

Environmental Policy Instruments and Uncertainty Under Free Trade and Capital Mobility

J. Scott Holladay Mohammed Mohsin Shreekar Pradhan *

Department of Economics, University of Tennessee

Knoxville, TN

Abstract

We develop a dynamic stochastic general equilibrium model for an open economy and evaluate three environmental policy instruments: cap-and-trade, pollution tax and emissions intensity standard, in the face of uncertainty. We evaluate the performance of these policies in terms of volatility of consumption, labor supply, pollution emissions, output and trade flows in response to productivity or abatement cost shocks. Cap-and-trade policies dampen the business cycle while intensity targets smooth the impact of reduced abatement costs. Cap-and-trade policies have a significant impact on international trade across business cycle while pollution taxes have the largest impact on trade after an abatement cost shock.

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*Email addresses: Holladay (jhollad3@utk.edu), Mohsin (mmohsin@utk.edu) and Pradhan (spradhan@vols.utk.edu). Acknowledgment: We would like to thank William Neilson, Don Clark, Don Bruce and Garth Heutel for their valuable comments. Thanks are also due to the participants of Camp Resources 2014.

1 Introduction

Since Weitzman (1974)'s seminal article, economists have been weighing the merits of different environmental policy instruments. More recently the ability of environmental policy to respond to the business cycle has been an important metric in evaluating the policy instrument choice. Pizer (2005), Webster et al. (2010) and Ellerman and Wing (2003) compare policies that index emissions levels to output, known as intensity targets, to pollution taxes and cap-and-trade policies.¹ Fischer and Springborn (2011) and Angelopoulos et al. (2010) are among the few that have compared the performance of emission caps, emission taxes and indexed standards with uncertain economic growth.

The results suggest that cap-and-trade policies reduce the intensity of the business cycle relative to a pollution tax. Intensity based standards may lower expected cost and provide lower volatility than business as usual scenario. At the same time the ability of environmental policy instruments to respond to uncertain abatement costs has been of increasing interest. There is evidence that the abatement costs of environmental policy are often overestimated (Harrington et al., 2000) and abatement costs for reducing carbon emissions are highly uncertain (Fischer and Morgenstern, 2006). Hoel and Karp (2001) and Newell and Pizer (2003) among many other analyze the relative merits of different environmental policy instruments in the face of uncertain abatement costs. The results suggest that pollution taxes are most efficient for controlling emissions, but the results are somewhat sensitive to the type of shock (see Parsons and Taschini (2013)).

In this paper we analyze the properties of environmental policy instruments in the face of uncertainty for an economy that is open to international trade and capital mobility. We first develop a small open economy (SOE) dynamic stochastic general equilibrium (DSGE) model that incorporates three static environmental policy instruments: cap-and-trade, pollution tax and emission intensity standard. In our model we

¹See Peterson (2008) and Hepburn (2006) for reviews of this literature.

introduce exogenous temporary productivity shocks to simulate business cycles and an exogenous temporary abatement cost shock to represent reduced costs of clean inputs (for example cheap natural gas due to fracking). We then compare impacts on welfare, pollution levels, outputs, consumption, investment, supply of labor and trade flows in the economy across the pollution tax, cap-and-trade policy and emissions intensity standard.

Our results suggest that the preferred environmental policy instrument varies with the source of uncertainty. The cap-and-trade policies are best suited to smooth the business cycle while pollution taxes and intensity targets are most effective in the face of abatement cost shocks. We find that cap-and-trade and pollution tax policies have similar welfare impact in both closed and open economies. However, under uncertain economic growth in an open economy a cap-and-trade policy dominates a pollution tax policy which is in contrast to the existing literature which suggests superiority of pollution tax over cap-and-trade in welfare. We also find that the magnitude of the productivity shock's impact on the economy swamps the impact of an abatement cost shock. This suggests that a cap-and-trade policy, which performs best in the face of productivity shocks, should be the preferred policy instrument in most cases. In our model, calibrated to Canadian data, a one standard deviation productivity shock has nearly an order of magnitude larger impact than a one standard deviation abatement cost shock. The result is intuitive, a productivity shock has an economy wide effect while an abatement cost shock merely reduces the cost of reducing pollution emissions for a given level of output. As long as the impact of a productivity shock dominates the impact of an abatement cost shock the cap-and-trade policy will be the most attractive policy instrument for limiting pollution emissions.

The existing literature mainly adopts a closed economy framework to address these concerns. The economies in the contemporary world are more than ever financially integrated with each other. In a world with almost perfect capital mobility and in-

ternational trade flows, the domestic economy is no longer fully constrained by its own resources.² Any fluctuation in income will induce a rational consumer or welfare maximizer to adjust its intertemporal savings and investment decisions in order to smooth consumption and welfare.³ The agent could borrow (capital inflow) or invest in foreign assets (capital outflow) to maximize her lifetime utility. Additionally, our framework allows us to evaluate the impact of environmental policy instrument choice on trade and capital flows in the face of uncertainty.⁴ We find that a cap-and-trade policy smooths the impact of a productivity shock on trade flows reducing the export boom and bust cycle that an unregulated economy faces. The intensity standard and to a lesser extent the pollution tax, reduce the variation associated with an abatement cost shock. As with the domestic economic results, the international economic variables respond much more strongly to a productivity shock than an abatement cost shock. This provides further evidence in favor of cap-and-trade policies based on their ability to smooth trade and capital flows and reduce international debt in response to shocks. An additional benefit of the proposed framework is our ability to analyze the impact of domestic environmental regulation on the rest of the world's economic and environmental performance. While all environmental policy instruments are associated with increased imports and pollution emissions in foreign countries in our model, the cap-and-trade program mitigates this effect relative to the other policy instruments.

There is a long literature evaluating the environmental policy instrument choices that regulators face. Several studies have considered environmental policy instruments in the presence of uncertainty in both benefit and cost when they are correlated (Quirion, 2010; Shrestha, 2001; Stavins, 1996). Antoniou et al. (2012); Heuson (2010)

²For example, domestic consumption is not completely constrained by domestic production alone and national investment is not solely determined by domestic savings only.

³In a closed economy the agent adjusts the supply of labor in response to changes in the relative price of leisure and the productivity of labor. In an open economy, however, with an access to foreign assets/debts via international capital flows, the relative price of leisure and the productivity of labor are now affected by the exogenous world's real rate of return.

⁴This is like studying the effects of various fiscal policies in an open economy and their importance in macroeconomic stabilization.

and Quirion (2005) have considered choice of environmental policies on both uncertain economic growth and uncertain abatement costs. Antoniou et al. (2012) have considered the instruments under international duopoly in a static model while Heuson (2010) has considered the choice under uncertainty in market power and abatement costs. Quirion (2005) considers the choice of environmental instruments under both uncertain economic growth and abatement cost under autarky. To date this literature has either focused on either economies under autarky or in a static modeling framework with a focus on strategic interaction among agents and thus ignore an additional channel of international trade and capital mobility that may smooth the intensity of business cycle shock or abatement cost breakthrough.

There is considerable evidence that environmental regulation can impact international trade flows. Copeland (1994) and Copeland and Taylor (2003) recognize the interaction between international trade and pollution in a small open economy. Ederington et al. (2005) shows that environmental regulations have a significant impact on trade flows between developed and developing nations particularly in more mobile industries. McAusland (2008) analyzes the impact of environmental regulation on international trade flows while comparing pollution associated with production and consumption. This literature relies on a static model and assumes a constant marginal utility from consumption. In our paper, we relax those assumptions to incorporate intertemporal effects of environmental regulation under uncertainty. The intertemporal effects are important in consumers' investment decisions under uncertainty since regulations like cap-and-trade fixes the amount of emissions while inducing uncertain outcomes in the cost of abatement. Emission tax fixes the cost of abatement while inducing uncertain outcomes in emissions. These effects are even more important in economies that are open to international trade and capital mobility because of additional channel for investment. We extend this literature by showing that the choice of environmental policy instruments affects the levels of trade and investment flows.

Most similar to our study are three recent papers that examine the robustness of different environmental policy instruments to business cycle shocks. Heutel (2012) evaluates the optimal evolution of dynamic environmental regulation across the business cycle and finds that the optimal carbon taxes and cap-and-trade policies to be pro-cyclical. We employ a static exogenous environmental regulation to evaluate how economies respond to the exogenous environmental regulation rather than evaluate the path for optimal policy that may not be implemented by policy makers during business cycle peaks and troughs. Fischer and Springborn (2011) and Angelopoulos et al. (2010) evaluate carbon taxes, emissions caps and emissions intensity standards across the business cycle. Their results suggest that emissions caps reduce the intensity of productivity shocks relative to an emission tax while emission tax is more volatile. Also they find that emission intensity has lower volatility than business as usual and is also welfare enhancing. We expand on this approach by allowing endogenous abatement and incorporating a labor-leisure choice in a small open economy model. In a review article Fischer and Heutel (2013) describes the emerging literature employing real business cycle models to evaluate environmental policy. These models do not include international trade or investment. We extend these results by comparing exogenous environmental policy instruments across the business cycle for economies that are open to international trade and capital mobility.

The rest of the paper is organized as follows. Section 2 outlines the model and functional forms, Section 3 solves the model in the steady state and evaluates the policies when there is no uncertainty, and Section 4 presents the numerical analysis of the model and evaluates environmental policy instruments in the face of economic growth and abatement cost uncertainty. Section 5 takes advantage of the proposed framework to evaluate the impact of unilateral changes in environmental regulation in one country on global emissions. Section 6 concludes.

2 The Model

We consider an economy that has a continuum of households with identical preferences. Households make consumption and labor/leisure decisions to maximize lifetime expected utility. The economy is open to trade and capital which are allowed to flow internationally. The role of the domestic government is limited to implementing an environmental policy and redistributing revenues, if any, to the households in a lump-sum fashion. Output is either consumed, invested domestically or exported. If domestic consumption exceeds production, the economy imports from the rest of the world. We assume our economy is small compared to the rest of the world and thus, agents are price takers. Households do not control the stock of pollution which affects their welfare level, but firms can abate emissions. We solve the problems of households and firms separately.

Households' problem

With capital mobility, households can borrow internationally but face an upward-sloping supply schedule due to country-specific risk premium that increases with the level of debt. Following Schmitt-Grohé and Uribe (2003), we employ a debt-elastic interest rate:

$$r_t = r^* + P(\exp^{\tilde{d}_t - \bar{d}} - 1) \quad (1)$$

where r^* is the exogenous interest rate in international capital markets, $P(\cdot)$ is the economy's risk premium, \tilde{d}_t is the aggregate debt of the economy and \bar{d} is the steady state debt level. Borrowing cost are increasing in the stock of debt issued ($P' > 0$). For a representative economy, we have $\tilde{d}_t = d_t$.

The representative household maximizes the present value of her expected lifetime utility:

$$\max_{c_t, h_t} E_0 \sum_{t=0}^{\infty} \beta^t U(c_t, h_t, S_t) \quad (2)$$

where $\beta \in (0, 1)$ is the fixed subjective discount factor, c_t is consumption, h_t represents

the amount of labor supplied by the agent and S_t is the stock of pollution. We assume that the representative agent is endowed with one unit of time and we abstract from population growth. Thus, $1 - h_t$ represents leisure. Consistent with Copeland (1994), the stock of pollution is treated as a public bad that lowers utility but it has no effect on production. The functional form of the utility and time preference satisfy: $U_c > 0$, $U_h < 0$, $U_{cc} < 0$, $U_{hh} < 0$ and $U_{ch} > 0$.

