The Welfare Implications of Climate Change Policy ⋆

Andrew J. Leach

HEC Montréal, CIRANO, CIRPÉE

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Abstract

The response to four different climate change policies is measured within a general equilibrium model of world output, technological change, greenhouse gas emissions, and climate-based changes in productivity. Proposed policies, including an approximation to the Kyoto protocol, are shown to differ greatly in how they mitigate climate change, support economic growth, and allocate rents across generations. Benefits of policies relative to a no-policy *status quo* do not accrue to the generations that bear the costs. The framework is used to analyze the social value and political acceptability of policies. In particular, the Kyoto protocol is shown to be strongly welfare-preferred to the *status quo* when emissions rights are distributed on a per-capita basis, while the opposite is true when these rights are grandfathered to emitting firms.

Key words: Climate Change; Environmental Taxes; Environmental Regulation.

JEL classification: Q21; H23; L51.

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Email address: `andrew.leach@hec.ca` (Andrew J. Leach).

Preliminary version.

1 Introduction

Global climate change induced by atmospheric accumulation of carbon dioxide (CO_2) and other greenhouse gases (GHG) threatens future standards of living. Climate science suggests that average global temperatures could rise by between 1.5 and 5.5 degrees Celsius by the end of this century, while estimates in the economics literature place the cost of such changes at over 10 percent of total factor productivity (Knutti et al, 2002; Nordhaus and Boyer, 2000). The costs of climate change policies are also large, as immediate reductions in GDP of 1-3% are predicted to result from the Kyoto protocol (Shogren, 2000). This paper addresses the distribution of the benefits and costs of climate change mitigation policies over time in a general equilibrium model of world output, technological change, GHG emissions, and climate-based changes in productivity. The model is calibrated to match International Energy Agency data for gross world product (GWP), carbon emissions, energy consumption, and population and used to assess the intergenerational welfare outcomes of four different climate change policies. Proposed policies, including an approximation to the Kyoto protocol, are shown to differ greatly in their abilities to mitigate climate change, support economic growth, and allocate rents across generations. Sensitivity analysis shows that, while the costs of policies vary minimally with the assumed severity of climate change, the benefits of these policies are subject to much larger uncertainties.

This paper builds on benchmark integrated assessment models (IAM) developed in Manne and Richels (1992) and Nordhaus and Boyer (2000), which are in turn based on the optimal growth models of Ramsey (1928), Cass (1965), and Koopmans (1965). Several elements not present simultaneously in existing IAMs are introduced here in order to focus on the choice of policy instruments and the politics of adopting costly policies that pay off only in the distant future.

First, the world climate and economy are studied within a general equilibrium overlapping generations model (Diamond, 1965). The overlapping generations structure is well suited for the climate change policy problem, since the benefits of reduced climate change do not accrue to those generations harmed by the policies relative to a no-policy *status quo*. There has been some attention in the literature to combining the features of climate and economic models with the environment proposed in Diamond (1965). Howarth (1998), Gerlagh and van der Zwaan (2000, 2001), Rasmussen (2002), and Kavuncu and Knabb (2002) each present models of climate change featuring overlapping generations of agents. A similar model is used to address the intergenerational redistribution of finite resource rents in Gerlagh and Keyzer (2001). The emission of GHG to fuel current consumption can be thought of as borrowing from future generations to support current consumption, while investment in climate change mitigation passes on more environmental capital to future generations. Additionally, since global carbon resources are finite, reducing carbon emissions will transfer cheaper, more plentiful resources to future generations. Finally, the choice of climate change policy and the allocation of scarcity rents may have important inter-generational redistribution effects.

Besides the generational approach, three additional attributes of the model allow policy evaluation on dimensions previously not extensively explored in the literature. First, a new cohort of agents is born into the model in each year. This allows the results to capture in fine detail the distribution of benefits across agents and over time. Second, since the model is decentralized, its transitions are determined by the optimal consumption decisions of agents conditional on technology and policy. It is therefore possible to separate the normative issue of the choice of welfare function for policy evaluation from the specification of firm and agent behaviour. Policy evaluation results are therefore reported for a continuum of *ex post* social discount factors. Finally, the general equilibrium analysis provides a complete picture of the likely long-term growth and emissions consequences of climate policy.

This paper provides a comprehensive welfare analysis of four climate change mitigation policies. First, using the Kyoto protocol as inspiration, a binding emissions quota set to 6% below 1990 levels is imposed on the global economy. This policy is then relaxed slightly, constraining the economy to per capita emissions 6% below 1990 levels. For comparison, a price mechanism for emissions rights is imposed in the model in two ways; a flat rate tax of $10 per ton of carbon, which corresponds to the current price of a European carbon emissions future, and a time-varying tax which solves the optimal global policy problem proposed in Nordhaus and Boyer (2000). A key feature of the Kyoto protocol is the creation of internationally tradeable emissions permits. As the model here is one of a single world economy, this mechanism is not directly relevant but the effects are comparable to a hypothetical, global carbon tax. Tax revenues are assumed to be recycled lump-sum to agents, while the rights to carbon emissions are initially allocated to polluting firms. While the emissions constraint policies are shown to have the most important effects in terms of climate change mitigation, they place significant constraints on economic growth, and are shown to have negative net present value. Further, it is shown that the first generation to be made better off by these policies will not be born for more than 50 years after the policies are imposed. The tax mechanisms place less binding constraints on growth and emissions, and thus have less important mitigation effects. However, they are welfare-prefered to the *status quo* by all agents alive when they are imposed, as well as by all future generations.

Policies introduced in parties to the Kyoto protocol have favoured a grandfathering regime for emissions rights, which implies that much of the scarcity rent is allocated to the owners of current firms. [1], [2] The results of the present study show that the net present value of the Kyoto-style emissions constraint is negative for discount rates over one percent when these rights are allocated to previous emitters. In contrast, the results of an additional exercise show that, holding the constraint constant, when the emissions rights are allocated to agents on a per-capita basis rather than to firms, the sum of un-discounted willingness to pay for this policy is increased from $\$US_{1995}9$ trillion to over $\$US_{1995}33$ trillion.

To account for the uncertainty which exists regarding the possible severity of climate change, the policy analysis results are replicated for two additional scenarios which vary assumptions on the temperature change likely to be induced by a doubling of atmospheric CO_2 (see Wigley et. al. (1998)). This exercise clearly demonstrates that, while the costs of implementing climate change mitigation policy may be relatively certain, the long-run benefits of these policies are not. Thus, balanced inter-generational allocations of costs and benefits are perhaps critical to gaining support for adopting climate change policies.

The remainder of the paper proceeds as follows. The model is presented in Section 2. The solution and simulation algorithm is outlined in Section 3. The model is calibrated

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[1] The McCain-Lieberman Climate Stewardship Act, proposed in 2003 in the United States, provides for sector-based allocations of GHG emissions permits. The Canadian policy represents an extreme example of scarcity rent transfer, as the government has not only chosen to allocate permits based on historic emissions, but also to use tax revenues to insure firms against increases in the international price of permits above $15/ton.

[2] A parallel literature including papers by Fischer and Fox (2004), Burtraw et al. (2002), and Bovenberg and Goulder (2000) examines emissions permit allocation rules.

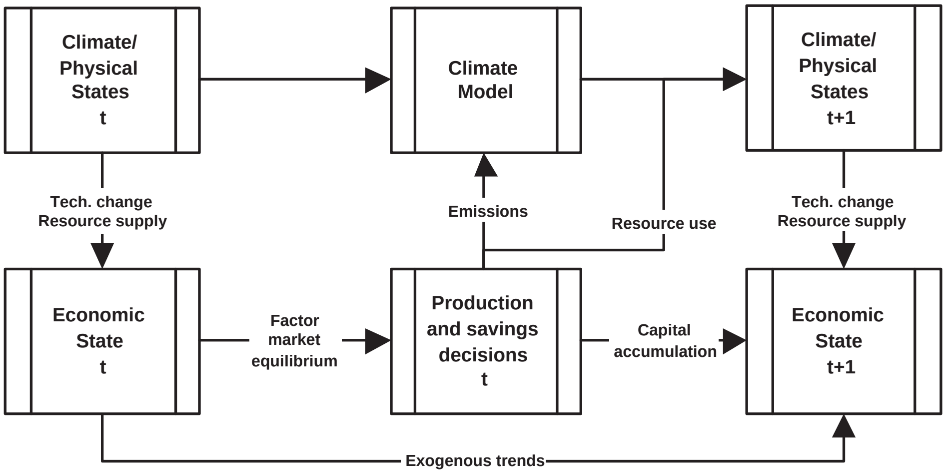

Fig. 1. Schematic Diagram of the Integrated Assessment Model

in Section 4. Section 5 presents the policy evaluation results. Section 6 concludes.

