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The welfare implications of climate change policy

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ABSTRACT

The response to three different climate change policies is measured within a general equilibrium model of world output, technological change, greenhouse gas emissions, and climate-driven changes in productivity. The 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 alternative policies, relative to the *status quo*, do not necessarily accrue to the generations that bear the costs. The results also show that the chosen rent distribution rule has a profound effect on policy evaluation. In particular, policies which allocate rents on a per-capita basis are shown to be systematically welfare-preferred to situations where emissions rights are grandfathered to emitting firms. This implies that both the optimal level of emissions and the welfare cost of reaching a given target of emissions or atmospheric concentration would be lower under a per-capita allocation of emissions permits or carbon tax revenues.

1. Introduction

This paper evaluates the distribution of the benefits and costs of climate change mitigation policies over time in a general equilibrium model of world output, technological change, greenhouse gas (GHG) emissions, and climate-driven changes in productivity. Global climate change induced by atmospheric accumulation of carbon dioxide (CO_2) and other GHGs threatens future standards of living. Climate science suggests that average global temperatures could rise by between 1 and 6 °C by the end of this century [14]. Estimates in the economics literature place the cost of such changes at over 10% of total factor productivity [23]. The potential costs of climate change policies are also large, as immediate reductions in GDP of 1–3% may result from the implementation of the Kyoto protocol [29].

In this paper, I first develop and then simulate a model of climate and economy under three different climate change mitigation policies and a no-policy benchmark. For each of the proposed policies, including an approximation to the Kyoto protocol, I examine aggregate effects to show how the policies differ in their abilities to mitigate the intensity of climate change and support economic growth. I measure the allocation of net policy benefits both across time and across generations, and examine the effect of altering policy rent allocation rules on these results.

The model I present in this paper has a unique combination of three attributes important for policy evaluation. Most importantly the model is solved for a dynamic, decentralized, general equilibrium, as opposed to characterizing the solution to a social planner's problem. The transition path is determined by rent-maximizing resource extraction decisions as well as the privately optimal consumption decisions of agents and production and investment decisions of firms, conditional on technology and policy. The decentralized framework makes it possible to separate the normative issue of the

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choice of welfare function for policy evaluation from the specification of firm and agent behaviour. I report policy evaluation results for are reported for several *ex post* social discount factors. Secondly, the model economy is populated by overlapping generations of finite-lived agents. The generational approach is particularly well-suited to the evaluation of climate change policies, since the benefits of reducing the intensity of climate change do not necessarily accrue to those generations that bear the costs of the policies. Thirdly, resources exhibit increasing extraction costs and are extracted so as to maximize the net present value (NPV) of oligopoly rents over time. Optimal behaviour in the resource sector implies that extractive resource rents will change with climate policy. As a result, the calculated benefits of emissions control policies include both changes in extractive resource rents and the induced transfer of cheaper resource supplies to future generations.

The present study builds on the integrated assessment model (IAM) developed by Nordhaus and Boyer [23] by introducing the demographic dynamics of the Diamond overlapping generations model [3] in order to better assess the distribution of costs and benefits of climate change mitigation policies over time.[1] My results show that the timing of welfare changes induced by climate policy does not follow exactly the response of economic aggregates. Total factor productivity increases quickly as emissions are reduced, while total output lags the business-as-usual (BAU) trend for 65 years under the least stringent policy considered, and longer for more stringent policies. However, while economic activity remains below benchmark levels, the welfare of agents born as early as 30 years after the policies are introduced may be increased. Results derived from sensitivity analysis show that, while the costs of policies vary minimally with the assumed severity of climate change, the benefits and therefore the welfare effects of these policies are subject to much larger uncertainties.

My results demonstrate that the allocation of policy-generated scarcity rents has important aggregate welfare and inter-generational allocation effects. When emissions rights are allocated to agents on a per-capita basis, the NPV at market rates of return of a Kyoto-style policy increases by over \$5 trillion 1995 US dollars relative to the same policy with emissions rights allocated to firms. In fact, policies with per-capita allocation of associated revenues are shown to be systematically welfare-preferred to an equivalent constraint with emissions rights grandfathered to emitting firms. This implies that both the optimal level of emissions and the welfare cost of reaching a given target of emissions or atmospheric concentration would be lower under a per-capita allocation of emissions permits or carbon tax revenues. Goulder et al. [10] show how climate policy may be correct for efficiency losses due to imperfect markets. In the present study, the missing market lies in the fact that agents from cohorts not yet born are not able to purchase shares in the production firm in order to capture permit rents, and therefore these agents receive none of the rents from permits under a grandfathering regime.[2] These results also echo to those of Parry [24], which show that grandfathered emissions permits are regressive as a result of the fact that they implicitly transfer rents to the wealthiest agents.[3]