The household is subject to the following budget constraint:

$$d_t = (1 + r_{t-1})d_{t-1} + c_t + i_t + \Phi(k_t - k_{t-1}) - w_t h_t - R_t k_{t-1} - G_t \quad (3)$$

where d_t is the household's stock of foreign debt, k_t is the stock of capital, i_t is investment and $\Phi(\cdot)$ is investment related adjustment cost (with $\Phi(0) = 0$, $\Phi'(0) = 0$), w_t is the wage per unit labor supplied to firms, R_t is the rental per unit of capital supplied to firm and G_t is a lumpsum transfer from government, if any.

Capital stock evolves as:

$$k_t = i_t + (1 - \delta)k_{t-1} \quad (4)$$

where δ is the depreciation rate.

The representative household chooses processes $[c_t, h_t, k_t, d_t]_{t=0}^{\infty}$ to maximize her life-time expected utility Eq.(2) subject to the constraint Eq.(3), (4), a no-ponzi constraint, $\lim_{j \rightarrow \infty} E_t \left(\frac{d_{t+j}}{\prod_{s=1}^j (1 + r_s)} \right) \leq 0$, $k_0 > 0$ and $d_0 \geq 0$ and $S_0 > 0$. With λ_{1t} being the Lagrangian multiplier for the budget constraint, households' maximization problem can be represented by the following Lagrangian:

$$\begin{aligned} \max_{c_t, h_t, k_t, d_t} \mathcal{L} = E_t \sum_{t=0}^{\infty} \beta^t [& U(c_t, h_t, S_t) + \lambda_{1t} [d_t - (1 + r_{t-1})d_{t-1} - c_t - k_t + (1 - \delta)k_{t-1} \\ & - \Phi(k_t - k_{t-1}) + w_t h_t + R_t k_{t-1} + G_t]] \end{aligned} \quad (5)$$

The first order conditions are:

$$c_t : U_{c_t}(c_t, h_t, S_t) = \lambda_{1_t} \quad (6)$$

$$h_t : -U_{h_t}(c_t, h_t, S_t) = \lambda_{1_t} w_t \quad (7)$$

$$k_t : \lambda_{1_t} [1 + \Phi'(k_t - k_{t-1})] = \beta E_t [\lambda_{1_{t+1}} [(1 - \delta + R_{t+1} + \Phi'(k_{t+1} - k_t))] \quad (8)$$

$$d_t : \lambda_{1_t} = \beta E_t \lambda_{1_{t+1}} (1 + r_t) \quad (9)$$

These are standard Euler equations. Eq. (6) shows that households' optimal consumption level occurs when marginal utility from consumption is equal to the marginal utility from income. In Eq. (7), we see that households optimally supply labor when marginal utility from leisure is equal to wage per unit labor supplied. Eq. (8) shows that households optimally invest one unit of capital when marginal cost of the investment (in terms of utils) is equal to the expected present value of marginal benefit of the investment next period. The marginal cost of investment is shown in the LHS of Eq. (8) and the expected present value of marginal benefit of investment next period is shown in RHS of the equation. Likewise, Eq. (9) gives us the cost and benefit of borrowing a unit of debt. The LHS of Eq. (9) is the utility the agent receives from one unit of borrowing while the RHS is the expected present value of the cost of the repayment of debt (in utils).

Firm's problem

We model the representative firm's problem as follows. The representative firm maximizes profit:

$$\pi_t = x_t - w_t h_t - R_t k_{t-1} \quad (10)$$

where $x_t = e_t^\xi y(A_t, k_{t-1}, h_t)^{1-\xi}$ and e_t is the amount of emissions, modeled here as the joint output of production y_t , (i.e. output before abatement), and $\xi(0 \leq \xi < 1)$ is

the fixed emissions intensity per unit of goods output (or equivalently the elasticity of emissions w.r.t. the net output). For any emission tax below ξ firms do not find it cost effective to abate emissions and thus choose not to abate. A_t is (exogenous) total factor productivity, k_t is the stock of capital, i_t is investment and $\Phi(\cdot)$ is investment related adjustment cost (with $\Phi(0) = 0$, $\Phi'(0) = 0$).

The production function models pollution emissions as a joint output of production. Firms have the opportunity to respond to an environmental policy by abating emissions. For simplicity, we model the abatement technology using the final good output as an input as in Copeland and Taylor (2003).⁵ Production of output (y_t) generates pollution emissions (e_t) as a joint output of production. Units of emissions are indexed so that, in the absence of abatement, one unit of production generates one unit of emissions. In that case, output is given by $x_t = y(A_t, k_{t-1}, h_t)$ and emissions are $e_t = y_t$. If firms choose to abate, output is given by $x_t = e_t^\xi y(A_t, k_{t-1}, h_t)^{1-\xi}$, $0 \leq \xi < 1$. If we define $0 \leq \theta_t \leq 1$ as the fraction of final output spent on abatement of emissions, then output (x_t) net of abatement expenditure can be written as:

$$x_t = (1 - \theta_t)y_t \tag{11}$$

Following Copeland and Taylor (2003), we can then model emissions as:

$$e_t = (1 - \theta_t)^{\frac{1}{\xi}}y_t \tag{12}$$

This equation links expenditure on abatement to the level of emissions. The higher the abatement, the lower will be the emissions. This approach assumes that abatement has the same factor intensities as final goods in production. As ξ increases, abatement becomes less effective and more final good output is required to reduce emissions by the

⁵This approach has been used in a series of influential general equilibrium trade and environment papers including Copeland (1994), Copeland and Taylor (1994) and Antweiler et al. (2001) among others.

same amount. Plugging $(1 - \theta_t)$ from Eq.(12) into Eq.(11), we obtain the production function used in Eq.(10). This structure of emission modeling allows for a corner solution. For example, if the government does not have an environmental policy then firms will choose not to abate. With zero abatement ($\theta_t = 0$), $x_t = y_t$ and $e_t = y_t$ and emissions are proportional to output.

The no abatement condition holds if the marginal cost of emissions is less than ξ . That is, if the marginal cost of emitting an additional unit of pollution exceeds the value of final output required to abate a unit of emissions then there will be no abatement. An interior solution under an emission tax policy requires the emission tax level to be strictly higher than the parameter ξ . As Copeland and Taylor (2003) notes, pollution can also be treated as a joint input of production for analytical convenience. Polluters can reduce the emissions intensity of output by substituting more factors and adopting less-polluting production techniques.⁶

To address the externalities associated with pollution emissions we assume government imposes an environmental policy $CAP(y_t)$. For now, we model a cap-and-trade policy (emissions quota) where a permit is required to emit each unit of pollution. The number of permits is exogenously chosen to reduce emissions and could be sub-optimal.⁷ We assume that the environmental policy is binding on firms:

$$CAP(y_t) = e_t \tag{13}$$

and the Lagrangian of the representative firm's problem is:

$$\max_{h_t, k_t, e_t} \mathcal{L} = E_t \sum_{t=0}^{\infty} \beta^t \left[e_t^\xi y_t(A_t, k_{t-1}, h_t)^{1-\xi} - w_t h_t - R_t k_{t-1} + \hat{\lambda}_{2t} (CAP(y_t) - e_t) \right] \tag{14}$$

⁶Copeland and Taylor (2003) and Siebert et al. (1980) show that under some reasonable regularity conditions you can invert the production function to treat pollution as an input.

⁷Heutel (2012) assumes efficient environmental policy and analyzes how that optimal policy should evolve across the business cycle. We focus on the effectiveness of a static policy across the business cycle.

where $\hat{\lambda}_{2_t}$ is the effective shadow price of the policy constraint.

The first order conditions are:

$$h_t : (1 - \xi) e_t^\xi y_t^{-\xi} y_{h_t}(A_t, k_{t-1}, h_t) + \hat{\lambda}_{2_t} Cap_{y_t}(y_t) y_{h_t}(A_t, h_t, k_{t-1}) = w_t \quad (15)$$

$$k_t : (1 - \xi) e_{t+1}^\xi y_{t+1}^{-\xi} y_{k_t}(A_{t+1}, k_t, h_{t+1}) + \hat{\lambda}_{2_{t+1}} Cap_{y_{t+1}}(y_{t+1}) y_{k_t}(A_{t+1}, k_t, h_{t+1}) = R_{t+1} \quad (16)$$

$$e_t : \xi e_t^{\xi-1} y_t(A_t, k_{t-1}, h_t)^{1-\xi} = \hat{\lambda}_{2_t} \quad (17)$$

These are also standard Euler equations for the firms' problem. Firms choose factor inputs labor (Eq. (15)) and capital (Eq. (16)) as per their marginal factor return. Eq.(17) shows that firm optimally abates such that the marginal cost of emission abatement is equal to the shadow price of environmental policy.

Plugging w_t and R_{t+1} from the firm's problem into the household's problem, we get the following equilibrium conditions for a small open economy model with international trade, capital mobility and an emission externality:

$$U_{c_t}(c_t, h_t, S_t) = \lambda_{1_t} \quad (18)$$

$$-U_{h_t}(c_t, h_t, S_t) = \lambda_{1_t} (1 - \xi) e_t^\xi y_t^{-\xi} y_{h_t} + \lambda_{2_t} CAP_{y_t} y_{h_t} \quad (19)$$

$$\lambda_{1_t} [1 + \Phi'(k_t - k_{t-1})] = \beta E_t [\lambda_{1_{t+1}} [(1 - \xi) e_{t+1}^\xi y_{t+1}^{-\xi} y_{k_t} + 1 - \delta + \Phi'(k_{t+1} - k_t)] + \lambda_{2_{t+1}} CAP_{y_{t+1}} y_{k_t}] \quad (20)$$

$$\lambda_{1_t} = \beta E_t \lambda_{1_{t+1}} (1 + r_t) \quad (21)$$

$$\xi e_t^{\xi-1} y_t^{1-\xi} = \frac{\lambda_{2_t}}{\lambda_{1_t}} \quad (22)$$

where we replace $\hat{\lambda}_{2_t} = \frac{\lambda_{2_t}}{\lambda_{1_t}}$.

Using firm's zero profit condition in an equilibrium i.e. $w_t h_t + R_t k_{t-1} = e_t^\xi y(A_t, k_{t-1}, h_t)^{1-\xi}$,

we obtain the resource constraint in an open economy as follows:

$$d_t = (1 + r_{t-1})d_{t-1} - e_t^\xi y_t^{1-\xi} + c_t + i_t + \Phi(k_t - k_{t-1}) \quad (23)$$

Note that $G_t = 0$ if there is no environmental policy or the environmental policy is a cap-and-trade policy or an intensity target policy. Under those policies firms are not subject to any collection from government. In these cases, the transfer G_t remains zero. However, in the case of emission tax policy, government collects emission tax revenue from firms. In our model it is represented by $\hat{\lambda}_{2t}e_t$ in Eq. (14). We assume government has a balanced budget each period then the transfer $G_t = \hat{\lambda}_{2t}e_t$. From firm's zero profit condition, then we obtain $w_t h_t + R_t k_{t-1} = e_t^\xi y(A_t, k_{t-1}, h_t)^{1-\xi} - \hat{\lambda}_{2t}e_t$. So, G_t is washed out from the economy's resource constraint.