2 The Model

In this section, a framework that simultaneously models climate and the economy is introduced. The modeling strategy, shown in Figure 1, is similar to the DICE model in Nordhaus and Boyer (2000), where the use of carbon fuel in production affects global climate, which, in turn, affects factor productivity over a long time horizon. There are three important attributes of the model. First, the model is decentralized and solved for general equilibrium rather than for an optimal policy. Final goods are produced by a representative firm using carbon fuel, capital, and labour, for which it pays competitive prices. Second, overlapping generations of finite-lived agents supply capital and labour for final production. Finally, quasi-finite resource stocks extracted by competitive firms are included in the model, such that current resource use affects future extraction costs.

Competitive markets exist for three commodities in the economy: capital, K, effective labour, N, and carbon resources, R. Prices are defined as ι_t for a unit of physical capital, w_t for a unit of effective labour, and q_t for a ton of carbon-equivalent fuel. A government uses price mechanisms and quantity constraints to affect firms' decisions, and remits (collects) per-capita net proceeds (costs) to agents through lump-sum subsidies (taxes) in each period. The government is assumed to be able to implement emissions constraints at zero cost.

2.1 Agents

Labour supply is specified exogenously in the model and is independent of climate or factor productivity. A new cohort of agents, $N_{1,t}$, is born each period and supplies labour inelastically for L periods, after which they die. The effective labour supply of an age l agent is determined by age-specific productivity e_l which is time-invariant. The exogenous trend for the size of each cohort, given an initial condition, is given by:

$$N_{1,t} = N_{1,t-1}\left(1 + \gamma_n (1 - \delta_n)^t\right). \tag{2.1}$$

Aggregate labour supply, N_t, is given by the rule for the size of the new cohort born each period, a human capital profile ($e_l \, \forall l = 1..L$), and deterministic lifespan L:

$$N_t = \sum_{l=1}^{L} e_l N_{l,t}. \tag{2.2}$$

The optimal savings behaviour of agents determines the supply of capital in the economy. Each agent in a cohort faces the same optimization problem, since they begin with the same asset holdings, have the same certain lifetimes, and face the same income. Each agent is also endowed with a share of the resource extraction firm which pays a dividend in each period. Agents choose consumption and savings to maximize their lifetime utility, which is given by:

$$\sum_{l=1}^{L} \beta^{l-1} U(c_{l,t+l-1}). \tag{2.3}$$

where $\beta \in (0,1)$ gives the agent's discount factor, $c_{l,t}$ is consumption by an age l agent at time t. Utility is assumed to exhibit constant relative risk aversion, with risk aversion parameter σ such that

$$U(c_{l,t}) = \frac{c_{l,t}^{1-\sigma}}{1-\sigma}. \tag{2.4}$$

Income in each period comes from the gross rate of return on asset holdings net of depreciation δ_k, $r_t = (1 + \iota_t - \delta_k)$, labour income $w_t e_l$, a resource extraction dividend y_r, and fiscal redistribution τ_t, according to:

$$y_{l,t} \equiv w_t e_l + r_t a_{l,t} + y_r + \tau_t. \tag{2.5}$$

Agents allocate income, $y_{l,t}$, between the accumulation of assets in the form of claims on future physical capital, $a_{l,t+1}$, and consumption, $c_{l,t}$, according to the individual budget constraint:

$$a_{l,t+1} = y_{l,t} - c_{l,t}. \tag{2.6}$$

Agents retain ownership of capital net of depreciation.[3] Initial conditions for each cohort of agents are defined by their endowment $a_{1,t} \in \mathbb{R}$. A representative age l agent's optimal savings problem yields a system of difference equations:

$$\left(y_{l,t} + r_t a_{l,t} - a_{l+1,t+1}\right)^{-\sigma} = \beta r_{t+1}\left(y_{l+1,t+1} + r_{t+1} a_{l+1,t+1} - a_{l+2,t+2}\right)^{-\sigma} \forall l = 1..L, \tag{2.7}$$

the solution to which describes asset holdings through time, subject to a known sequence of capital rates of return and income. Agents are assumed not to value the consumption of other agents, either present or future, so there are no asset bequests or transfers in the model, and agents will set $a_{l,t} = 0 \; \forall \, l > L, t$. Aggregate physical capital, K, evolves according to agents' asset holdings decisions, such that:

$$K_t = \sum_{l=1}^{L} \left(a_{l,t} * N_{l,t}\right). \tag{2.8}$$

2.2 Carbon Resource Supply

Resource supply is treated, similarly to Nordhaus and Boyer (2000), by assuming that a firm, with ownership shared equally among the agents, provides resources competitively each period, such that price equals marginal extraction cost plus the cost of the carbon tax. The marginal cost of extraction (q_t) increases non-linearly in the cumulative extraction of carbon (X_t). Parameters values X^*, ξ_1, ξ_2, and ξ_3 are used to define the marginal extraction cost function given by:

$$q_t = \tau_t^c + \xi_1 + \xi_2 \left[\frac{X_t + R_t}{X^*}\right]^{\xi_3}. \tag{2.9}$$

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[3] Since agents own the capital stock, they bear the cost of depreciation of their assets. The relative incidence of this cost on the agent and the firm will be determined in equilibrium.

Carbon taxes add to the marginal costs of the carbon extraction firm, where τ_t^c is the carbon tax rate. Recall that per-capita tax revenues are assumed to be re-distributed lump-sum to agents in the model.

The cumulative extraction of the resource stock evolves as a function of resource use given by:

$$X_{t+1} = X_t + R_t. \tag{2.10}$$

This structure implicitly treats the extraction of resources as a common-pool problem. In this context, firms will extract resources in the current period until the offered price is equal to their extraction cost. While there is zero profit at the margin, since the resource extraction cost function is increasing, there will be producer surplus. To close the economy, this is remitted to agents as a per-capita dividend, y_r, in each period.[4] Accounting for the strategic use of resources by firms within an integrated assessment context represents an important direction for future work in this area.

2.3 Production

Production in the economy is Cobb-Douglas with three inputs: capital, K, labour, N, and carbon fuel, R, for which the representative firm faces competitive prices. Technology in production is specified by two parameters; total factor productivity Ω and energy efficiency ϕ, which maps carbon fuel into energy services. The firm also faces an emissions constraint, $\bar{R}$. Let the firm's constrained maximization problem be given by:

$$\max_{K_t,R_t} \Pi = \Omega_t \, K_t^{\alpha} \, N_t^{1-\alpha-\theta_t} (\phi_t R_t)^{\theta_t} - w_t N_t - \iota_t K_t - q_t R_t, \tag{2.11}$$

subject to:

$$R_t \leq \bar{R}_t. \tag{2.12}$$

The solution to the firm's problem in (2.11), subject to the Kuhn-Tucker conditions for the emissions constraint in (2.12), yields factor demands as a function of prices and the

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[4] The Nordhaus and Boyer (2000) RICE model includes a regional mark-up term to capture rent-seeking behaviour of firms with resource endowments. This is not considered in this paper and, as such, the model will account for an upper-bound on extraction.

shadow price of the emissions constraint, denoted by Λ_t:

$$\frac{\partial \Pi_t}{\partial K_t} = \iota_t, \tag{2.13}$$

$$\frac{\partial \Pi_t}{\partial N_t} = w_t, \tag{2.14}$$

$$\frac{\partial \Pi_t}{\partial R_t} = q_t + \Lambda. \tag{2.15}$$

The energy share of production, θ, is specified to be time varying. This allows the model to be consistent with the fact that global energy share in production has been declining over time, and when combined with the carbon-augmenting parameter ϕ, allows for carbon intensity and energy intensity to evolve separately over time.[5,6] The evolution of the value of θ over time is governed by growth rate γ_θ which declines at rate δ_θ according to:

$$\theta_t = \theta_{t-1} \left(1 + \gamma_\theta (1 - \delta_\theta)^t\right). \tag{2.16}$$

Similarly and using the same notation, the value of ϕ over time is determined according to:

$$\phi_t = \phi_{t-1} \left(1 + \gamma_\phi (1 - \delta_\phi)^t\right). \tag{2.17}$$

Total factor productivity in the model has exogenous and endogenous components. The exogenous trend for factor productivity, ω, is specified to be:

$$\omega_t = \omega_{t-1} \left(1 + \gamma_\omega (1 - \delta_\omega)^t\right). \tag{2.18}$$

The link between climate, emissions, and productivity occurs in the determination of total factor productivity, Ω_t, which captures the likelihood that changes in climate will lead to a lowering of our ability to use factors of production effectively.[7] As is standard in the

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[5] This structure is used in the RICE model to account for regional changes in the structure of their economy, but not in the global DICE model. (Nordhaus and Boyer, 2000)

[6] For a discussion of the potential sensitivity of model results to the choice of aggregate production function, the interested reader is directed to Saunders (1992). In Section 4, trend parameters for ϕ and θ are chosen to match historic data, with the implicit assumption that the economy will continue to be able to produce energy with fewer emissions, and output with less energy.

[7] The use of a feedback through total factor productivity is standard in the literature, with the exception of the use of labour-augmenting technical change as the affected measure in Pizer (1999).

literature, ω_t is reduced by a multiplier parameterized by values of b_1 and b_2 which is affected by changes in temperature, G_t:

$$\Omega_t = \frac{\omega_t}{(1 + b_1 G_t + b_2 G_t^2)}. \tag{2.19}$$

2.4 The Climate and Emissions Model

The climate model provides a law of motion for climatic state variables resulting from emissions of GHGs in production. A slightly modified Nordhaus and Boyer (2000) DICE climate model is used, and presented briefly below for clarity of notation.