2. The model

In this section, I introduced a climate and economy model similar to the DICE-99 model of Nordhaus and Boyer [23], where the use of fossil fuels in production affects global climate, which, in turn, affects factor productivity over a long time horizon. There are three important attributes of the model which differentiate it from DICE-99. First, the model is decentralized and solved for general equilibrium rather than for a social planner's optimal emissions and capital accumulation policy. Second, overlapping generations of finite-lived agents supply labour and own shares in the final production firm, and dividends from production accrue to these shareholders. Third, resource deposits are owned and extracted by dynamic, oligopolistic firms who maximize the NPV of these deposits conditional on the evolution of the economic state and remit rents to agents on a per-capita basis.

Markets exist for four commodities in the economy: effective labour, N, fossil fuels, R, the rights to carbon emissions, P, and shares in the final production firm, S, with respective prices denoted by w_t for a unit of effective labour, η_t for a ton of carbon-equivalent of fossil fuels, π_t for the right to emit a ton-of-carbon-equivalent of GHGs, and r_t for a share.

A representative, dynamically optimal, price-taking firm produces a numeraire good for investment and consumption. The firm solves a dynamic investment problem to maximize the discounted value of profits, and therefore the value of a stream of dividends which are paid out in each period to its shareholders. In equilibrium, the discount factor employed by the firm, β_f, will be equal to the endogenous rate of time preference of agents.

Production technology is Cobb–Douglas with three inputs: capital, K, labour, N, and fossil fuels, R. The technological state is determined by three variables: total factor productivity Ω, emissions efficiency of energy production ϕ, and the energy share of production θ. With the exception of total factor productivity which is endogenously determined by climate

[1] Papers by Howarth [12], Gerlagh and van der Zwaan [7,8], Rasmussen [27], and Kavuncu and Knabb [19] also present models of climate change specifying overlapping generations of agents, while Gerlagh and Keyzer [6] use a similar model to address the inter-generational allocation of finite resource rents.

[2] A parallel literature including papers by Fischer and Fox [5], Burtraw et al. [2], and Bovenberg and Goulder [1] further examines emissions permit allocation rules.

[3] While the model I present does not feature income heterogeneity within cohorts, across cohorts there exists a wealth distribution and the wealthiest cohorts alive when the policies are imposed receive larger shares of the rents when permits are allocated to firms.

change, these trends are exogenous. The firm must purchase labour and fossil fuels at market prices which it takes as given, and its capital stock is an endogenous product of its initial endowment and its investment decisions.

The firm must also purchase emissions permits to offset emissions in excess of allocated permits in each period. Let the competitive price of emissions permits (the shadow price of the emissions constraint) be given by π_t, and let the firm's emissions permit allocation be given by $\{P_{f,t}\}_{t=0}^{T}$. As will be formalized below, the proceeds of permit sales will be remitted to agents by the government through lump-sum transfers. The NPV of the emissions permits allocated to the firm is $\sum_{t=0}^{T}(\beta^t \pi_t P_{f,t})$ which will be capitalized into the value of shares of the firm.

The energy share of production, θ, and fossil fuel-augmenting parameter, ϕ, are specified to be independently time-varying. This allows the model to be consistent with the fact that the global energy share in production has been declining over time, while the energy produced per unit of emissions has been increasing.[4,5] Denoting growth rates by γ's and the rates at which growth declines by δ's, each with appropriate subscripts, the value of θ over time is determined by $\theta_t = \theta_{t-1}\,(1+\gamma_\theta(1-\delta_\theta)^t)$, while the value of ϕ over time is determined by $\phi_t = \phi_{t-1}\,(1+\gamma_\phi(1-\delta_\phi)^t)$.

