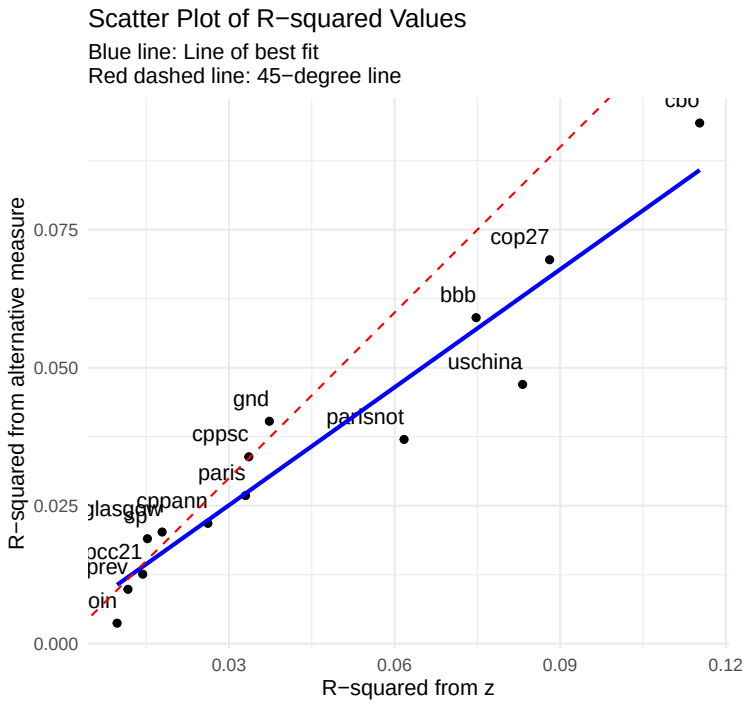


FIGURE C.1

This figure shows the R-squared values from a regression of abnormal returns on exposure score, market cap, and industry. The x axis shows the R squared from the regression using my exposure score z. The y axis uses the climate regulatory risk exposure score from Sautner et al. (2023)

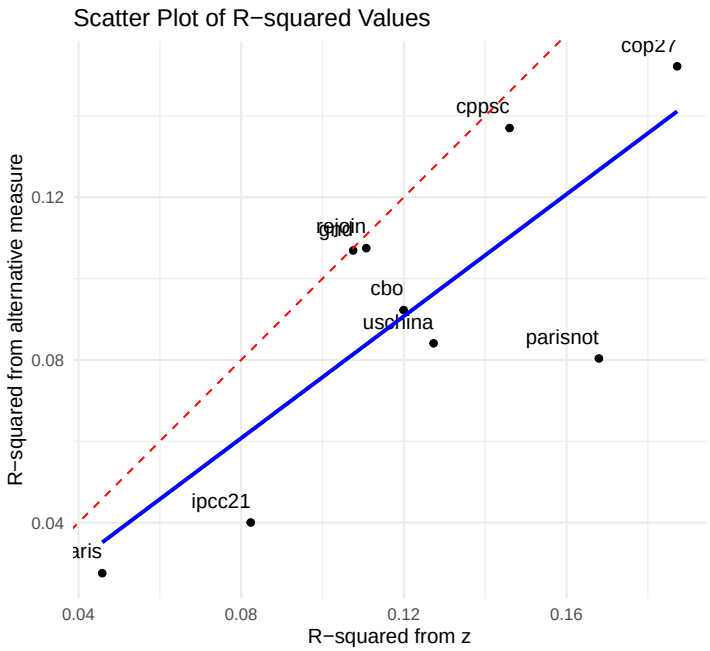


FIGURE C.2. Predictive power of exposure score trained on a subset of the announcement dates.

This figure shows the R-squared values from a regression of abnormal returns on exposure score, market cap, and industry. The x axis shows the R squared from the regression using my exposure score z trained on a randomly selected subset of the climate policy announcement dates and tested on the other half. The y axis uses the climate regulatory risk exposure score from Sautner et al. (2023).

C.3.3. Sign Restriction SVAR

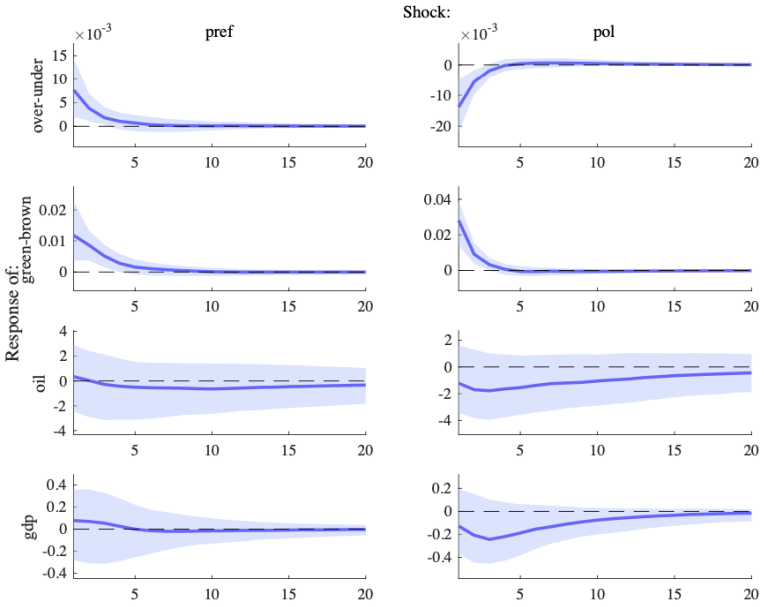


FIGURE C.3. SVAR IRFs

Note: This figure presents the IRFs from the policy and preference shocks identified via the sign restriction SVAR

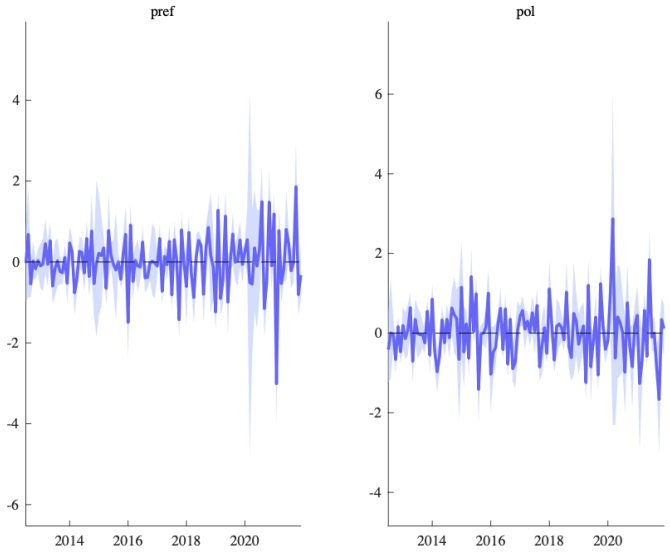


FIGURE C.4. Structural Policy and Preference Shocks

This figure presents the structural policy and preference shocks identified by the sign restriction VAR

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