2.4.1 The Carbon Cycle

The use of carbon resources in production leads directly to carbon emissions. Denote by m_t the atmospheric content of carbon, and by m_b the pre-industrial value for this measure. The atmospheric carbon retention rate is δ_m for current stock net of pre-industrial levels, such that the law of motion for atmospheric carbon is given by:

$$m_t = m_b + R_{t-1} + \delta_m (m_{t-1} - m_b). \tag{2.20}$$

2.4.2 Radiative Forcing and Temperature

Atmospheric carbon causes a change in radiative forcing, increasing heat retention. Recall that G represents deviations from the mean of surface temperature in ^oC, and let O represent the same measure for the change in temperature in the world's upper oceans. The evolution of temperature occurs through a slow warming of the world's oceans and atmosphere, which is prevented in the short run by thermal inertia, and is modeled as a two-stage process where surface temperature evolves according to:

$$G_t = \lambda_1 G_{t-1} + \lambda_2 \left(\frac{\log\left(\frac{m_t}{m_b}\right)}{\log(2)} \right) + \lambda_3 O_{t-1}, \tag{2.21}$$

and ocean temperature follows:

$$O_t = \lambda_4 O_{t-1} + (1 - \lambda_4) G_{t-1}. \tag{2.22}$$

The value of parameter λ_2 is measured in ^oC, while other parameters have scalar values. These laws of motion parameterize the long-run warming for a doubling of atmospheric carbon as $\frac{\lambda_2}{1-\lambda_1-\lambda_3}$.[8] Parameters values for $\lambda_1 \in (0, 1)$ and $\lambda_4 \in (0, 1)$ capture the persistence of deviations in surface and ocean temperature respectively. Recall that it is the value of G_t that feeds back through (2.19) to generate total factor productivity.

3 Dynamics and Computation

In order to characterize the transition path of the model economy, an intuitively appealing algorithm which solves for prices along the transition path is used. A sequence of three prices, $\{\iota, w, q\}_{t=1}^{\infty}$, determines the supply and demand of each of the traded commodities in the economy. Although the economy has no terminal conditions, it is comprised of a series of finite-horizon problems. Since the lives of agents and firms are finite, it is possible to solve for the the evolution of the economy over a significant but finite horizon, denoted by $t = 0..T$ with minimal approximation error.

Two assumptions are used to render the model finite. In the first time period, cohorts of agents of ages $1..L$ are introduced to the economy, each with an initial asset endowment. Since they are born at an age greater than 1, these agents live shorter lives than would otherwise be the case. Agents born after $t = T - L$ are assumed to live their full lives, but to face period-T prices for every period until their death. Given this truncation, equilibrium is defined as follows:

Definition 1 *Equilibrium along the transition path is defined by a sequence of prices* $(\iota_t, w_t, q_t)_{t=1}^{T}$ *for capital, labour, and resources and time horizon* T*, given population, initial physical states and a positive, initial capital endowment. Along the transition path, the price sequence must be such that:*

(1) Agents supply capital in accordance with their Euler equations given in (2.7) and supply labour inelastically.

(2) Resources are supplied at marginal cost according to (2.9).

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[8] The characterization of forcing relative to that produced by a doubling of atmospheric CO_2 is standard in both the scientific and economic literature on climate change.(see Nordhaus and Boyer (2000) or Wigley et al. (1998).)

(3) The firm maximizes profits subject to emissions constraints as given in (2.13-2.15).
(4) Factor markets for capital, labour, and resources clear.

The computational algorithm uses a sequence of prices to evaluate a corresponding sequence of excess demands, and adjusts prices to converge to the vector of prices which satisfies the equilibrium conditions over time. Given a convergence criterion, the transition path of the economy from starting values is established as follows:

Algorithm 1
Objective: Solve transition path for the parameterized model of climate and economy given initial state variables and a convergence criterion ϵ.

Preliminaries: Choose T *and an initial guess for the sequence of prices* $\{w_t, \iota_t, q_t\}_{t=0}^{T}$.

Step 1: Solve the system of Euler equations (2.7) given the sequence of prices for all time periods. This solution determines capital supply.

Step 2: Solve for the capital demanded by the final production firm in each period given prices using (2.13).

Step 3: Set the capital stock equal to the average of capital demand and supply.

Step 4: Compute a new guess of prices iteratively for each period as follows:

4.1. Solve for equilibrium in the carbon resource market using (2.9) and (2.15) given capital stock, exogenous labour supply, and climate-induced productivity changes.
4.2. Solve for equilibrium wages given resource supply calculated above, exogenous labour supply, and climate-induced productivity changes using (2.14).
4.3. Update the interest rate given capital, resource, and labour supplies and climate-induced productivity changes using (2.13).
4.4. If not in the last period, use emissions and the climate model defined by (2.20-2.22) to update climate-induced productivity for the next period.
4.5. If not in the last period, return to 4.1.

Step 5: Evaluate convergence measure as the sum of squares of the elements of the $T \times 1$ *vector of excess capital demands, and return to Step 1 if the convergence criteria is greater than* ϵ.

4 Calibration

To calibrate the model, parameter values are chosen to match economic and climate data from 1971-2002, and projections for 2003-2050 provided in United Nations (UN) (2004) and the International Energy Agency (IEA)(2004). Since the data do not allow all parameter values to be directly identified, some values are fixed in accordance with the literature. Below, the sources of parameter values and initial conditions for the climate model and the calibration of the economy are presented in turn.

4.1 Climate and Emissions Sectors

Values for the set of parameters λ which defines the evolution of the temperature system are established as follows. The coefficient of autoregression in surface temperature, $\lambda_1 = .947369$, and ocean temperature $\lambda_4 = .002$, as well as the mixing parameter $\lambda_3 = .01012$ are set to values used in the DICE model of Nordhaus and Boyer (2000), adjusted to annual rates. The parameter λ_2, which is a key parameter of interest in the model, is set to capture a 2.98^0C change in long run temperature for a doubling of atmospheric CO_2. This is consistent with both Nordhaus and Boyer (2000) and Pizer (1999).

While the model discussed in this paper assumes perfect foresight, it is important to examine the sensitivity of the conclusions to different assumptions about climate change; in particular, the temperature response to changes in carbon levels. In the benchmark case, parameters in the climate system allow for a temperature increase of 2.98^oC for a doubling of atmospheric carbon. In Knutti et al. (2002), a probability density function for this relationship is developed, and it is consistent with the findings of this study to specify a confidence interval of 1.5^oC around this relationship. This is captured in the present study through a re-calibration of λ_2 to generate temperature increases of 1.5^oC and 4.5^oC for a doubling of atmospheric carbon.[9] This increase (decrease) in the value of λ_2 is labeled the pessimistic (optimistic) scenario for climate change.

The model uses the quadratic relationship in (2.19) to map deviations in global surface temperature into an average decline in global factor productivity, and abstracts from

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[9] This is also consistent with the findings of the Intergovernmental Panel on Climate Change (2001).

Table 1
Initial Period (1970) Values

Variable	Description	Calibrated Value
K_0	Capital Stock, US$_{1995}$	35.78×10^{12}
N_0	Effective Labour Supply	3550×10^6
m_0	Atmospheric CO_2 levels, GtC	690.6
G_0	Surface temperature change, ^oC	.2946
O_0	Ocean temperature change, ^oC	.05146

regional differences. The parameter values defining this mapping are chosen to match those used in Nordhaus and Boyer (2000).

The parameter values for the benchmark climate scenario are reported in Table A.1. Initial (1970) values for climate states, shown in Table 1, are endogenous products of simulations with starting (1950) values fixed as follows. Initial atmospheric carbon is taken from Joos and Siegenthaler (1999). Initial surface temperature is taken from Jones et al. (2005), and initial ocean temperature is fixed to be at its average level (i.e. $O_0 = 0$).

4.2 Economic Sector

The calibration of the economic sector of the model proceeds iteratively from parameters which can be calibrated directly from the data toward those which must be fixed using endogenous behaviour in the model.

Starting values and trend parameters for population growth are fixed such that the model population matches patterns of population from the UN (2004) data and median projections on world population. Initial population is shown in Table 1, and Figure A.1 shows the population of agents in the model, who are assumed to live from age 16-76, compared with UN median global population estimates for people over the age of 15. Sensitivity analyses are also reported using a high-growth scenario. This is derived by imposing less decay in the growth rate for initial generation size, $\delta_n = .04$, such that the model population matches historic population data, but grows to close to 15 billion people, which is consistent with the high growth scenario from UN (2004).

Fig. 2. Earnings Profile (Productivity ratio to mean=1)

An earnings distribution is used to calibrate age-specific human capital, as in Huggett (1996). Data are obtained from the Canadian Labour Force Survey, 1998.[10] Median wages for agents in 5 year age groups are used to construct the productivity profile, and the remaining wages are interpolated using a cubic spline. The values are adjusted so that the mean labour contribution is 1 unit. The resulting age-earnings profile is shown in Figure 2.