The other market clearing condition is the environmental policy constraint:

$$CAP(y_t) = e_t \quad (24)$$

The trade balance (tb_t) is defined as domestic production minus domestic absorption:

$$tb_t = e_t^\xi y_t^{1-\xi} - c_t - i_t - \Phi(k_t - k_{t-1}) \quad (25)$$

The trade balance could be positive (net exporter), negative (net importer) or zero. Capital flow is captured by the net asset position of the economy. Thus the current account is given by:

$$ca_t = -(d_t - d_{t-1}) \quad (26)$$

Note that the price of the domestic good is the numeraire in this model and all variables thus in the model are in real (in terms of domestic goods). In other words, if the cost of production of the good goes up then consumption, investment etc. will be expensive in real terms.

Finally, we assume total factor productivity, A_t , to have the following auto-regressive process:

$$\log A_t = \rho \log A_{t-1} + \epsilon_t \quad (27)$$

where, $0 < \rho < 1$ is the autocorrelation coefficient that captures the persistence of the productivity shock. ϵ_t is a normally distributed innovation with mean 0 and the standard deviation of σ_A .

2.1 The Model Under Autarky

Under autarky, there is no international flow of goods and financial assets across countries. Households' decisions are constrained by domestic resources. Output is either consumed or invested. The budget constraint of the representative household is thus:

$$w_t h_t + R_t k_{t-1} + G_t = c_t + i_t + \Phi(k_t - k_{t-1}) \quad (28)$$

The model under autarky is implemented as a special case of the proposed model in which the trade balance and foreign debt are constrained to be equal to zero at any given time t . Under autarky, the representative household chooses a process $[c_t, h_t, k_t]_{t=0}^{\infty}$ so as to maximize the life-time expected utility (Eq.(2)) subject to the constraint Eq.(28), (4), a no-ponzi constraint, $k_0 > 0$, and $S_0 > 0$. The firm's problem is same under autarky. As in an open economy, from firm's zero profit condition, the resource constraint under autarky is:

$$e_t^\xi y_t^{1-\xi} = c_t + i_t + \Phi(k_t - k_{t-1}) \quad (29)$$

Assuming the environmental policy is binding, we obtain the optimal equations similar to Eq. (18), (19), (20), (22) and market clearing constraints: Eq.(29) and Eq.(24). Under autarky, the real interest rate is determined by domestic financial

market through the effective marginal product of capital.

2.2 Functional Forms

We employ a constant relative risk aversion (CRRA) utility function as is standard in the literature,⁸ which is separable in the stock of pollution and non-separable in consumption and leisure.

$$U(c_t, h_t, S_t) = \frac{[c_t^\alpha (1 - h_t)^{1-\alpha}]^{1-\sigma} - 1}{1 - \sigma} - D \frac{S_t^{1+\sigma} - 1}{1 + \sigma} \quad (30)$$

where, α is the elasticity of consumption and σ is the relative risk aversion parameter, D (with $0 \leq D \leq 1$) is intensity of dis-utility from pollution.⁹

We employ Cobb-Douglas production function with constant returns to scale and thus, $y(A_t, k_{t-1}, h_t) = A_t k_{t-1}^{\alpha_1} h_t^{1-\alpha_1}$. We use the following form for the adjustment cost of investment: $\Phi(k_t - k_{t-1}) = \frac{\phi}{2}(k_t - k_{t-1})^2$, where $\phi(> 0)$ is an adjustment shift parameter.

The stock of pollution evolves according to $S_t = \rho_s S_{t-1} + e_t$ where ρ_s is the autocorrelation coefficient of stock of pollution (pollution persistency parameter). For example, radioactive pollution would have $\rho_s \approx 1$ (permanent effect) while noise pollution has $\rho_s = 0$ (only instantaneous effect). In this model we will have $0 < \rho_s < 1$. The functional form of the $CAP(y_t)$ depends upon the type of environmental policy being imposed.

⁸See Angelopoulos et al. (2010) for example.

⁹Fischer and Springborn (2011) models utility as unaffected by pollution. We show in appendix that whether and how pollution enters the utility function has a significant impact on the evaluation of environmental policy instruments.

3 Steady State Analysis

This section solves for the response of the economy to the introduction of each of the selected policies in the absence of a productivity shock. In the steady state, there is no uncertainty in the economy and the system is in long-run equilibrium. So, we abstract from using time subscripts. We begin with the open economy and in the appendix we describe the closed economy counterpart.

3.1 Under Trade and Capital Mobility

Incorporating the functional forms in Eq.(18), (19), (20), (21) and (22) we have the following equations that will hold in the steady state:

$$\frac{\alpha}{c}(c^\alpha(1-h)^{1-\alpha})^{1-\sigma} = \lambda_1 \quad (31)$$

$$\frac{h}{1-h} = \frac{\alpha(1-\alpha_1)}{1-\alpha} \frac{\left((1-\xi) \left(\frac{e}{y}\right)^\xi + \hat{\lambda}_2 CAP_y \right)}{\frac{c}{y}} \quad (32)$$

$$\frac{k}{y} = \alpha_1 \frac{\left((1-\xi) \left(\frac{e}{y}\right)^\xi + \hat{\lambda}_2 CAP_y \right)}{\frac{1}{\beta} - 1 + \delta} \quad (33)$$

$$\frac{1}{\beta} = 1 + r^* \quad (34)$$

$$\frac{e}{y} = \left(\frac{\xi}{\hat{\lambda}_2} \right)^{\frac{1}{1-\xi}} \quad (35)$$

In the steady state the market clearing condition (Eq.23) can be rewritten by dividing through by output:

$$\frac{c}{y} = \left(\frac{e}{y} \right)^\xi - \delta \frac{k}{y} - r^* \frac{d}{y} \quad (36)$$

With these equations we can obtain the reduced form for ratios for each economic variable w.r.t. output and use those ratios to evaluate the effects across environmental

policies. The ratios can help develop intuition that underlies much of the stochastic analysis.

No policy

In the absence of environmental policy, the effective shadow price of the environmental policy constraint ($\hat{\lambda}_2$) is zero and there is no abatement technology ($\xi = 0$). Representative households choose the level of outputs that maximizes their welfare. In this case, emissions generated will be $e = y$ assuming each unit of output is associated with one unit of pollution. That produces a capital-output ratio of $\frac{k}{y} = \frac{\alpha_1}{r^* + \delta}$. In equilibrium the ratio decreases with an increase in the exogenous interest rate in international capital market. With higher interest rates households will invest in foreign assets and domestic capital will decrease due to the capital flight. The capital-output ratio will increase in elasticity of capital w.r.t. output since the increase in the elasticity will increase the rate of return on domestic investment.

From Eq.(36), we have $\frac{c}{y} = 1 - \frac{\delta\alpha_1}{r^* + \delta} - r^* \frac{d}{y}$ under no policy. We rewrite the consumption-output ratio as $\frac{c + r^*d}{y} = 1 - \frac{\delta\alpha_1}{r^* + \delta}$, with parameterization such that $0 < \frac{k}{y} < 1$ is a constant in the steady state, any increase in the debt-output ratio will have to be matched by decreases in the consumption-output ratio. An increase in the debt level will require more resources be allocated to service the debt. As a result, consumption-output ratio will decline. Increases in the exogenous interest rate have an ambiguous effect on consumption. It decreases through the income effect arising from the increase in debt servicing while it increases through the substitution effect arising due to more capital outflows which will reduce domestic investment.¹⁰

We find the labor-leisure ratio from Eq.(32), $\frac{h}{1-h} = \frac{\alpha}{1-\alpha} \frac{(1-\alpha_1)}{\frac{c}{y}} = \frac{\alpha}{1-\alpha} \frac{(1-\alpha_1)}{1 - \frac{\delta\alpha_1}{r^* + \delta} - r^* \frac{d}{y}}$. Increases in debt are associated with increases in employment in this economy since more output is needed. The labor leisure ratio increases with an increase in the ratio

¹⁰For our parameterization to Canadian data, based on Schmitt-Grohé and Uribe (2003), we find $\frac{\delta\alpha_1}{(r^* + \delta)^2} > \frac{d}{y}$ and thus, the substitution effect dominates which results an increase in consumption.

of marginal elasticity of consumption to leisure. Households with more consumption expenditure will have less leisure and thus will have more labor supply. The ratio increases with an increase in elasticity of labor in production which is obvious. With an increase in r^* , consumption-output increases and as a result labor-leisure ratio decreases.

Cap and Trade

Under a cap-and-trade system, the government imposes a fixed cap on emissions to regulate pollution. In this policy, the emission is bounded by $e = CAP$ and $CAP_y = 0$. This provides capital-output ratio of $\frac{k}{y} = \frac{\alpha_1(1-\xi)(\frac{CAP}{y})^\xi}{r^* + \delta}$ and consumption-output ratio of $\frac{c}{y} = \left(\frac{CAP}{y}\right)^\xi \left(1 - \frac{\delta\alpha_1(1-\xi)}{r^* + \delta}\right) - r^*\frac{d}{y}$. We find the labor-leisure ratio $\frac{h}{1-h} = \frac{\alpha}{1-\alpha} \frac{(1-\xi)(1-\alpha_1)(\frac{CAP}{y})^\xi}{\left(\frac{CAP}{y}\right)^\xi \left(1 - \frac{\delta\alpha_1(1-\xi)}{r^* + \delta}\right) - r^*\frac{d}{y}}$. From Eq.(35), we have $\frac{e}{y} = \frac{CAP}{y} = \left(\frac{\xi}{\lambda_2}\right)^{\frac{1}{1-\xi}}$.

Then, we can rewrite the consumption-output ratio $\frac{c}{y} = \left(\frac{\xi}{\lambda_2}\right)^{\frac{\xi}{1-\xi}} \left(1 - \frac{\delta\alpha_1(1-\xi)}{r^* + \delta}\right) - r^*\frac{d}{y}$

and capital-output ratio $\frac{k}{y} = \frac{\alpha_1(1-\xi)\left(\frac{\xi}{\lambda_2}\right)^{\frac{\xi}{1-\xi}}}{r^* + \delta}$. Likewise, the labor-leisure ratio $\frac{h}{1-h} = \frac{\alpha}{1-\alpha} \frac{(1-\xi)(1-\alpha_1)}{\left(1 - \frac{\delta\alpha_1(1-\xi)}{r^* + \delta}\right) - r^*\frac{d}{y} \frac{\xi}{\left(\frac{\xi}{\lambda_2}\right)^{\frac{\xi}{1-\xi}}}}$. Since, $\frac{CAP}{y} < 1$ and $(1 - \xi) < 1$, it is evident from above

that capital-output ratio is smaller than in no policy case while we cannot sign the difference in consumption-output and labor-leisure ratios. The relatively smaller capital-output ratio increases consumption-output ratio but, in the other hand, the debt-to-output ratio decreases consumption-output ratio as it gets bigger with the smaller output level under the environmental policy constraint.