In order to keep the model relatively simple, I have chosen to maintain the traditional specification of exogenous changes in the emissions efficiency of energy production. Allowing for induced innovation in the energy sector would reduce the medium-term costs of climate policy and enhance the long-term benefits. While such a change in modeling strategy would change the magnitude of some results, it seems unlikely that it would affect the spirit of the conclusions drawn from the relative comparisons presented in this study.[6]

Total factor productivity, Ω_t, has exogenous and endogenous components, but is taken as given by the firm. Using the same notation as above, the exogenous trend for factor productivity, ω, is $\omega_t = \omega_{t-1}\,(1+\gamma_\omega(1-\delta_\omega)^t)$. The link between climate, emissions, and productivity determines the magnitude of total factor productivity relative to this exogenous trend. As is standard in the literature, ω_t is reduced by a multiplier, parameterized here by values of b_1 and b_2, which is affected by changes in temperature, G_t[7]:

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

Capital accumulation is assumed to be completely reversible, such that each period's capital stock must be greater than the sum of the previous period's total output net of factor payments and the undepreciated capital stock. The firm's optimization problem is therefore to choose investment and input demand to solve:

$$\begin{aligned} \max_{\{I_t,R_t\}_{t=0}^{T}} \quad & \Pi = \sum_{t=0}^{T} \beta_f^t [\Omega_t K_t^\alpha N_t^{1-\alpha-\theta_t}(\phi_t R_t)^{\theta_t} - w_t N_t - \eta_t R_t - \pi_t(R_t - P_{f,t}) + K_t - I_t] \\ \text{subject to} \quad & K_{t+1} = (1-\delta)I_t \;\; \forall t \geqslant 0, \quad K_0 \text{ given}, \\ & R_t \leqslant \overline{R}_t. \end{aligned} \tag{2}$$

The solution to the firm's problem in (2), subject to the Kuhn–Tucker conditions for the capital accumulation and emissions constraints, yields an investment stream and (inverse) factor demands for labour and resources, while the shadow value of the emissions constraint, denoted by π_t, constitutes the market price paid for emissions permits not allocated to the firm. Profits from production defined as the solution to (2) above are remitted to shareholders in the form of dividends.

An infinite stock of fossil fuels is available at increasing marginal extraction costs, as defined in Nordhaus and Boyer [23]. My assumptions differ from Nordhaus and Boyer in that resource property rights are owned in equal proportion and extracted by a set of Z dynamically optimal firms. The ownership of these firms is shared equally among the agents and the firms are assumed to be collectively of small enough size so as to not affect global capital or labour markets. Firms engage in Cournot competition to provide fossil fuels to the final production firm and, in so doing, maximize the NPV derived from their resource extraction activities conditional on the (symmetric in equilibrium) extraction decisions of each of their rivals. Large values of Z will imply a perfectly competitive market for fossil fuels with many firms owning small deposits, while $Z = 1$ implies monopoly ownership and extraction. In equilibrium, the discount factor employed by each firm, β_f, will be equal to the endogenous rate of time preference of agents.[8]

[4] This structure is used in the RICE model to account for regional changes in the structure of the economy, but not in the global DICE model in Nordhaus and Boyer [23].

[5] For a discussion of the potential sensitivity of model results to the choice of aggregate production function, the interested reader is directed to Saunders [28]. In material provided in the JEEM online respiratory 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.

[6] Papers by Goulder and Schneider, Goulder and Mathai, Nordhaus, and Popp [11,9,22,26] have addressed the sensitivity of IAM results to the assumption that technological change is independent of policy.

[7] G is used to denote the global temperature, to avoid confusion with T used to denote the terminal time-period.

[8] The Nordhaus and Boyer RICE model in [23] includes a regional markup term to capture rent-seeking behaviour of firms with resource endowments. This is not included in the cost function used in this paper, as rents are determined optimally. In the calibration section, the value of $Z = 2$ is chosen such that equilibrium rents in the initial period are equal to approximately \$100 per ton, a value comparable to those included in the Nordhaus and Boyer specification.

Each individual firm $z \in \mathbb{Z}, 1 \leqslant z \leqslant Z$, owns a deposit for which marginal extraction costs are increasing in the cumulative extraction ($X_{z,t}$) from that deposit. These costs are given by

$$q_t = \xi_1 + \xi_2 \left[\frac{Z(X_{z,t} + R_{z,t})}{X^*}\right]^{\xi_3}, \tag{3}$$

and resource stocks evolve such that

$$X_{z,t+1} = X_{z,t} + R_{z,t}. \tag{4}$$

This cost function ensures that, regardless of the choice of the number of firms Z, the relationship between aggregate extraction and marginal extraction cost will be identical to that used in Nordhaus and Boyer [23] as long as the same parameter values used by Nordhaus and Boyer are assigned to ξ_1, ξ_2, and ξ_3.