The carbon intensity of energy is parameterized to match data and predictions for the same values in IEA (2003). The exogenous trend for ϕ, the ratio of gigaton-oil-equivalent (Gtoe) energy units to carbon emissions in gigatons (GtC), is calibrated with starting value $\phi_0 = 1.30$, and growth rate parameters $\gamma_\phi = 0.0121$ and $\delta_\phi = 0.0519$.

Certain parameters of the model are not readily identifiable in the data. Agents' saving behaviour is fixed using the Pizer (1999) values for the coefficient of relative risk aversion of $\sigma = 1.2213$ and the discount factor of $\beta = .96$. Since agents do not face uncertainty over future prices, these values serve to determine the agents' intertemporal substitution of consumption.[11] Capital depreciation is fixed at $\delta_k = .045$. The capital share in production

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[10] The Canadian data are used as a proxy for the difference in productivity levels by age. Wage rates are determined in equilibrium.

[11] These parameter values will generate more savings and smoother optimal consumption profiles than those in Nordhaus and Boyer (2000), which uses logarithmic utility and a discount factor

is fixed by setting $\alpha = .3$, which is identical to the value in the regional model of Nordhaus and Boyer (2000), which, like the present model, has energy as a separate argument in the production function.

Finally, the laws of motion for exogenous factor productivity and the energy share of production are fixed numerically. The model is solved for 280 time periods, and the first 20 periods and last 60 periods are removed from the analysis, leading to 200 periods of reference, taken to begin in 1970.[12] The capital stock in the initial period of the reference sample, shown in Table 1, is an endogenous result of the simulations. The benchmark simulation begins with a 1950 capital stock of 35.227. Optimal savings behaviour then determines the capital distribution at the beginning of the reference period. In order to reduce the sensitivity to this initial allocation, capital was distributed among the initial cohort in the same ratio as was predicted by the model for agents in the 2050 birth cohort, however, to ensure tractability for all possible price vectors, agents in the initial cohort are not endowed with debt. A quasi-Newton minimization algorithm is used to choose the values of the trend parameters which minimize the sum of squared residuals between model simulations and the GWP and primary energy supply data. The energy share of production is calibrated with starting value $\theta_0 = 0.0287$, and growth rate parameters $\gamma_\theta = -0.0116$ and $\delta_\theta = 8.36 * 10^{-4}$. The evolution of exogenous factor productivity is found to be best described by starting value $\omega_0 = 0.0192$, and growth rate parameters $\gamma_\omega = 0.00905$ and $\delta_\omega = 5.27 * 10^{-7}$.

The ability of the model to match population, gross world product, energy use, and carbon emissions data is shown graphically in Figures A.1 to A.4.

5 Policy Evaluation

Having solved the business-as-usual (BAU) version of the model under the benchmark climate scenario for calibration, two types of policies are imposed in the economy. The

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of $\beta = .9$. This effect is magnified slightly by the choice of a lower rate of capital depreciation, $\delta_k = .045$. For a comprehensive discussion of the effect of these parameters on agents' savings behaviour, see Kocherlakota (1996).

[12] The model is solved and simulated using Ox Version 3.30. (Doornik, 2003). The convergence criterion used is $\epsilon = 10^{-4}$.

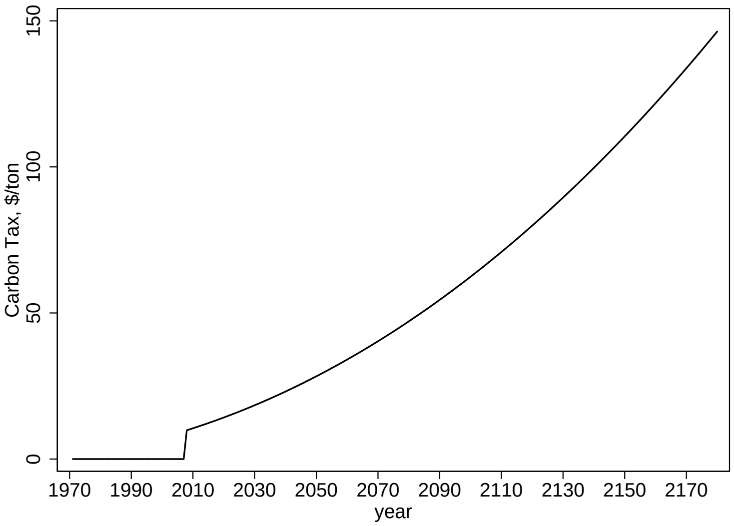

Fig. 3. Nordhaus and Boyer Optimal Carbon Tax

model admits both carbon taxes and emissions constraints, which are discussed in turn. The effects of policies on the physical and economic environment are reported, and followed with discussion of how the costs and benefits of these policies are distributed across generations. Each set of results is subjected to sensitivity analysis using the optimistic and pessimistic climate change scenarios.

The set of feasible tax policy choices is countably infinite, so policies which are representative of the choices available to policy-makers are imposed. The optimal carbon tax profile for the DICE model in Nordhaus and Boyer (2000), shown in Figure 3 is contrasted with a constant carbon tax of \$10 per ton, which corresponds roughly to current prices of emissions futures on global markets. Each of the taxes are imposed as of 2008.

Binding emissions quotas, $\{\bar{R}_t\}_{t=0}^{T}$, are introduced to the model to examine the effects of fixing emissions to a particular aggregate level or a fixed quantity per capita. In particular, two emissions quota policies are considered. First, a Kyoto protocol-style quota constraining the economy to emissions of 6% below 1990 levels for periods beyond 2008 is imposed. This is contrasted with a time-varying quota which maintains the same per capita emissions levels as the Kyoto-inspired quota imposes for 2008. Since population is exogenous, it is possible to specify a per-capita constraint without altering the structure of the final production firm's problem shown in (2.11).

5.1 The Growth and Temperature Effects of Policy

Climate change mitigation policies will have important effects on economic growth. Agents compute their optimal savings decisions as a function of future wage rates and returns to physical capital, each of which will be influenced by climate policy. The aggregate effects on the economic and physical environment are detailed below.

5.1.1 Benchmark Climate Change Scenario

Initial differences in total output constitute an aggregate measure of the cost of future environmental capital. The immediate slowdown effects induced by each of the policies are shown in Figure A.5. It is also important to note evidence of the effect of policies on capital accumulation in this Figure, where production increases slightly in the periods before the policies are put into place as agents accumulate savings to smooth consumption over future periods.

The climate change mitigation effects of the policies are shown in Figure A.6. The model predicts a temperature change of $2.87^{o}C$ after 100 years under the BAU assumptions. The emissions quotas have the largest effect here, reducing this by over $1^{o}C$ for both the level and per-capita quota. The effects of the taxes are less important, measuring less than half a degree. The damage-mitigation effects of each of the policies are reflected through changes in total factor productivity, Ω, under each of the policies, relative to that of the BAU transition. These effects are shown in Figure A.7.

Changes in the economy's emissions profile, leading to changes in surface temperature, are the means through which eventual benefits of the policies are delivered. Cumulative emissions are predictably lower after the implementation of each of the policies. Figure A.8 shows the changes in atmospheric carbon dioxide concentration induced by each of the policies.[13] The quota policies are more stringent, and each stabilize the concentration of carbon within 100 years, while carbon concentrations are still increasing after 100 years under each of the tax policies.

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[13] In this Figure, ppmv is used as the unit of measure to provide a point of reference to CO_2 concentration stabilization scenarios often reported in the literature. The relevant conversion factor is 1 ppm by volume of atmospheric $CO_2 = 2.13$ GtC.

5.1.2 Sensitivity to Climate Change and Growth Assumptions

In the calibration of the model, optimistic and pessimistic climate change scenarios were introduced. The temperature effects of the policies under each of the assumptions give context to the scenarios. The BAU temperatures in 2108 are respectively 1.46^oC and 4.28^oC in the optimistic and pessimistic scenarios, compared to the benchmark scenario temperature change of 2.87^oC. Figures A.9 and A.10 show the evolution of temperature under the additional scenarios for each of the policies.

The effects of policies on aggregate economic performance are clearly sensitive to the choice of climate change scenario. Consider Figures A.11 and A.12 which show the policy-induced output changes under each of the policies for the optimistic and pessimistic scenarios. This figure captures an important aspect of the climate change policy debate: the costs of climate change policy are much more certain than are the benefits. Under the optimistic scenario, GWP is negatively affected for over 100 years by each of the policies, while under the pessimistic scenario, each of the policies has positive economic effects within 50 years.

The transition path of the economy is also sensitive to the assumed population trend. Under the high-growth population scenario and without mitigation policies, a temperature change of 3.08^oC occurs by 2108 as a result of increased economic activity from the larger population. GWP, emissions, and energy use all outstrip baseline values during the entire model period. Intuitively, the increased magnitude of baseline climate change is such that the policies have marginally greater benefits in the future, while initial costs are identical. The exception to this is the emissions quota, for which the growth constraint imposed on the economy becomes much more costly as population increases.