Intuitively, cap-and-trade increases price of consumption inducing negative income effect while also restricts output lowering investment. The negative income effect reduces consumption and leisure while increase in prices substitute consumption to leisure. Also, consumption should increase because of the substitution from lower investment taking place. As the result the effect on consumption depends upon which effect is dominating. In the case of leisure, in addition to the income and substitution

effects opposing each other, the leisure is also going to be affected (increase) by the value (increase) of debt-service compared to no policy because of overall price change (increase). The effects of debt level and international interest rate under the cap and trade are similar to no policy.

Tax

In the case of an environmental tax policy, government imposes a constant pollution tax (τ) charged on each unit of pollution. In our model, the effective shadow price $\hat{\lambda}_2$ is the tax rate (i.e. $\hat{\lambda}_2 = \tau$). We choose the tax rate such that the level of emission in the steady state is equivalent to that under the cap-and-trade policy. In such case, we obtain $CAP_y = 0$ and since tax revenue is distributed to households in a lump-sum transfer, we find the emission-output ratio $\frac{e}{y} = \left(\frac{\xi}{\tau}\right)^{\frac{1}{1-\xi}}$, consumption-output ratio $\frac{c}{y} = \left(\frac{\xi}{\tau}\right)^{\frac{\xi}{1-\xi}} \left(1 - \frac{\delta\alpha_1(1-\xi)}{r^* + \delta}\right) - r^* \frac{d}{y}$, capital-output ratio $\frac{k}{y} = \frac{\alpha_1(1-\xi)\left(\frac{\xi}{\tau}\right)^{\frac{\xi}{1-\xi}}}{r^* + \delta}$ and labor-leisure ratio $\frac{h}{1-h} = \frac{\alpha}{1-\alpha} \frac{(1-\xi)(1-\alpha_1)}{\left(1 - \frac{\delta\alpha_1(1-\xi)}{r^* + \delta}\right) - r^* \frac{d}{y} \left(\frac{\xi}{\tau}\right)^{\frac{\xi}{1-\xi}}}$. As in the cap-and-trade policy, we find the capital-output ratio, consumption-output ratio and the labor-leisure ratios equal to that under the cap-and-trade policy. Thus, steady-state level of these ratios under an environmental tax is the same as that under cap-and-trade policy. The effect of debt level and international interest rate on consumption and employment are similar to no policy case.

Intensity Target

For an intensity target, the government requires a maximum fixed ratio of emission per unit output $\hat{R} = \frac{e}{y}$. Then, the intensity target policy can be represented by $CAP(y) = \hat{R} y$ where $CAP(y)$ is the emission level under the cap-and-trade policy. So, we know that $CAP_y = \hat{R}$ and on substitution into the optimal equations in an equilibrium, we find emission-output ratio $\frac{e}{y} = \hat{R}$ and capital-output ratio $\frac{k}{y} = \frac{\alpha_1 \hat{R}^\xi}{r^* + \delta}$. The consumption-output ratio $\frac{c}{y} = \hat{R}^\xi \left(1 - \frac{\delta\alpha_1}{r^* + \delta}\right) - r^* \frac{d}{y}$ and labor-leisure ratio $\frac{h}{1-h} =$

$\frac{\alpha}{1-\alpha} \frac{1-\alpha_1}{\left(1-\frac{\delta}{r^*+\delta}\right)^{-r^*} \frac{d}{R\xi}}$. The effective shadow price of the emission in this case is $\hat{\lambda}_2 = \frac{\xi}{R^{1-\xi}}$.

We find that the capital-output ratio is bigger than the cap-and-trade policy but smaller than under the absence of environmental policy. Since $\xi < 1$, the consumption-output ratio in this case is the smallest and the labor-leisure ratio in the intensity target is the biggest. If zero debt level, the labor-leisure ratio under the intensity target will be equal to the no policy case. Also the effects of debt level and international interest rate are similar to no policy case.

3.2 Policies Across Open and Closed Economies

Table 1 summarizes the economic variables relative to output for each environmental policy in the open and closed economy.¹¹ We find that the effects of the cap-and-trade and pollution tax policies are equivalent in the steady-state in the open economy and closed economy but the effects differ in intensity target case as illustrated in Table 1. Capital-output ratios decline from no environmental policy case in both economies. For intensity target policy, in both economies, the capital-output ratio is bigger than cap-and-trade and smaller than no environmental policy. Under the intensity target in open economy, consumption-output ratio is smaller than no policy while the supply of labor is relatively bigger than no policy case but in the closed economy, an intensity target has no effect on the supply of labor.

We find that in an open economy the level of debt plays a significant role which is absent in closed economy. For example, if the open economy has a positive steady-state level of domestic debt with a price increase due to environmental regulation the value of debt-services will increase. This has negative income effect which negatively affects leisure more than under autarky and for that reason, the open economy has higher supply of labor compared to the no policy baseline. Higher the debt level, lower will

¹¹See the appendix for details on the derivations of the ratios for the closed economy. The closed economy is a special case of the open economy model presented above with international trade and capital mobility exogenously set to zero.

be the consumption-output ratio in open economy while capital-output ratio is not affected. Since higher output is warranted in an open economy for a sustained debt level, consumption will thus relatively decline with an increase in debt level while stock of capital will be relatively higher than a closed economy. So, with lower debt level the ratios get closer to the ratios in closed economy.

In absence of uncertainty, our model suggests that cap-and-trade and pollution tax policies are equivalent in economy under autarky which is consistent with the findings of Fischer and Springborn (2011) and also these policies are equivalent in an open economy.

Table 1: Effects across policies under open and closed economies in the steady-state

Ratios	Open economy		
	No policy	Cap-and-trade	Tax
$\frac{c}{y}$	1	$\left(\frac{\xi}{\lambda_2}\right) \frac{1}{1-\xi}$	$\left(\frac{\xi}{\tau}\right) \frac{1}{1-\xi}$
$\frac{k}{y}$	$\frac{\alpha_1}{r^*+ \delta}$	$\frac{\alpha_1(1-\xi)\left(\frac{\xi}{\lambda_2}\right) \frac{1}{1-\xi}}{r^*+ \delta}$	$\frac{\alpha_1(1-\xi)\left(\frac{\xi}{\tau}\right) \frac{1}{1-\xi}}{r^*+ \delta}$
$\frac{c}{y}$	$1 - \frac{\delta\alpha_1}{r^*+ \delta} - r^* \frac{d}{y}$	$\left(\frac{\xi}{\lambda_2}\right) \frac{1}{1-\xi} \left(1 - \frac{\delta\alpha_1(1-\xi)}{r^*+ \delta}\right) - r^* \frac{d}{y}$	$\left(\frac{\xi}{\tau}\right) \frac{1}{1-\xi} \left(1 - \frac{\delta\alpha_1(1-\xi)}{r^*+ \delta}\right) - r^* \frac{d}{y}$
$\frac{h}{1-h}$	$\frac{\alpha}{1-\alpha} \frac{(1-\alpha_1)}{1 - \frac{\delta\alpha_1}{r^*+ \delta} - r^* \frac{d}{y}}$	$\frac{\alpha}{1-\alpha} \frac{(1-\xi)(1-\alpha_1)}{\left(1 - \frac{\delta\alpha_1(1-\xi)}{r^*+ \delta}\right) - r^* \frac{d}{y}} \frac{\left(\frac{\xi}{\lambda_2}\right) \frac{1}{1-\xi}}{\left(\frac{\xi}{\lambda_2}\right) \frac{1}{1-\xi}}$	$\frac{\alpha}{1-\alpha} \frac{(1-\xi)(1-\alpha_1)}{\left(1 - \frac{\delta\alpha_1(1-\xi)}{r^*+ \delta}\right) - r^* \frac{d}{y}} \frac{\left(\frac{\xi}{\tau}\right) \frac{1}{1-\xi}}{\left(\frac{\xi}{\tau}\right) \frac{1}{1-\xi}}$
			$\hat{R} \left(1 - \frac{\delta\alpha_1}{r^*+ \delta}\right) - r^* \frac{d}{y}$
			$\frac{\alpha}{1-\alpha} \frac{1-\alpha_1}{\left(1 - \frac{\delta\alpha_1}{r^*+ \delta}\right) - r^* \frac{d}{y}} \frac{d}{R\xi}$
			\hat{R}
Ratios	Closed economy		
	No policy	Cap-and-trade	Tax
$\frac{c}{y}$	1	$\left(\frac{\xi}{\lambda_2}\right) \frac{1}{1-\xi}$	$\left(\frac{\xi}{\tau}\right) \frac{1}{1-\xi}$
$\frac{k}{y}$	$\frac{\alpha_1}{\beta - 1 + \delta}$	$\frac{\alpha_1(1-\xi)\left(\frac{\xi}{\lambda_2}\right) \frac{1}{1-\xi}}{\beta - 1 + \delta}$	$\frac{\alpha_1(1-\xi)\left(\frac{\xi}{\tau}\right) \frac{1}{1-\xi}}{\beta - 1 + \delta}$
$\frac{c}{y}$	$1 - \frac{\delta\alpha_1}{\beta - 1 + \delta}$	$\left(\frac{\xi}{\lambda_2}\right) \frac{1}{1-\xi} \left(1 - \frac{\delta\alpha_1(1-\xi)}{\beta - 1 + \delta}\right)$	$\left(\frac{\xi}{\tau}\right) \frac{1}{1-\xi} \left(1 - \frac{\delta\alpha_1(1-\xi)}{\beta - 1 + \delta}\right)$
$\frac{h}{1-h}$	$\frac{\alpha}{1-\alpha} \frac{(1-\alpha_1)}{1 - \frac{\delta\alpha_1}{\beta - 1 + \delta}}$	$\frac{\alpha}{1-\alpha} \frac{(1-\xi)(1-\alpha_1)}{1 - \frac{\delta\alpha_1(1-\xi)}{\beta - 1 + \delta}}$	$\frac{\alpha}{1-\alpha} \frac{(1-\xi)(1-\alpha_1)}{1 - \frac{\delta\alpha_1(1-\xi)}{\beta - 1 + \delta}}$
			$\hat{R} \left(1 - \frac{\delta\alpha_1}{\beta - 1 + \delta}\right)$
			$\frac{\alpha}{1-\alpha} \frac{1-\alpha_1}{\left(1 - \frac{\delta\alpha_1}{\beta - 1 + \delta}\right)}$

Note: α is the elasticity of consumption to utility, β is the fixed subjective discount factor, c is consumption, h represents the amount of labor supply, k is the stock of capital, y is output, e is the amount of emissions, ξ is the abatement parameter, r^* is the fixed exogenous interest rate in international capital market, d is the steady state debt level, δ is the rate of depreciation, $\hat{\lambda}_2$ is the effective shadow price of environmental policy, α_1 is the share of capital in final outputs, τ is the emission tax rate, \hat{R} is the emission intensity ratio. All the variables are at their steady state levels.