Each firm will choose to supply fossil fuels to maximize the NPV of their resource deposit. Denote by R_z the quantity supplied by an individual firm, by $\widetilde{R}$ the quantity supplied by each other firm, and recall that $\eta(\Omega_t, N_t, K_t, R_z + (Z-1)\widetilde{R}, \overline{R})$ represents the marginal product of fossil fuels, and therefore their market price, derived from the solution to the production firm's problem conditional on the final production firm's state and the emissions constraint, $\overline{R}$. The maximization problem for each resource firm is given by

$$\max_{\{R_{z,t}\}_{t=0}^{T}} \quad \sum_{t=0}^{T} \beta_{\mathrm{f}}^{t} \left[\eta(\Omega_t, N_t, K_t, (Z-1)\widetilde{R}_t + R_{z,t}, \overline{R}_t) R_{z,t} - \xi_1 R_{z,t} - \int_{X_{z,t}}^{X_{z,t}+R_{z,t}} \xi_2 \left(\frac{Z\widetilde{X}}{X^*}\right)^{\xi_3} \mathrm{d}\widetilde{X}\right]$$
$$\text{subject to} \quad X_{z,t+1} = X_{z,t} + R_{z,t} \ \ \forall 0 < z < Z, \ \ t > 0, \quad X_{z,0} = 0 \ \ \forall z \text{ given.} \tag{5}$$

Firms are symmetric so $\widetilde{R} = R_z$ in equilibrium, under which total fossil fuel supply is denoted by $R = ZR_z$. Resource rents and the producer surplus from extraction, given by

$$Y_{r,t} = Z\left[\eta(\Omega_t, N_t, K_t, R, \overline{R}_t) R_{z,t} - \xi_1 R_{z,t} - \int_{X_t}^{X_{z,t}+R_{z,t}} \xi_2 \left(\frac{Z\widetilde{X}}{X^*}\right)^{\xi_3} \mathrm{d}\widetilde{X}\right], \tag{6}$$

are remitted to agents on a per-capita basis, with the payment to each individual denoted by $y_{r,t}$.

The assumptions of an oligopoly structure and equal per-capita ownership of resource firms are significant. Market power will allow resource firms to capture some of the rents created by climate policy. Results would not differ significantly if resource markups were fixed and policies imposed a per-capita issuance of emissions permits. However, if we were to consider the resource firm as also being part of the shareholders' portfolios, both increased resource rents and permit rents created by climate policy would accrue to shareholders, and this would widen the equity gaps reported below.

The economy is populated by overlapping generations of finite-lived agents. A new cohort of agents, $N_{1,t}$, is born each period and lives L periods, after which they die with certainty. The exogenous trend for the size of each cohort, given an initial condition, is given by

$$N_{1,t} = N_{1,t-1}\,(1 + \gamma_n (1-\delta_n)^t). \tag{7}$$

Agents seek to maximize their lifetime utility, which is given by

$$\sum_{l=1}^{L} \beta^{l-1} U(c_{l,t+l-1}), \tag{8}$$

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

$$U(c_{l,t}) = \frac{c_{l,t}^{1-\sigma}}{1-\sigma}. \tag{9}$$

Labour supply is inelastic and independent of climate or factor productivity. The effective labour supply of an age l agent is determined by age-specific productivity e_l which is time-invariant. Aggregate labour supply, N_t, is given by the rule for the size of the new cohort born each period, a human capital profile ($e_l \ \forall l \in \mathbb{Z}, 1 \leqslant l \leqslant L$), and lifespan L:

$$N_t = \sum_{l=1}^{L} e_l N_{l,t}. \tag{10}$$

Agents can smooth consumption over time through the accumulation of equity in the form of shares of the final production firm. Denote by $a_{l,t} \in \mathbb{R}$ the shares of the firm owned by each agent in age-cohort l at time t, and by r_t the share price in each period.[9] Initial conditions for each cohort of agents are defined by their endowment, $a_{1,t} \in \mathbb{R}^+$, of shares.

[9] Individuals may hold negative share balances. In equilibrium, the total number of shares held in each period, $\sum_{l=1}^{L} N_{l,t} a_{l,t}$, is equal to those available, which is set to 1.

Outside the initial cohorts, no initial endowments are assumed. Each agent in a cohort faces the same optimization problem, since they begin with the same equity holdings, have the same certain lifetimes, and receive the same income.