5.2 The Welfare Effects of Climate Policy

Above, the aggregate costs and benefits of each of the policies are characterized. The overlapping generations structure allows the distribution of costs and benefits across agents to be used as a measure of policy evaluation, which is not possible in a representative, infinitely-lived agent model. Although agents have perfect foresight about future rates of return to capital and income, they do not internalize the effects of their capital accumulation decisions on other cohorts of agents. The social cost of carbon extraction is also not internalized by either the extraction or production firms. Of course, there also does not exist a market through which future cohorts can purchase current output or emissions reductions. As such, there will be a scope for policy to improve welfare by correcting these externalities.

Agents' lifetime indirect utility provides a utilitarian measure of welfare in the present study. It is traditional in the IAM literature to define optimal policy as that which maximizes a population-weighted sum of discounted, per-capita utility. An analog to this traditional social welfare function in the OLG context is:

$$W \equiv \sum_{t=0}^{T} \rho^t N_{1,t} \sum_{l=1}^{L} \beta^{l-1} U(c_{l,t+l-1}) = \sum_{t=0}^{T} \rho^t N_{1,t} V(t). \tag{5.1}$$

The discounted summation over L defines the private welfare from consumption for an agent born in time t. Where consumption choice is decentralized, this is equivalent to the indirect utility for an agent born in time t, denoted by V(t). This value is aggregated by the number of agents in the cohort born at time t, $N_{1,t}$, and discounted by a social discount factor, ρ. The social discount factor has no impact on the transition of the economy, and only determines the importance placed on the distribution of consumption across cohorts, *ex post*. Where the social discount factor is set to one, social welfare is the sum of the utilitarian measure for all agents born during the investigation horizon, and values of $\rho < 1$ ($\rho > 1$) place less (more) weight on the utility of agents born in later time periods. The social discount factor is set to $\rho = 1$ to derive initial results, and then varied to test sensitivity to this assumption in Section 5.2.3.

A measure of compensating or equivalent variation for each policy choice is complicated by the dynamic, general equilibrium nature of the model. There exists an infinite number of potential sequences of transfers over time which would make an agent indifferent between the policy and the BAU transition path. For this reason, a compensating variation in first period consumption is used. While this is not immune to the fact that, were this transfer to be offered to agents, it would both distort their savings decisions and have general equilibrium effects in the market for capital, the measure is meant only to translate the values from utility units into a more informative measure in units of output.

In particular, the following definition of compensating variation of a policy choice is used. Denote by $V_B(t)$ and $V_P(t)$ the indirect utility for an agent born at time t under the

Table 2
First birth cohort made better off by climate policies, by policy and scenario

Policy	Optimistic Scenario		Benchmark Scenario		Pessimistic Scenario	
\$10/ton Carbon Tax	2000	(1)	1996	(1)	1986	(1)
1990 per capita emissions quota	NA	(3)	2061	(3)	2034	(3)
Nordhaus and Boyer Tax Profile	2003	(2)	2000	(2)	1991	(2)
5.40 GtC quota	NA	(4)	2063	(4)	2036	(4)

*Policy rankings in brackets. NA implies that, within the sample period, no generation is better off under the policy than under the BAU transition. Tie-breaker for rankings is the least costly in the last period.

BAU and policy simulations respectively. Similarly, denote by $U(c_{1,t}^P)$ the utility from first period consumption under the policy choice. The compensating variation for cohort t, κ_t, is derived by solving the following:

$$V_B(t) - V_P(t) = U(\kappa_t c_{1,t}^P) - U(c_{1,t}^P). \tag{5.2}$$

The solution to this equation for κ_i defines the relative change in first period consumption that would be required in order to make an age i agent indifferent between the policy and the BAU transition. Thus, $(\kappa_t - 1)c_{1,t}^P$ is the compensating variation in consumption units.

5.2.1 Benchmark Climate Change Scenario

The results of the welfare evaluation demonstrate the importance of addressing the distribution of policy benefits across generations. Table 2 provides a sense of the delay in the onset of benefits from the policies. The first generation made better off by least stringent of policies, the \$10/ton tax, is the generation born in 1996, 12 years before the policies are instituted. Conversely, the quota policies fare worst, with the first cohort made better off being born 55 years after the policies are implemented. This is a result of the fact that even today's young are not alive long enough to see the effects in terms of climate change mitigation, while they bear most of the costs of economic slowdown. In contrast, the tax policies are prefered since they provide a per-capita income transfer. The carbon tax recycling has much larger benefit to younger agents, since agents no longer have to borrow as much to smooth consumption.

Figure A.13 shows the compensating variation for agents born in each time period of the model for each of the policies. The constant emissions quota policy places the greatest constraint on the economy, and thus has high costs to young agents, but comes with important future benefits such that future generations are made better off by the quota than by any of the other policies. The generation made the worst off by the quota, born in 2031, are indifferent between this policy and a 14.6% cut to their first period consumption (equivalent to a transfer of $\$US_{1995}96.5 \times 10^9$), while the generation born in 2108 would be willing to pay the equivalent of $\$US_{1995}784 \times 10^9$ for the quota policy to be imposed. Since it solves an optimal policy problem, it is not surprising that the Nordhaus and Boyer tax balances benefits and costs. In fact, this policy imposes a maximum 1% cut to first period consumption on the most affected generation, while the best off generation receiving the equivalent of a 30% subsidy.

5.2.2 Sensitivity to Climate Change Assumptions

Climate change mitigation policy is an investment in future environmental capital, and the severity of climate change determines the rate of return to this investment. As such, the distribution of benefits over time, and thus cohort welfare levels, will be greatly affected by assumptions on the severity of climate change. This is confirmed in Table 2, where the most stringent policy, the constant emissions quota, shows positive welfare effects 33 years earlier than under the benchmark case. Conversely, no generations born within the considered time horizon are made better off by the quota policy under the optimistic assumptions. The tax policies continue to do well under all scenarios, again for the important reason that the carbon tax recycling provides benefits to younger agents.

Figures A.14 and A.15 show the magnitude of the welfare effects under the optimistic and pessimistic scenarios. In these figures, a very important problem facing policy makers is highlighted; the costs of climate change mitigation are much more certain than benefits. While future agents might be willing to pay substantial amounts for emissions reduction today if climate change is severe, as in Figure A.15, the policy maker must weigh this against the fact that, under more optimistic forecasts, future generations actually bear a cost of climate policies, as shown in A.14. Current generations see the certain costs, and uncertain benefits, and these are likely to weigh against our will to act.

Table 3
Net present (2005) value, by discount factor, of compensating variation transfers in billions of $1995US

	Social Discount Factor (ρ)							
Policy	0%		1%		5%		10%	
Nordhaus tax	16812.79	(1)	7685.86	(1)	607.25	(2)	43.72	(1)
Per-capita quota	9854.09	(2)	2341.08	(3)	-2125.13	(3)	-2930.61	(3)
5.40 GtC quota	9010.76	(3)	1665.44	(4)	-2438.43	(4)	-3228.19	(4)
$10/ton tax	5850.54	(4)	2838.04	(2)	319.25	(1)	40.7210	(2)

* Policy rankings in brackets.

5.2.3 The Net Present Value of Climate Change Mitigation

Much of the literature on optimal climate change policy seeks to maximize a social welfare function as described in (5.1), with a social discount factor $0 < \rho < 1$. In this model, the social discount factor only has an *ex post* role, such that it is possible to test the sensitivity of policy evaluation to the specification of the social welfare function, without distorting assumed agent behaviour.

The welfare metric defined in (5.2) represents the consumption increase that would have to be offered to an agent in a particular cohort to render them indifferent between the policy and the BAU transition paths. The net present values of these transfers, using discount factors of 0, 1%, 5%, and 10%, are reported in Table 4.[14]

The policy ranking and, to a greater degree, the net present value are sensitive to the chosen social discount factor. Table 4 can first be interpreted as a measure of the sensitivity to which optimal policy models may be subject in terms of the choice of the discount factor. We also see that, among the policies studied, only the tax-based policies have a positive net social benefit when any discounting over 1% is applied. This is partly as a result of the tax policy being a less stringent policy, allowing the economy to use more resources than under either of the quota policies. There is however another important difference;

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[14] It is important to note that all measures of social welfare, particularly where negative discounting is applied, are sensitive to the truncation of the economy. This introduces a downward bias in most cases, as long as the benefits to climate change mitigation policies are increasing in time. There may also be a bias for policies which have significant benefits or costs to older agents born before 1970, which are not included in the NPV.