4 Numerical Analysis

4.1 Model Calibration

Since we could not analytically sign some of the differences in output normalized economic variables between the open and closed economy, we solve the model numerically. We follow Schmitt-Grohé and Uribe (2003) to calibrate our model to the Canadian economy using parameters standard in RBC literature. The parameter values are shown in Table 2.

Table 2: Structural parameters used in the model

σ	α_1	ξ	δ	ϕ	r^*	β	D	α
2	0.32	0.09	0.1	0.028	0.04	0.96	0.4	0.22

For our analysis, the value of elasticity of consumption (α) in the utility function is particularly important. In the steady state, the value for α influences the labor-leisure ratio while α does not directly appear in the other ratios. The amount of labor supply is, however, affected by the choice of α and thus eventually affects output. Our numerical analysis in the steady state and with the stochastic productivity shock is thus influenced by our assumed value of α . Following Uribe (2002), we choose 20% as the amount of labor supplied by households in the steady state which implies a 0.22 for α . The other parameter of interest is $\xi = 0.09$ the fixed ratio of emission abatement expenditure to the output which requires our emission tax policy to be higher than 0.09 for firms to abate. Fischer and Springborn (2011) estimated the parameter as 0.09 for the US economy using the mean ratio of total energy expenditure to the GDP (1970-2001). On the other hand, we obtain the average ratio of Canadian pollution total operating expenditure to the real GDP as 0.078 for 1995 to 2010 in an irregular interval. The operating expenditure covers all industries.¹² However, taking either

¹²The expenditure accounts all expenditures on environmental protection by industry and activity.

0.078 or 0.09 materially does not affect our results as long as our effective policy variable is higher than the selected parameter for firms to undertake abatement. So, we use $\xi = 0.09$. Also, we use the weight of the stock of pollution in the utility $D = 0.4$ as in Angelopoulos et al. (2010).

Table 3 compares the ratios of consumption, capital and pollution emissions with respect to output, and labor-leisure ratios in the steady state level across open and closed economies. The debt level in the open economy model is set to 0.098 corresponding to average debt-output ratio of 0.33 in Canada (1961-2008)¹³. In both open and closed economies, cap-and-trade and tax policies produce significantly higher levels of consumption per unit of output than in the no policy baseline or intensity target. In both economies the ratio declines under intensity target compared to no policy. The capital-output ratio declines for all environmental policy instruments in both open and closed economies. We find the ratio declines more under cap-and-trade or tax policy compared to the intensity target case. The ratios are nearly similar across policies in both economies. The labor-leisure ratio also declines under the cap-and-trade and tax policies in both economies but under the intensity target in both economies the ratio remains about the same as the no environmental policy baseline. The emissions-output ratio required to maintain same level of emissions under cap-and-trade or pollution tax in open economy is smaller than closed economy but similar under intensity target.

4.2 Uncertainty and Environmental Policy

We now turn to evaluating the properties of the pollution tax, cap-and-trade and intensity target in the presence of uncertainty. We simulate uncertain economic growth by employing a temporary positive stochastic productivity shock. This productivity shock dissipates according to the persistence parameter ρ . We track all economic vari-

Source: Statistics Canada, Environment Accounts and Statistics Division.

¹³The ratio of gross federal debt level to gross domestic product (expenditure-based), source: Statistics Canada

Table 3: Steady-state ratios across policies between open and closed economies

Variables	Economy Under Free Trade				Economy Under Autarky			
	No pol- icy	Cap- and- Trade	Tax	Int Tar- get	No pol- icy	Cap- and- Trade	Tax	Int Tar- get
Consumption- output ratio	0.760	0.773	0.773	0.745	0.774	0.789	0.789	0.759
Capital- output ratio	2.259	2.041	2.041	2.216	2.259	2.041	2.041	2.216
Labor- Leisure ratio	0.252	0.224	0.224	0.252	0.248	0.220	0.220	0.248
Emissions- output ratio	1.000	0.923	0.923	0.807	1.00	0.925	0.925	0.807

ables across the shock’s life-cycle and compare the effects on consumption, labor/leisure trade off, pollution emissions and welfare across policy instruments in both the open and close economies. We also simulate uncertain abatement costs to evaluate the possibility of technological breakthroughs, such as carbon capture and sequestration, which could greatly lower pollution abatement costs. We again track the outcome of all economic variables in response to permanent negative shock in abatement costs and show that the environmental policy instruments have different impacts in open and closed economies.

4.2.1 Environmental Policy Instruments and the Business Cycle

Finding a reduced form solution of the stochastic model is difficult because of nonlinearities in the system of equations. We are forced to solve the stochastic model numerically. First, we calculate the steady-state values as described above given the structural parameters. Then, the model is approximated around the steady state values by using the method of second order Taylor approximation. Although the first order approximation is widely popular, we use the second order approximation to rule out the

welfare reversal as suggested by Kim and Kim (2003). We analyze the impact of two different shocks: a temporary one standard deviation positive shock to productivity, which simulates the business cycle and a one standard deviation negative shock to pollution abatement costs which simulates a breakthrough in abatement technology.

We follow Schmitt-Grohé and Uribe (2003) to calibrate our model to the Canadian economy using parameters standard in RBC literature. The parameter values used in addition to Table 2 are shown in Table 4.

Table 4: Additional structural parameters used in the model

ρ	σ_A	ρ_s
0.42	0.025	0.8

Table 5: Static environment policies imposed in the model

	Cap	Tax	Intensity Target
Policy	0.2331	0.0966	0.8073

Note: The Cap policy represents 20% reduction of emissions from the no policy case. Tax and intensity target policy above also represents the respective policies required for the 20% reduction of emissions from the no policy case.

To simulate the business cycle we employ a one period temporary productivity shock that falls back to its steady-state value consistent with its persistency parameter.¹⁴ We, then, evaluate impulse response functions from the productivity shock across the three selected environmental policies. These static policies are summarized in Table 5. The model is first solved for no policy case as a baseline. As in Fischer and Springborn (2011), we model a 20% emission reduction from the steady-state emissions from the no

¹⁴The shock differs from Fischer and Springborn (2011), which rely primarily on permanent series of random shocks. In our case we follow standard RBC literature and introduce a one period temporary random shock and it allows us to trace the impulse response function for each variable. See Heutel (2012); Uribe (2002, 1997); Schmitt-Grohé and Uribe (2003). We also find that our results are consistent with the US figures in Fischer and Springborn (2011) (See appendix).

environmental policy level.¹⁵ We model an emissions cap at 20% below the baseline and then introduce emission taxes and intensity targets such that the amount of emission reductions are the same across each of the policies.

The existing literature has used the variation in economic variables across the business cycle to evaluate environmental policies. We follow this precedent by calculating the coefficient of variation (CV) across the business cycle for each environmental policy and the no policy baseline. The results are reported in Table 6. Each CV provides a measure of dispersion of the corresponding variable in terms as a percentage of its theoretical mean. The cap-and-trade policy consistently has the lowest CV for the economic variables. For emissions this is obvious, after the positive productivity shock the level of emissions remains unchanged at twenty percent below the baseline case so there is no variation. This inflexible emissions cap reduces the benefits of the positive productivity shock so consumption, investment, labor and output all increase by less under a cap-and-trade policy than in the no environmental policy baseline. In both the open and closed economy the cap-and-trade policy reduces the severity of the business cycle which is consistent with the results in Fischer and Springborn (2011).¹⁶

Table 6 describes the theoretical mean and coefficient of variation for the economic outcome variables across each of the environmental policy instruments. For each of the economic outcome variables the intensity target leads to bigger theoretical mean values than cap-and-trade or pollution tax policies. The flexibility of the intensity target allows emissions to rise during the boom reducing the cost of complying with environmental regulation across the business cycle.

The impact of environmental regulation on jobs has been a particular concern of policy makers and economists. In our model the labor supply, which is a function of the

¹⁵The European Union has a target reducing emissions 20% from 1990 levels by 2020 and both the Waxman-Markey and Kerry-Lieberman bills proposed in the U.S. Congress targeted a 20% emissions reduction.

¹⁶The model is symmetric so a negative productivity shock to model the trough of the business cycle would give the same results. Reduced economic activity would reduce the shadow price of the cap and reduce the negative impact of the shock, once again dampening the business cycle.

Table 6: Theoretical moments for uncertain economic growth

Variables	Economy Under Free Trade				Economy Under Autarky			
	No pol- icy	Cap	Tax	Intensity Target	No pol- icy	Cap	Tax	Intensity Target
Consumption c.v.	0.226 (4.25%)	0.199 (3.66%)	0.199 (4.26%)	0.220 (4.23%)	0.226 (5.09%)	0.199 (4.47%)	0.199 (5.22%)	0.220 (5.10%)
Labor c.v.	0.197 (8.01%)	0.179 (6.58%)	0.179 (9.12%)	0.197 (8.06%)	0.199 (2.22%)	0.180 (1.89%)	0.180 (2.17%)	0.199 (2.22%)
Investment c.v.	0.066 (56.55%)	0.051 (45.91%)	0.051 (63.94%)	0.064 (57.05%)	0.066 (15.28%)	0.052 (14.15%)	0.052 (16.05%)	0.064 (15.29%)
Output c.v.	0.291 (11.73%)	0.252 (10.20%)	0.251 (12.81%)	0.288 (11.80%)	0.292 (6.88%)	0.253 (6.57%)	0.253 (6.93%)	0.289 (6.88%)
Emission c.v.	0.291 (11.73%)	0.233 (0.00%)	0.233 (12.82%)	0.233 (11.82%)	0.292 (6.88%)	0.233 (0.00%)	0.234 (6.93%)	0.234 (6.90%)
Welfare s.d.	-0.932 (0.112)	-0.742 (0.021)	-0.745 (0.070)	-0.738 (0.065)	-0.935 (0.049)	-0.743 (0.014)	-0.747 (0.017)	-0.740 (0.017)

Note: The debt level and trade balance in open economy is assumed to be zero in the steady state to facilitate comparison with the closed economy. c.v. is the coefficient of variation, the standard deviation divided by the theoretical mean level and s.d. is the standard deviation of the variable in response to a one standard deviation positive productivity shock. We report the standard deviation when the theoretical mean for a variable is zero or negative.

labor leisure trade-off and marginal product of labor, allows us to estimate the impact of each environmental policy instrument on employment choices and variation across the business cycle. The intensity target is associated with the larger labor supply than cap-and-trade and pollution tax policies.

The cap-and-trade policy leads to the lowest level of variation in the outcome variables across the business cycle. The cap does not change during the boom causing the cost of complying with the environmental policy to increase. This increased compliance cost acts as a drag on the economy smoothing out the business cycle. Relative to the no environmental policy baseline, the tax and intensity target have little impact on the severity of the business cycle while the cap-and-trade policy smooths the business cycle. The variation in all economic variables is bigger in open economy compared to the closed economy with the exception of variation in consumption which is lower in

the open economy.

The level of welfare in an open economy is higher than in the closed economy. The intensity target policy has the highest welfare in both economies. The emission tax policy however has a lower welfare level than the cap-and-trade policy in both economies suggesting superiority of cap-and-trade policy both in terms of welfare and volatility.