Income, $y_{l,t}$, earned by an age l agent in period t comes from the gross rate of return on equity holdings (share price, r_t, plus dividends, d_t), labour income, $w_t e_l$, resource extraction dividends, $y_{r,t}$, and net policy rent allocation, τ_t. They must allocate income between consumption $c_{l,t}$ and the accumulation of future equity claims, $a_{l,t+1}$, according to the individual budget constraint:

$$c_{l,t} + r_t a_{l,t+1} = y_{l,t} \equiv w_t e_l + (r_t + d_t) a_{l,t} + y_{r,t} + \tau_t. \tag{11}$$

A representative age l agent's utility maximization problem yields a system of Euler equations:

$$(y_{l,t} - r_t a_{l+1,t+1})^{-\sigma} = \beta \frac{r_{t+1} + d_{t+1}}{r_t} (y_{l+1,t+1} - r_{t+1} a_{l+2,t+2})^{-\sigma} \quad \forall l \in \mathbb{Z},\ 1 \leqslant l \leqslant L, \quad a_{L+1,t} = 0\ \forall t, \tag{12}$$

the solution to which describes equity holdings (and thus consumption) through time, subject to a known sequence of rates of return and income. Agents are assumed not to value the consumption of other agents, either present or future, so there are no equity bequests or transfers in the model, and agents will set $a_{l,t} = 0\ \forall l > L, t$.

In equilibrium, the demand for equity and the dividends paid by the final production firm determine the endogenous rate of time preference. Since there are no individual borrowing constraints and agents' savings paths satisfy the Euler equations balancing marginal utility across time, agents are indifferent between a dollar in period t and $\beta(r_{t+1} + d_{t+1})/r_t$ dollars in period $t+1$. As discussed above, in solving for the dynamic equilibrium of the economy I assume that this is the rate of time preference employed by the final production firm in solving its dynamic, profit maximization problem and by the resource extraction firms in solving their dynamic extraction problems.

I use the three-reservoir system defined in Nordhaus and Boyer [23] to characterize changes in global climate resulting from GHG emissions. I assume that emissions resulting from fossil fuel use are the only input to a three-reservoir climate system. Let m_t be a 3×1 vector representing the levels of carbon in each of three reservoirs representing the atmosphere, short-term sinks in the oceans and upper troposphere, and a deep ocean sink, respectively. Denote by δ_m a 3×3 matrix of transfer coefficients such that the law of motion for the carbon reservoir system is given by

$$m_{t+1} = \delta_m (m_t + (R_t\, 0\, 0)'), \tag{13}$$

where the notation $(R_t\, 0\, 0)$ captures the assumption that fossil fuel use contributes to the atmospheric reservoir only, and does not directly affect the ocean or trophospheric reservoirs.

Levels of atmospheric carbon exceeding preindustrial level cause a change in radiative forcing, increasing heat retention. Recall that G represents deviations from the mean of surface temperature in degrees Celsius, and let O represent the same measure for the change in temperature in the world's upper oceans. Global climate evolves through a vector autoregression such that

$$G_t = \lambda_1 G_{t-1} + \lambda_2 \left(\frac{\log\left(\frac{m_{1,t}}{m_{1,b}}\right)}{\log(2)} \right) + \lambda_3 O_{t-1} \tag{14}$$

and

$$O_t = \lambda_4 O_{t-1} + (1 - \lambda_4) G_{t-1}. \tag{15}$$

In (14), $m_{1,t}$ and $m_{1,b}$ represent current and preindustrial levels of carbon in the atmospheric reservoir in the carbon system in (13). The value of λ_2 is measured in degrees Celsius, while other parameters have scalar values. The steady state of this system when $m_1 = 2m_{1,b}$ yields the long-run warming for a doubling of atmospheric carbon, $\lambda_2/(1 - \lambda_1 - \lambda_3)$.[10] Parameter values for $\lambda_1 \in (0, 1)$ and $\lambda_4 \in (0, 1)$ capture the persistence of deviations in surface and ocean temperature, respectively, while the rate of mixing between surface and ocean temperature is determined by λ_3. Recall that it is the value of G_t that feeds back through (1) to generate total factor productivity.