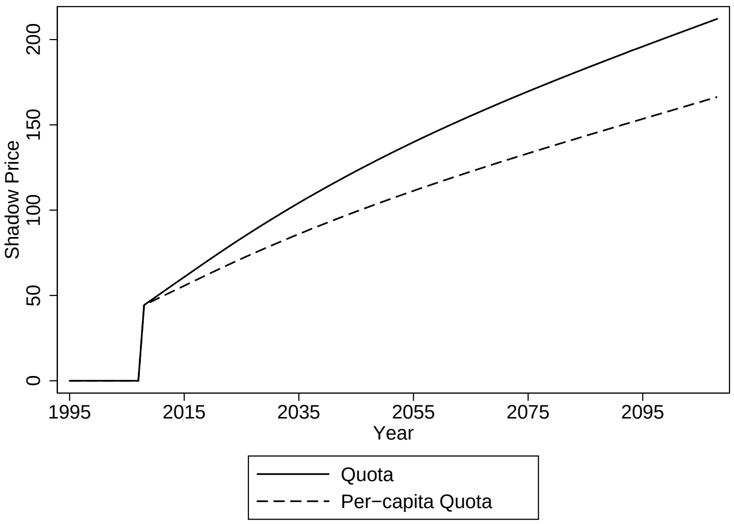

Fig. 4. Shadow prices ($/ton C) of the level and per-capita emissions constraints.

the tax revenues are recycled on a per-capita basis to agents while the permit rents are captured in higher proportion by the owners of the capital stock and those with the most productive labour endowment. In the next section, we explore the effect of altering this assumption such that scarcity rents of the permits are captured on a per-capita basis.

5.3 Revenue Recycling and Scarcity Rent Capture

Climate policies create scarcity rents. To this point, climate policies introduced worldwide have tended to prefer the grandfathering of emissions rights to firms, effectively allocating the majority of the scarcity rents (equiv. the value of the property rights) to the owners of the firms. In the simulations of the model proposed above, the policies are imposed such that there are important differences in terms of the capture of scarcity rents. The revenues from the carbon tax are assumed to be remitted as per-capita, lump-sum payments, while the emissions quota is designed such that the scarcity rents are, in effect, captured by the final production firm since they continue to pay the competitive price for carbon resources. This has an obvious effect on welfare, visible clearly in the payback periods shown in Table 2 and in the net present values shown in Table 4.

In order to show the importance of scarcity rent capture and recycling, the following change is introduced. Assume that emissions rights are allocated to the resource extraction

Table 4
Net present (2005) value, by discount factor, of compensating variation transfers in billions of $1995US by allocation of emissions rights.

	Social Discount Factor (ρ)							
Policy	0%		1%		5%		10%	
Per-capita quota								
Allocation to firms	9854.09	(4)	2341.08	(3)	-2125.13	(3)	-2930.61	(3)
Per-capita allocation	31735.25	(3)	14441.96	(2)	924.371	(1)	-404.49	(1)
5.40 GtC quota								
Allocation to firms	9010.76	(2)	1665.44	(4)	-2438.43	(4)	-3228.19	(4)
Per-capita allocation	33135.77	(1)	14942.98	(1)	842.96	(2)	-536.05	(2)

* Policy rankings in brackets.

firm, such that the final production sector much purchase both carbon fuel (at marginal extraction cost) and emissions rights (at the shadow price of the constraint). This is equivalent to allocating rights on an annual, per-capita basis, but computationally more tractable.[15]

In Figure 4, the shadow prices of the constant emissions and constant per-capita emissions constraints are shown. Allocating valuable emissions rights to agents implies an important transfer of wealth across generations, since the younger agents benefit from the transfer at the point where their consumption would have been most affected by the policies. In the original results, the first cohort made better off by the emissions constraint was born in 2063, while the first cohort made better off under the per-capita constraint was born in 2061. Allowing agents to capture a per-capita share of the scarcity rents changes these dates to 2005 and 2004 respectively, meaning that all generations born after the policy is introduced would be made better off.

In terms of net present value, consider Table 3 where the results for the quota policies are re-calculated with the per-capita capture of scarcity rents. These results clearly show the impact of revenue recycling. Further, even with a 5% discount factor, the quota policies with per-capita allocation also outrank each of the tax policies. In this case, the agents receive a large, per-capita transfer of scarcity rents which compensates them for having

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[15] This is also equivalent to maintaining the structure of the carbon tax, but setting its value to the shadow price of the emissions constraint in each period.

to live in a period of policy-induced economic slowdown.

6 Conclusions

The question of how we measure the costs and benefits of climate change mitigation policies is an important one. As evidenced in this paper, it is difficult to rank policies based on the predicted outcomes and have that ranking be impervious to uncertainty or to social discounting. The simulations demonstrate the fact that, while policies pass on a cleaner, more productive environment to future generations, these effects can be tempered by the growth constraints placed on the economy, specifically if the policy represents an input choice constraint. It is also shown that present-day policy makers must weigh reasonably certain current period costs against uncertain future benefits. In such an environment, the choice of policies which balance inter-generational allocations of costs and benefits is perhaps critical to gaining support for adoption.

The most important results of this paper are in terms of the welfare implications of revenue recycling and scarcity rent capture. While most policies thus far implemented world-wide have grandfathered rights based on previous emissions, it is shown that the net present value of a policy such as the Kyoto protocol may be up 7 times higher where the scarcity rents can be captured on a per-capita basis rather than by firms. Perhaps more importantly still, stringent climate change mitigation policies may be rejected on the basis of having a negative net present value where firms or older agents capture the rents, while these same policies would have significant, positive net present value were these rents able to be captured by the population as a whole. This suggests that it is certainly possible to set stringent climate policy which makes all agents at least as well off, and many cohorts of agents substantially better off.

The contribution of this paper is also, in part, methodological. The model presented here, and the solution and calibration algorithm provide a framework in which to answer many questions not extensively explored in the literature. These include issues of voting and endogenous climate policy, research and development under technology competition, and examination of secondary benefits to climate change mitigation, where the effects of reduction in other pollutants is likely to have age-specific effects.

It is clear that there are many assumptions required to calibrate a model to match the evolution of global economic variables. Furthermore, many of the variables fixed as exogenous processes in this paper will certainly be affected both by climate change and climate change policies. Specifically, the assumptions governing the evolution of the emissions efficiency of energy supply and the energy share in production are likely to have significant endogenous components. There are also very important regional aspects of the economic and physical environments which have been abstracted from in this paper. Nevertheless, the conclusion that redistribution of policy-induced scarcity rents may greatly alter the welfare gains realized through climate change mitigation policies is likely robust to these approximations.

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Table A.1
Calibrated and Fixed Parameter Values

Parameter	Description	Value
Fixed Parameters, Economic Sector		
σ	Coefficient of relative risk aversion	1.2213
β	Discount factor	.96
δ_k	Capital depreciation rate	.045
α	Production share of capital	.3
ξ_1	Minimum extraction cost of carbon($)	113
ξ_2	Linear rate in extraction cost of carbon	700
ξ_3	Exponent in extraction cost of carbon	4
Exogenous Trends, Economic Sector		
θ_0	Initial production share of resources	.0287814
γ_θ	Growth in production share of resources	-0.011604
δ_θ	Decay rate of production share of resources	0.000836023
ω_0	Initial factor productivity	.0191563
γ_ω	Growth rate of factor productivity	0.00905337
δ_ω	Decay rate of γ_ω	$5.26718 * 10^{-7}$
ϕ_0	Initial emissions intensity of energy	1.30316
γ_ϕ	Growth rate of emissions intensity of energy	0.0121315
δ_ϕ	Decay rate of γ_ϕ	0.0519368
N_{00}	1970 birth cohort	$101.66 * 10^6$
γ_n	Growth rate of population	0.02
δ_n	Decay rate of γ_n	.03
Fixed Parameters, Climate Sector		
m_b	Preindustrial concentration of CO_2	590
δ_m	Atmospheric retention of carbon	.9846
λ_1	AR(1) parameter for temperature deviations	.947369
λ_3	Rate of mixing for ocean and surface temperature	0.01012
$\frac{\lambda_2}{1-\lambda_1-\lambda_3}$	Temperature sensitivity to CO_2 doubling	2.980
λ_4	AR(1) parameter for ocean temperature deviations	0.002
b_1	Linear component in damages from temperature changes	-0.0045
b_2	Quadratic component in damages from temperature changes	0.0035