By construction each of the environmental policy instruments leads to the same steady-state level of pollution emissions, a twenty-percent reduction from the steady state in the no policy baseline. The cap-and-trade policy binds across the business cycle keeping emissions constant during the boom, but the flexibility of the tax and intensity target lead to increases in emissions during the boom which fade with the productivity shock.

4.2.2 Environmental Policy Instruments and Uncertain Abatement Costs

In this section we analyze the relative merits of the environmental policy instruments in the face of uncertain pollution abatement costs. Greenhouse gas as a stock pollutant has a relatively flat marginal benefit function for abatement in any single period while the marginal cost function slopes sharply. Pizer (1999) and Hoel and Karp (2001) find that a price control maximizes welfare given uncertainty on cost. In a more general model Parsons and Taschini (2013) suggest that taxes are more effective in the face of temporary shock to abatement costs and cap-and-trade policies are more appropriate in the face of permanent shock to abatement costs. These models do not consider the effect of trade and capital mobility. We extend the literature using a dynamic stochastic general equilibrium model to consider the impact of openness on the relative attractiveness of environmental policy instruments in the face of uncertain abatement costs. Our model is also flexible enough to compare intensity target policy to the cap and pollution tax policies.

To measure uncertainty in abatement costs we collect data from Canada’s Pollution Abatement Control Expenditures survey. This data is available from 1996 to 2010 at irregular intervals. We normalize that data by Canadian output (measured by real GDP) to create an abatement cost per unit of output series. We then use quarterly seasonally adjusted GDP data during that time span to estimate quarterly pollution abatement expenditures over from 1996 to 2010.¹⁷ We de-trend the series using Hodrick-Prescott (HP) filter (with λ filter coefficient = 1600 for quarterly data) before estimating AR models on the quarterly expenditure data to evaluate the variation in abatement costs. We select AR(1) model to be optimal one based on minimum Akaike Information Criterion (AIC). The estimated auto-correlation coefficient of abatement cost per unit GDP is 0.53.¹⁸

Uncertainty in the costs of pollution abatement can take different forms. We can imagine a world where an improvement in greenhouse gas (GHG) abatement technology like carbon capture and storage takes place and the cost of GHG reduction sharply declines. Similarly recent shifts in the price of natural gas relative to coal have made switching fuels a low cost way to reduce GHG emissions. In our model, we simulate a temporary decline in the cost of abatement by introducing a negative one standard deviation shock to parameter ξ which governs the degree of pollution abatement. As illustrated in Eq.(37), the shock to abatement technology follows:

$$\xi - \xi^{ss} = \rho_{\xi}(\xi_{t-1} - \xi^{ss}) + \epsilon_{\xi} \quad (37)$$

¹⁷There is not enough data on abatement costs to directly estimate uncertainty in abatement costs per unit of output series. This process introduces two sources of variation in quarterly abatement costs: variation in abatement costs per unit of output and variation in quarterly GDP. To the extent that per unit abatement costs and quarterly GDP are positively correlated this means we will overestimate variation in per unit abatement costs. For the Canadian data we estimate that correlation to be 0.56. For that reason our estimates of variation in quarterly abatement costs should be considered an upper bound on abatement per unit of output.

¹⁸We find the auto-correlation coefficient as 0.71 when we use manufacturing value added data instead of real GDP of Canada. However, our results do not differ significantly when we use this value.

where ξ^{ss} is the long-run steady state abatement parameter and ϵ_ξ is the exogenous innovation (where $\epsilon_\xi \sim iid N(0, \sigma_\xi)$). The steady-state level for ξ_{ss} is 0.09 and ρ_ξ is 0.53. We refer Abadie and Chamorro (2008) to estimate 1 standard deviation of the i.i.d. shock parameter ϵ_ξ as 0.00657 (7.3% from its steady state level).

Table 7: Theoretical moments for uncertain abatement costs

Variables	Economy Under Free Trade				Economy Under Autarky			
	No pol- icy	Cap	Tax	Intensity Target	No pol- icy	Cap	Tax	Intensity Target
Consumption c.v.	0.226 (0.35%)	0.199 (0.40%)	0.199 (0.10%)	0.219 (0.09%)	0.226 (0.40%)	0.199 (0.45%)	0.199 (0.30%)	0.219 (0.14%)
Labor c.v.	0.199 (1.36%)	0.180 (1.50%)	0.180 (0.44%)	0.199 (0.30%)	0.199 (1.01%)	0.180 (1.11%)	0.180 (0.56%)	0.199 (0.15%)
Investment c.v.	0.066 (11.25%)	0.051 (11.87%)	0.052 (1.94%)	0.064 (2.34%)	0.066 (2.43%)	0.051 (2.92%)	0.052 (1.17%)	0.064 (0.78%)
Output c.v.	0.291 (1.30%)	0.252 (1.39%)	0.252 (0.40%)	0.289 (0.28%)	0.291 (0.75%)	0.252 (0.87%)	0.252 (0.36%)	0.289 (0.10%)
Emission c.v.	0.291 (1.30%)	0.233 (0.00%)	0.233 (9.17%)	0.233 (0.26%)	0.291 (0.75%)	0.233 (0.00%)	0.233 (9.04%)	0.233 (0.13%)
Welfare s.d.	-0.928 (0.011)	-0.744 (0.003)	-0.745 (0.028)	-0.737 (0.002)	-0.928 (0.006)	-0.744 (0.003)	-0.745 (0.028)	-0.737 (0.001)

Note: The debt level and trade balance in an open economy is assumed to be zero in the steady state to facilitate comparison with the closed economy. c.v. is the coefficient of variation, the standard deviation divided by the theoretical mean and s.d. is the standard deviation of the variable in response to a one standard deviation positive productivity shock. We report the standard deviation when the theoretical mean for a variable is zero or negative.

Table 7 summarizes the theoretical means and variation across the abatement cost shock for the economic variables of interest. The theoretical means are obtained similar to the results reported in Table 6. In this model, the coefficients of variation reflect the evolution of these economic variables in response to a negative abatement cost shock, such as significant relative price movement in favor of cleaner inputs. Unlike the case of uncertain economic growth, the cap-and-trade policy is associated with significantly more variation in economic variables. The inflexibility that allowed the cap to dampen the business cycle also implies that the cap does not respond to changing abatement

costs. While the intensity target as a flexible policy responds to the the changing abatement costs by more emission abatement.

With a fixed emissions level in the cap-and-trade policy, the price of emissions goes down when there is a sudden reduction in abatement cost but the policy does not induce more abatement. However, in the pollution tax case, the price of emissions goes down and thus firms find optimal to abate as per the intensity of the shock. In the intensity target case, with a fixed ratio of emission to output, on reduction of the cost of abatement, the price of emissions goes down but to maintain the ratio, the price drops less than in the tax case and thus firms abate relatively less. The impacts on welfare levels across the two economies do not differ, suggesting uncertainty in the cost of abatement would not have significant differences across the two economies although open economy has relatively higher volatility.

To facilitate comparisons across the two sources of uncertainty and evaluate the variation in the economic variables across policies we produce impulse response functions (IRFs). The IRFs graph the evolution of consumption, labor, output and pollution emissions across each environmental policy instrument for both uncertain economic growth and uncertain abatement costs. Figure 1 displays these IRFs in uncertain economic growth and uncertain abatement cost in an open economy.¹⁹

After a positive productivity shock consumption rises across all four environmental policies (top left panel), but it rises least for the cap-and-trade policy. By forcing the shadow price of abatement to rise in response to the economic boom the cap-and-trade policy dampens the business cycle. The intensity target, which allows the shadow price of abatement to fall in response to the economic boom actually accelerates the business cycle slightly. After a negative abatement cost shock the result is reversed (top right panel). The intensity target and pollution tax lead to smaller surges in consumption while the cap-and-trade policy actually accentuated the consumption boom

¹⁹These IRFs are compared with the closed economy in appendix.

slightly relative to the no environmental policy baseline.

Not surprisingly labor supply increases in response to a positive productivity shock (middle left panel) as the marginal product of labor increases and the benefits of supplying labor to the market exceed the marginal utility from leisure. Again the cap-and-trade policy dampens the business cycle shock, while the pollution tax and intensity target are essentially no different than the no environmental policy baseline. The cap-and-trade policy also reduces the level of labor market overshooting as the productivity shock fades. For policy makers primarily concerned with the labor market impacts of environmental policy this could be an important benefit of cap-and-trade. Again the result is reversed after a negative abatement cost shock (middle right panel). The intensity target and pollution tax dampen the labor market impacts of the abatement cost shock while the cap-and-trade program is essentially the same as the no environmental policy baseline.

The bottom panels summarize the impact of a positive productivity shock (left panel) and abatement cost shock (right panel) on pollution emissions. The cap-and-trade policy has no variation because in each period the cap binds and emissions are constant across the business cycle. The pollution tax and intensity target allow emissions to increase after the productivity shock, but by less than in the no environmental policy case. As the shock fades the pollution tax and intensity target emissions levels fall below the cap. The productivity shock affects the marginal product of factor inputs in two ways: a direct effect in the marginal product of labor and capital, and an indirect effect in the marginal product of labor due to the effect on the capital stock. This phenomena is more subtle in the open economy than in the closed economy because of higher level of investment in the open economy. As the shock fades, the rate of the decline in the marginal product of labor will be faster than the rate of fall due to the indirect decelerating effect of the capital stock. For this reason, we find output and emissions fall below their steady state level in open economy. In the case of an

abatement cost shock, the intensity target allows emissions to increase, but less than the no environmental policy case. The pollution tax level of emissions is less than the cap-and-trade policy.

Each of the impulse response functions is graphed on its own axis to highlight the variation in the economic variable across the policy instruments. This hides potentially interesting variation in the magnitude of changes in response to the two shocks. Each are calibrated to Canadian data as a one standard deviation shock, but the response to the productivity shock is nearly an order of magnitude larger. The productivity shock increases the marginal product of labor increasing labor force participation and reducing leisure, increasing wages and affecting every aspect of the economy. The abatement cost shock has a more narrow impact on the amount of final output that the firm can sell after complying with the environmental regulation. Recall, that our process for estimating quarterly abatement costs in Canada will over-estimate variation in abatement costs per unit of output meaning the differences graphed in these IRF's likely understates the true difference in the impact of the random productivity and abatement cost shocks. For that reason, policy makers can focus on selecting the policy instrument that is robust to economic growth shocks. Barring abatement cost breakthroughs on the order of ten standard deviations over the observed abatement costs series the impact of productivity changes will swamp that of abatement cost shocks.

4.2.3 Environmental Policy Instruments and Openness

Evaluating environmental policy instruments in an open economy model allows us to consider their impact on international trade and capital flows. The interaction between environmental regulation and trade and capital flows has been widely studied in the literature,²⁰ but to our knowledge this is the first paper to evaluate how envi-

²⁰See Ederington and Minier (2003) and Copeland (1994) among many others.

ronmental policy instruments differ in their effect on trade and capital flows. In this section we briefly describe the steady-state differences in economic variables of interest across environmental policy instruments. We then follow the nascent environmental macro literature by focusing on the impact of environmental policy instruments on the variance of trade and capital flows.