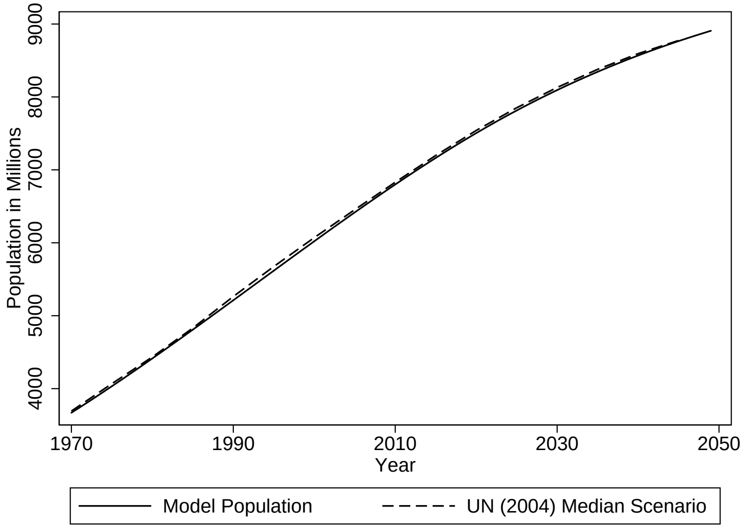

Fig. A.1. Population: Model and UN Projection

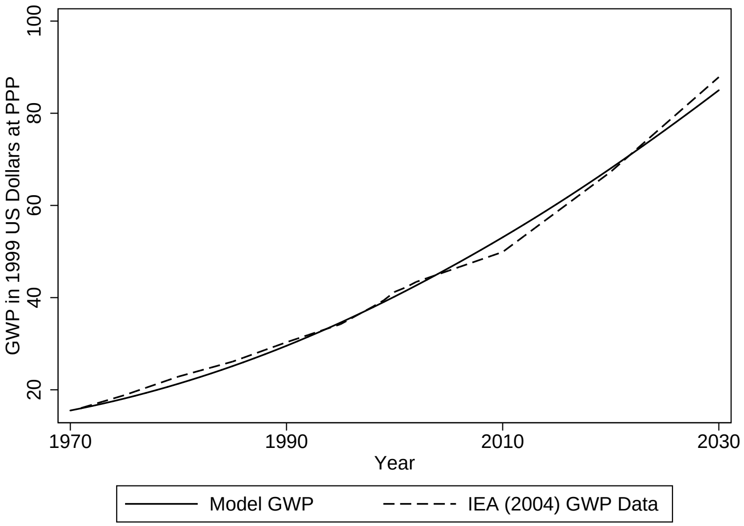

Fig. A.2. Predicted and Actual Gross World Product

Fig. A.3. Predicted and Actual Total Primary Energy Supply

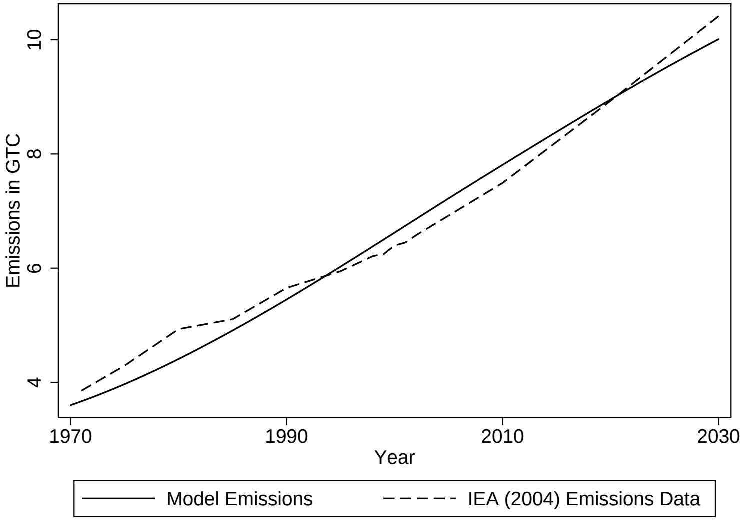

Fig. A.4. Predicted and Actual Emissions

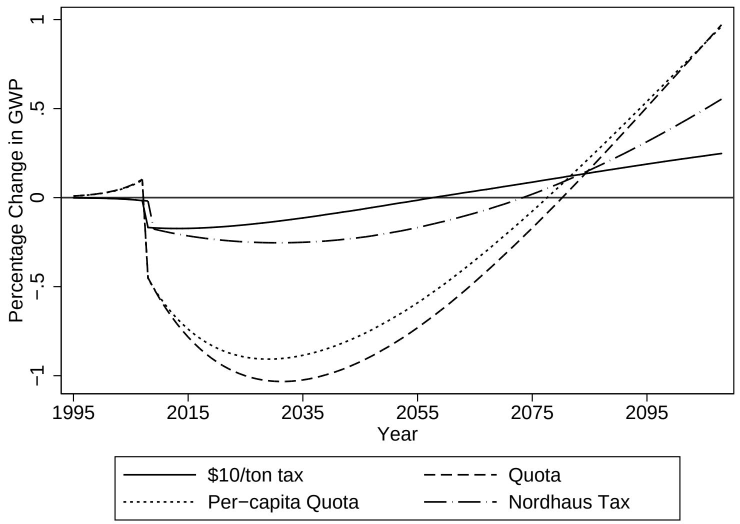

Fig. A.5. GWP changes (%) by policy, benchmark climate scenario

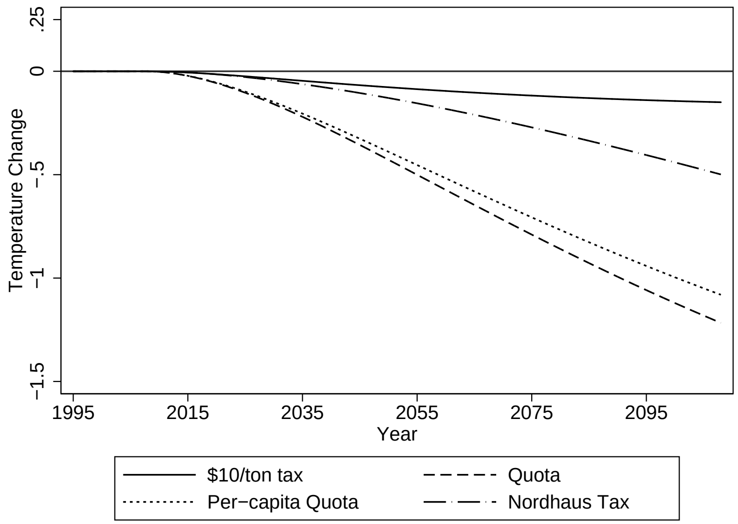

Fig. A.6. Temperature changes (^{o}C) by policy, benchmark climate scenario

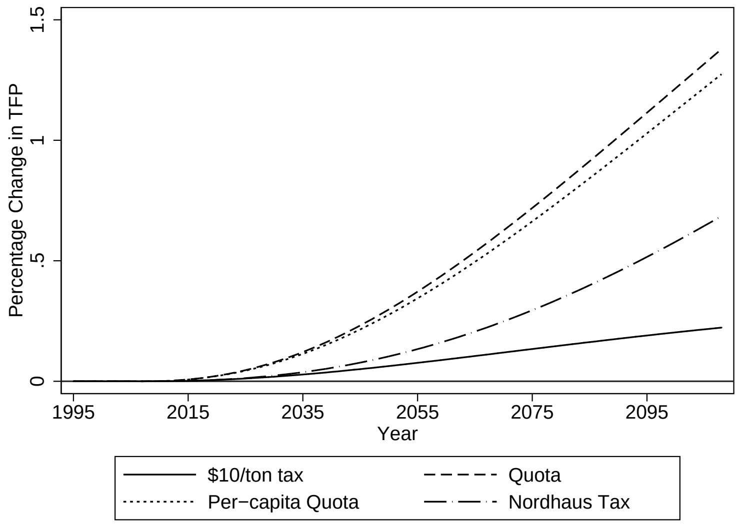

Fig. A.7. Total factor productivity changes (%) by policy, benchmark climate scenario

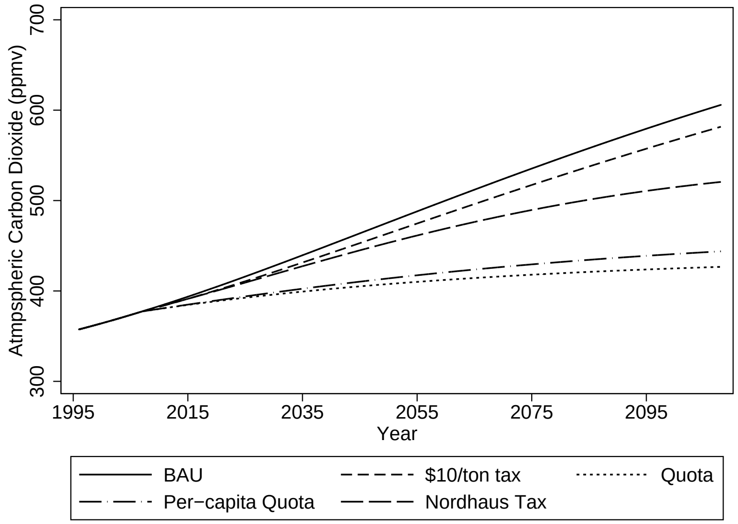

Fig. A.8. Atmospheric CO_2 (ppmv) by policy, benchmark climate scenario

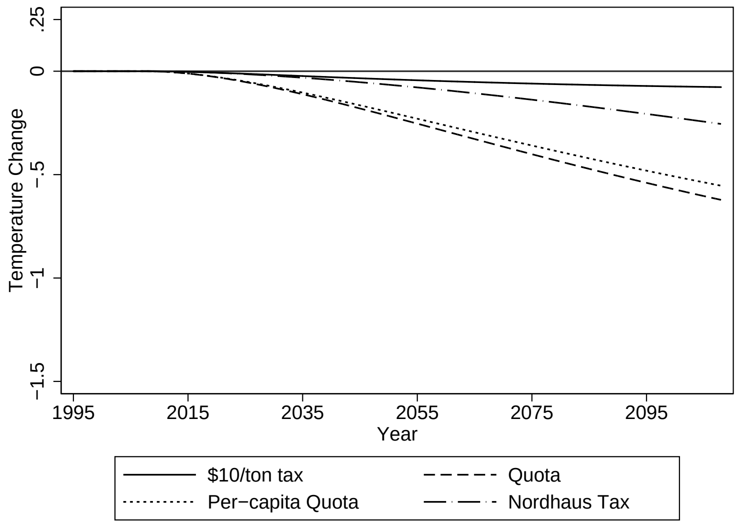

Fig. A.9. Temperature changes (^{o}C) by policy, optimistic climate scenario

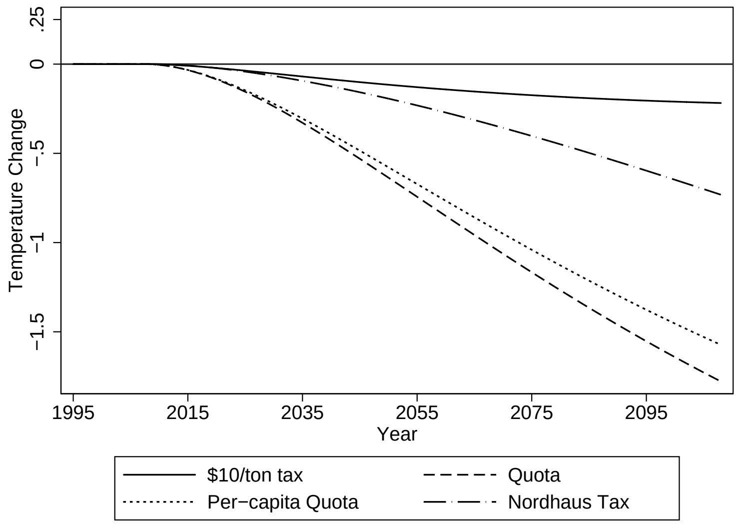

Fig. A.10. Temperature changes (^{o}C) by policy, pessimistic climate scenario

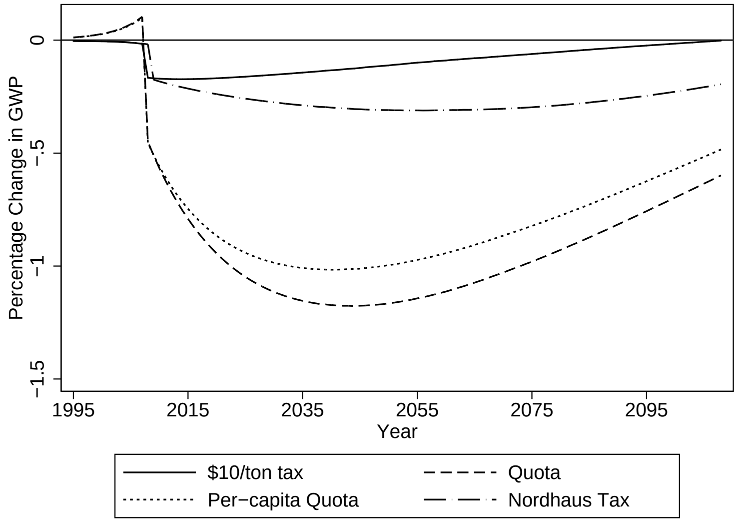

Fig. A.11. GWP changes (%) by policy, optimistic scenario

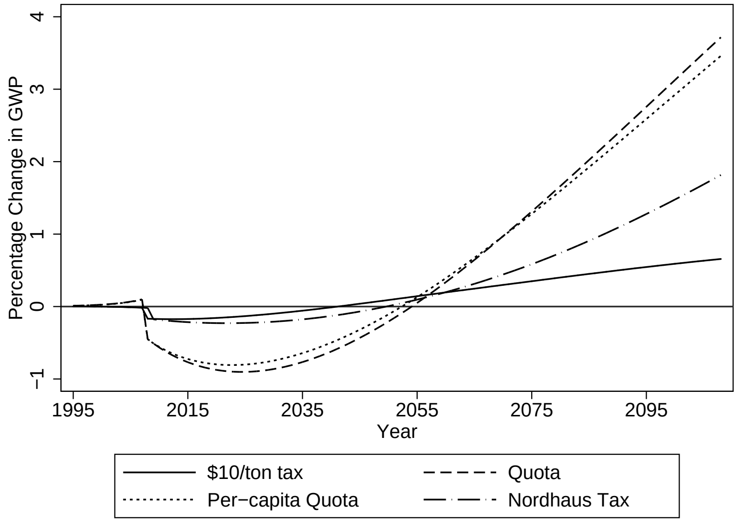

Fig. A.12. GWP changes (%) by policy, pessimistic scenario

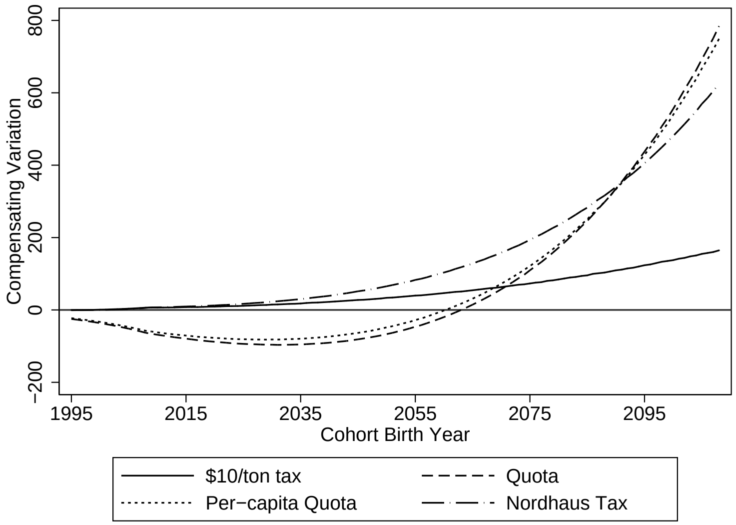

Fig. A.13. Cohort compensating variation ($\$US_{1995} \times 10^9$) by policy, benchmark climate scenario

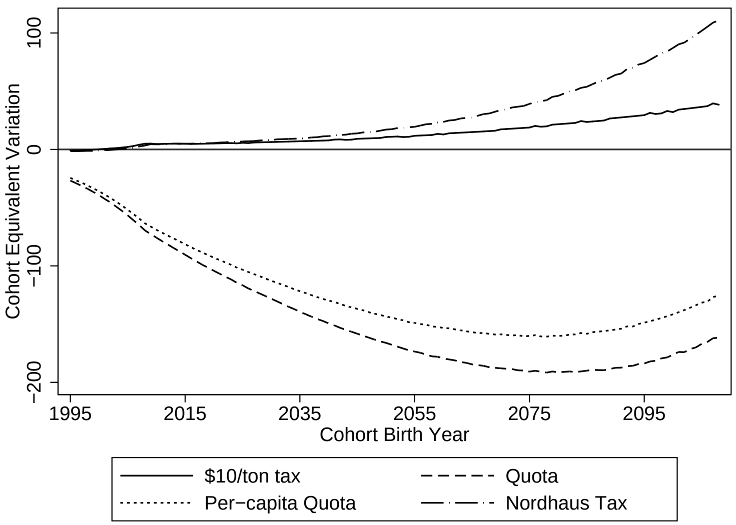

Fig. A.14. Cohort compensating variation ($\$US_{1995} \times 10^9$) by policy, optimistic climate scenario

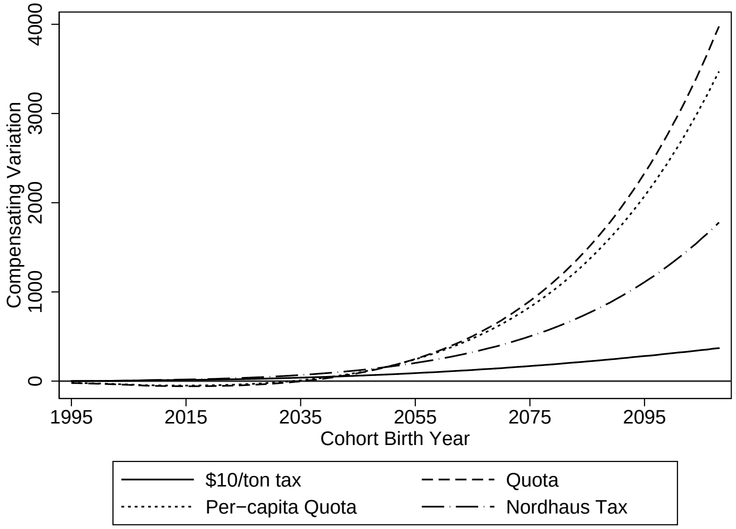

Fig. A.15. Cohort compensating variation ($\$US_{1995} \times 10^9$) by policy, pessimistic climate scenario