Table 8 compares the steady state level of consumption, investment, supply of labor and pollution emissions across open and closed economies. As in section 4.1, the debt level in the open economy model is set to 0.098 such that the debt-output ratio in the steady-state is 0.33, an average debt-output ratio (1961-2008). Comparing the steady-state levels of consumption, investment, employment, output and emissions across open and closed economies reveals that introducing a cap-and-trade program or pollution tax in an open economy lower consumption, investment, labor, output and (of course) emissions relative to the no-policy baseline. The introduction of an intensity target increases consumption, labor, output and investment while providing the same reduction in pollution emissions as the cap-and-trade and tax policies. The employment level in the intensity target case is nearly equal to our baseline no policy case. These results are consistent with our findings in Table 3 for both open and closed economies.

Table 8: Steady-state levels across policies

Variables	Open Economy				Closed Economy			
	No pol- icy	Cap	Tax	Int Tar- get	No pol- icy	Cap	Tax	Int Tar- get
Consumption	0.225	0.198	0.198	0.218	0.226	0.199	0.199	0.219
Labor	0.201	0.183	0.183	0.202	0.199	0.180	0.180	0.199
Investment	0.067	0.052	0.052	0.065	0.066	0.051	0.051	0.064
output	0.296	0.256	0.256	0.293	0.066	0.051	0.051	0.064
Emissions	0.296	0.236	0.236	0.236	0.291	0.233	0.233	0.233

We now turn to comparing environmental policy instruments' impacts on trade

balances and capital flows. Here we focus primarily on how these instruments affect variance in measures of openness. Similar to the previous section we introduce a random positive productivity shock to simulate the business cycle and a random negative abatement cost shock to simulate technical progress in abatement. Figure 2 displays the impulse response functions for the productivity shock (left) and abatement cost shock (right). The results suggest that the source of randomness matters crucially for choosing the most preferred environmental policy instrument.

The positive productivity shock leads to an initial drop in the trade balance (upper left panel) as increased demand is met by foreign production. This is followed by an increase in the trade balance as the country moves (even further) towards being a net exporter. Among the environmental policies, cap-and-trade dampens the effect of the business cycle most while a pollution tax and intensity target are essentially indistinguishable from the no environmental policy baseline. A negative shock to abatement costs similarly leads to an initial drop in the trade balance (upper right panel) as imports surge. This is followed by an increase in exports associated with decreased expenditures on abatement. The pollution tax and intensity target both smooth the impact of the abatement cost shock on the trade balance. The trade balance's evolution is similar under the cap-and-trade policy and the no environmental policy baseline.

The results on the current account are consistent with those on the trade balance. A cap-and-trade policy minimizes variation in the trade balance after an economic growth shock, while the tax and intensity targets minimize variation in the trade balance in response to an abatement cost shock. International debt adjusts more slowly to the shocks than the trade balance and current account. Immediately after the productivity shock debt increases to fund consumers' consumption smoothing. The country then moves towards becoming a creditor (relative to the steady state). The cap-and-trade policy reduces variation in debt levels relative to the no environmental policy baseline. A negative abatement cost shock leads to a similar relative increase in international

debt in the short term followed by a move to surplus under cap-and-trade and intensity targets. A pollution tax is associated with increased debt until the shock fades and the economy returns to steady state.

5 Leakage

Another advantage to analyzing environmental policy instruments in an open economy model is the ability to understand how domestic environmental policy affects world pollution emissions. The question of whether unilateral introduction of environmental regulation leads relocation of economic activity and associated pollution emissions has been widely studied.²¹ Holland (2012) examines the effectiveness of environmental regulation and finds that an intensity standard may limit movement of economic activity and associated increases in rest-of-world emissions, known as leakage. We are able to extend that literature by assessing the susceptibility to leakage of environmental policy instruments across the business cycle and in response to abatement cost shocks.

Leakage in our model can be summarized by the trade balance. We model a small country that does not affect world prices. Introducing an environmental policy, experiencing a productivity shock or an abatement cost shock does not affect the actions of the rest of the world. Rest of the world consumption and emissions intensity remain unchanged, implying that changes in foreign production will translate directly to changes in emissions. Increases in imports in response to productivity or abatement cost shocks suggest leakage.

Table 9 summarizes the impact of a one standard deviation positive productivity shock and a one standard deviation abatement cost shock on the discounted total change in trade balance. A positive productivity shock leads to increased imports in the no policy baseline and under each of the environmental policies because consumption

²¹See McAusland and Millimet (2013); Holland (2012); Manderson and Kneller (2012); Silva and Zhu (2009); Kellenberg (2009); McAusland (2008); Ederington et al. (2005) and Kuik and Gerlagh (2003).

risers sharply in response to the shock. The cap-and-trade policy leads to the lowest import increase while the tax induces the biggest import increase and thus the most leakage. This is consistent with our earlier results on consumption. Cap-and-trade leads to the lowest rise in consumption and the intensity target and tax induce higher consumption resulting in lower surplus in the tax and intensity target case. With the given parameters, we find that leakage in response to the policies differs with the type of shock. In an economic boom a cap-and-trade policy does the best at limiting leakage. The intensity target and tax have the highest leakage in the period the shock occurs and the lowest leakage as the shock fades away. After the shock dissipates the intensity target best limits leakage, which is consistent with the previous literature relies on static models.

The results reverse for an abatement cost shock. Introducing a pollution tax leads to the the largest increase in exports relative to the baseline followed by intensity target. A cap-and-trade policy in fact increases imports similar to the no policy baseline. The level of leakage across the three policies is a function of the stringency of the policy. Immediately after the shock, cap-and-trade has the biggest increase in imports while the intensity target has the smallest. As the shock fades the tax and intensity target do the best in limiting leakage.

Table 9: Leakage across policies and shock source

Variables	Productivity Shock			
	No policy	Cap-and-Trade	Tax	Int Target
Trade balance	-3.36	-2.59	-3.41	-3.30
Difference from No policy		0.77	-0.05	0.06
Variables	Abatement cost shock			
	No Policy	Cap-and-Trade	Tax	Int Target
Trade balance	-0.27	-0.27	0.25	-0.13
Difference from No policy		0.00	0.52	0.14

Note: Discounted change in trade balance from its steady state level across environmental policy instruments and shock types. Negative trade balance imply increased imports and thus increased foreign production and emissions under a particular environmental policy. Units are scaled by 10^{-4} to improve readability.

The impact of this potential leakage depends crucially on the emissions intensity of rest of the world production. This is beyond the scope of our model, but we can provide some evidence by assuming that global emissions intensity is the same as domestic emissions intensity after regulation. Changes in global emissions are a function of domestic consumption. We model a twenty percent reduction in pollution emissions, but in response to a positive productivity shock consumption increases by 13%, 14.9% and 14.9% of its steady state level in the cap-and-trade, tax and intensity target policies respectively. In the response, the emission leakage is 6.3%, 8.4% and 8.1% respectively in cap-and-trade, tax and intensity target policies. For an abatement cost shock, consumption increases by 1.2%, and 0.3% in cap-and-trade and intensity target policies respectively however, under the tax policy consumption decreases by 0.3%. In the response, emission leakage is 0.7% and 0.3% from its baseline emissions in cap-and-trade and intensity target policies while we see negative leakage of 0.6% under the tax case. The negative leakage is driven by the abatement resource effect (ARE) described in Baylis et al. (2014). The resources spent on pollution abatement under an environmental regulation negatively affect the demand for consumption relatively more than the output effect due to higher prices. This results in a positive trade balance and thus negative leakage.

6 Conclusions

Policy makers are faced with a variety of instruments to limit pollution emissions. Cost effectiveness is one important criteria, but an emerging literature suggests that considering environmental policy's impact across the business cycle is also important. As countries become increasingly integrated into the world economy the impact of environmental policy on trade flows has become a consideration as well. To address these questions we develop a dynamic stochastic general equilibrium model incorporating international trade and capital mobility. We then evaluate a pollution tax, a cap-and-

Table 10: Summary of the results

The policy instrument that best reduces the intensity of the a shock:		
	Productivity Shock	Abatement cost shock
Consumption	Cap-and-Trade	Tax or Intensity Target
Labor	Cap-and-Trade	Intensity Target
Investment	Cap-and-Trade	Intensity Target
Output	Cap-and-Trade	Intensity Target
Trade	Cap-and-Trade	Intensity Target

The most effective policy instrument to reduce leakage		
	Productivity Shock	Abatement cost shock
Cumulative leakage	Cap-and-Trade	Tax

Note: In the absence of uncertainty the intensity target leads to the highest level for all economic variables. The cap-and-trade and emissions tax are equivalent in the long-run with no uncertainty.

trade policy and an intensity target in response to the business cycle and uncertain abatement costs.

Our results are summarized in Table 10. We bring together two literatures to show that choosing the best environmental policy instrument depends crucially on policy maker priorities. Policies that perform best across the business cycle are less flexible in response to abatement cost shocks and vice versa. Depending on policy maker priorities and sources of uncertainty cap-and-trade, pollution taxes or intensity targets could be most preferred. Under uncertain economic growth an intensity target has the lowest welfare cost, but a cap-and-trade policy reduces the severity of the business cycle. Under uncertain abatement costs a pollution tax or intensity target may have the lowest welfare cost depending on the steepness of the marginal damage curve.

Examining environmental policy instruments in an open economy model also allows us to assess the impact of policy on international trade and capital flows. We find that cap-and-trade policies dampen the impact of business cycle on international trade flows, reducing exports during a boom and imports during a bust. Pollution taxes and intensity targets reduce the impact of an abatement cost shock on trade flows. Again, policy maker priorities and the relative importance of productivity and abatement cost

shocks dictate the most preferred environmental policy.

The model is solved by second order approximation around the steady state levels. Though the first order linear approximation is widely used, it is recommended that in an open economy the second order approximation is superior (Kim and Kim, 2003). An extension of the model to a two good-two factor framework to analyze policy impacts with differing shocks across the sectors could be of interest. Also, an extension of the model to analyze the possibilities of trade policy substitution by various environmental policies and policy impacts on economy and environment could provide context on the importance of trade policy in environment.

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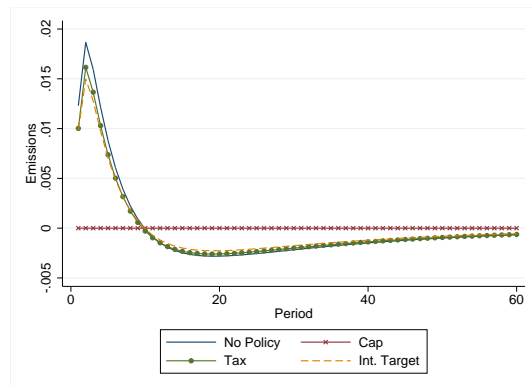
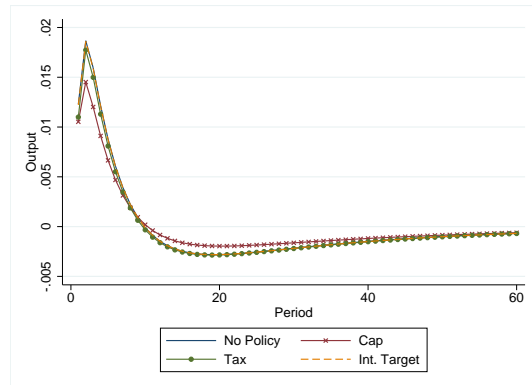
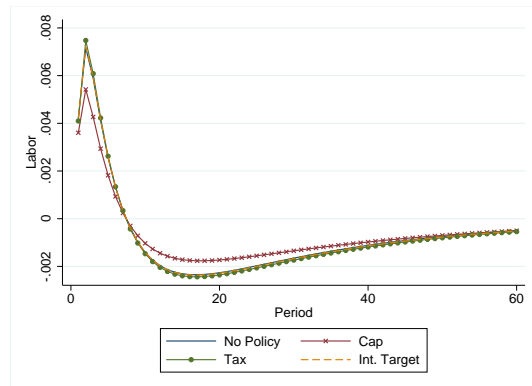
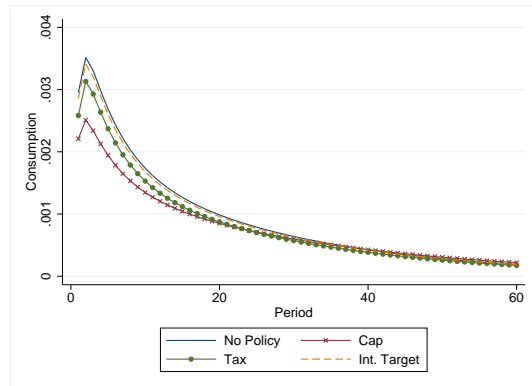
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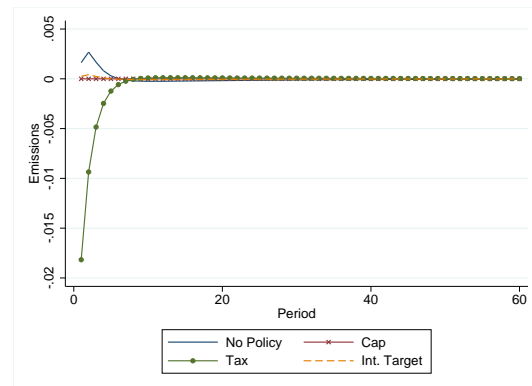
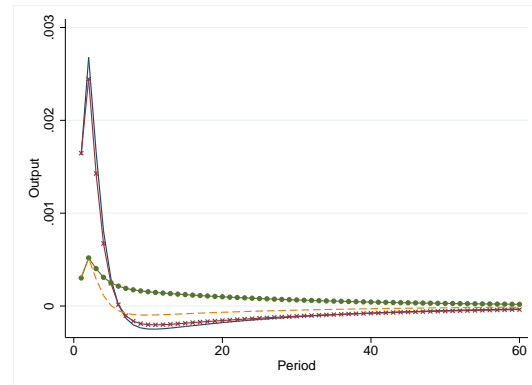
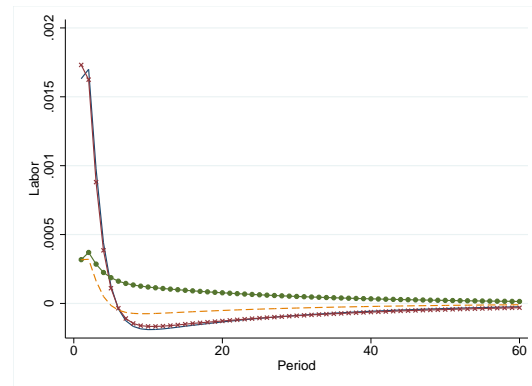
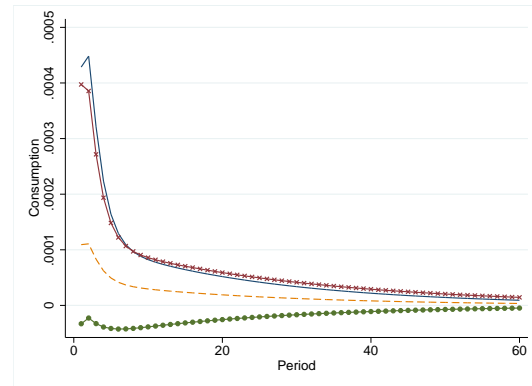
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Figure 1: Impulse responses function for a productivity or abatement cost shock.

Uncertain Economic Growth



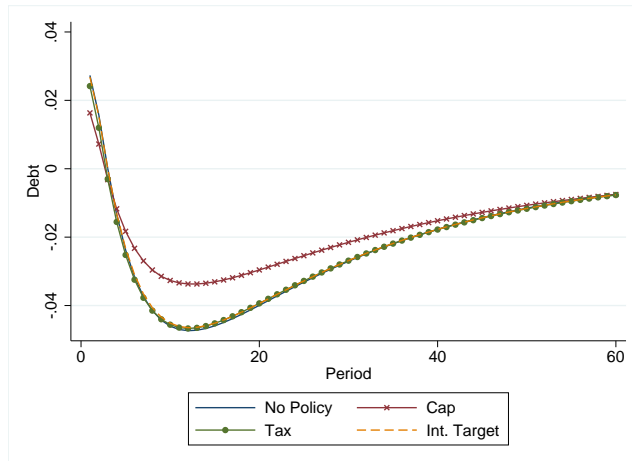
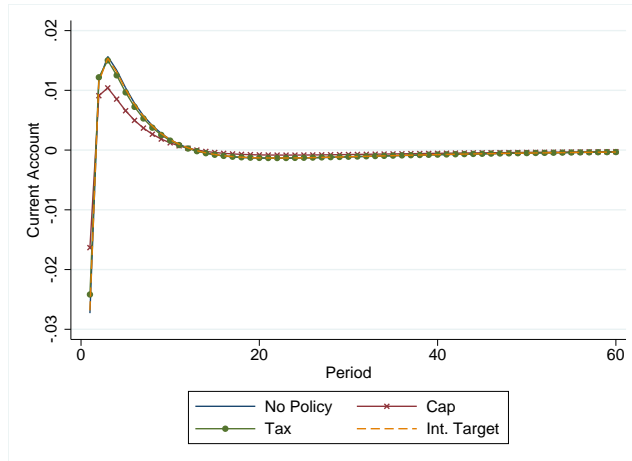
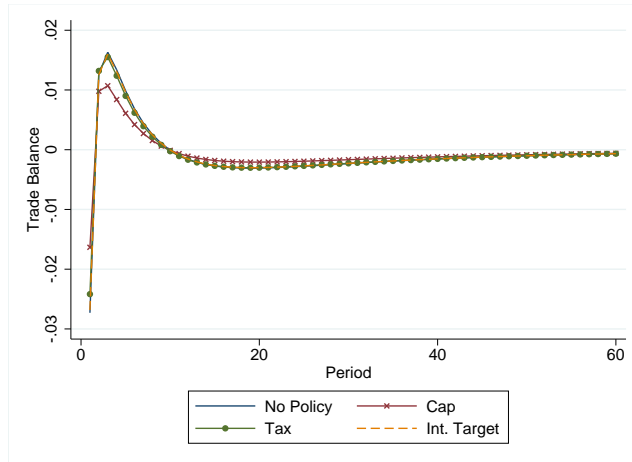
Uncertain Abatement Cost



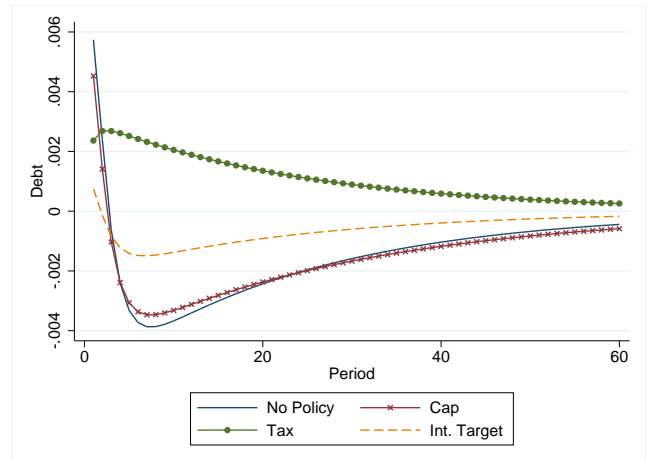
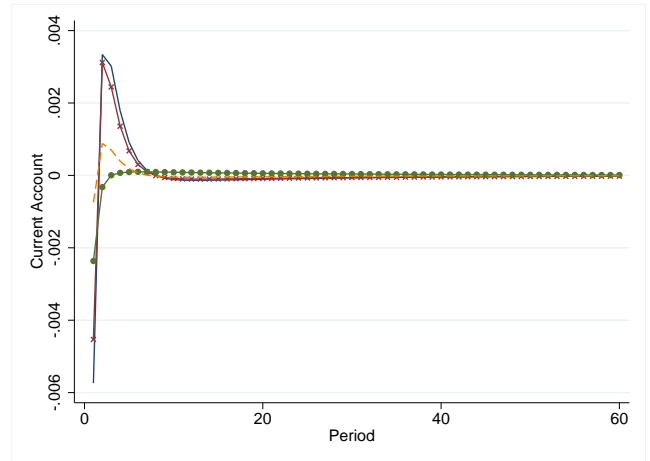
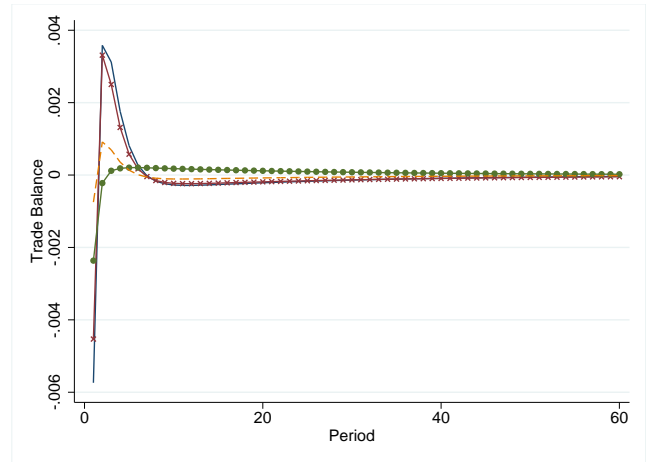
Note: The left column graphs consumption, labor, output and emissions respectively in response to a one standard deviation productivity shock. The right column graphs consumption, labor, output and emissions respectively in response to a one standard deviation abatement cost shock. Zero on the vertical axis represents the steady state level for each graph and each series is graphed on its own axis to highlight variation between policies. Note that a one standard deviation shock to productivity has a significantly larger impact on each series than a one standard deviation shock to abatement costs.

Figure 2: Impulse responses for openness measures to a productivity or abatement cost shock

Uncertain Economic Growth



Uncertain Abatement Cost



Note: The left column graphs the trade balance, current account and debt level respectively in response to a one standard deviation productivity shock. The right column graphs trade balance, current account and debt level respectively in response to a one standard deviation abatement cost shock. Zero on the vertical axis represents the steady state level for each graph and each series is graphed on its own axis to highlight variation between policies. Note that a one standard deviation shock to productivity has a significantly larger impact on each series than a one standard deviation shock to abatement costs.