Equilibrium is defined by a sequence of prices $(r_t, w_t, \eta_t, \pi_t)_{t=1}^{T}$ for shares of the final production firm, labour, resources, and emissions permits, given climate change policies, population, initial physical and technology states, and a positive initial capital endowment. The equilibrium price sequence must be such that each of the following are satisfied simultaneously:

1. The production firm solves (2) and remits profits to shareholders.
2. Resource supply decisions satisfy (5). Scarcity rents and surpluses from production are remitted to agents on a per-capita basis.
3. Agents consume and save in accordance with their Euler equations given in (12) and supply labour inelastically.
4. Production and resource extraction firms use a discount factor β_f which reflects the rate of time preference of agents.
5. Markets for equity, labour, resources, and emissions permits clear.

[10] The characterization of forcing relative to that produced by a doubling of atmospheric CO_2 is standard in both the scientific and the economic literature on climate change (see Nordhaus and Boyer or IPCC [14]).

3. Solution and calibration

The transitions of the economy are solved by using an iterative process to derive the sequence of equity rates of return ($\iota_t = (d_{t+1} + r_{t+1})/d_t$) which uniquely satisfies the equilibrium conditions of the economy.[11]

The model as written cannot be solved numerically without specifying initial and terminal conditions which truncate the time horizon as follows. First, cohorts of agents of ages 1 to L are introduced to the economy in the first time period, 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. Second, agents born after $t = T - L$ have normal lifespans but are assumed to face constant prices and equity rates of return for periods outside the model time horizon. Firms are assumed not to value production after the terminal time-period; however, firms are constrained to invest sufficiently in the last period to maintain the capital stock. Complete divestiture of the capital stock is not permitted in the last period, and so distortions in the equity market due to the truncation of the economy are reduced. Resources are not given a terminal value, but this is not a significant issue since market power leads firms to maximize rents, not extraction. The sensitivity of results to these assumptions is minimized by choosing a value of $T = 220$ years, and removing the last 60 years from the analysis sample.[12]

Parameter values for the simulations are consistent with assumptions the recent literature and ensure that predicted transitions match economic and climate data from 1971–2002, and projections for 2003–2050 provided by the IEA [15,16]. These data do not cover agent-level or firm-level behaviour, and so parameters governing agent and firm behaviour are fixed in accordance with the literature, while trend variables are fixed numerically using simulations of the model. Table 1 presents the parameter values used in the simulations and starting values for both endogenous and exogenous trends.

A complete description of the computational algorithm and further details on the procedure used to fix parameter and starting values are available through JEEM's online archive of supplementary material which can be accessed at http://www.aere.org/journal/index.html.

4. Policy evaluation

Having solved the BAU version of the model under the benchmark climate scenario for calibration, three emissions constraints are imposed on the economy. First, I impose a Kyoto-protocol-style quota which places the most significant constraints on emissions by imposing a cap of 94% of 1990 levels for periods beyond 2010. Second, I impose a time-varying quota which restricts emissions to 1.036 tons of carbon per person over the age of 16, the same per-capita emission levels as the fixed quota imposes for 2010. Since population is growing throughout the simulations, this policy is less stringent than the first. Finally, I examine a constraint which maintains a constant per tonne shadow value of carbon (which is equivalent to a constant carbon tax) of \$57.18 per ton, a level which induces the same emissions as the two quota policies in 2010. Fig. 1 shows the evolution of emissions and shadow prices under each of the considered emissions policies, which are each imposed by the allocation of emissions permits, with either a per-capita allocation of permit rents or the complete grandfathering of emissions permits to the final production firm. The former allocation rule is analogous to a carbon tax set at the values shown in the lower panel of Fig. 1 with lump-sum distribution of revenues on a per-capita basis.

I rely on comparative dynamics and welfare-based evaluations of the policies outlined above to draw my conclusions. I do not solve for an optimal carbon policy for the economy, which would involve a calculation of the solution to a social planner's problem treating the equilibrium conditions described above as constraints. There are two sources of market failure in the paper—the inter-generational transfer externality associated with Diamond models as well as the link between carbon emissions and climate change. An optimal carbon policy calculated in the spirit of the DICE model [23] would thus be a second-best policy which would correct both externalities imperfectly and would not be directly comparable to other IAM results.

4.1. The aggregate effects of climate policy

Climate change mitigation policies will have important effects on economic growth and the evolution of the climate system. Since the aggregate effects on the economic and physical environment vary little with the chosen rent-allocation scheme, the aggregate effects are reported for cases where all emissions rights are allocated to the final production firm.

The induced differences in total output (GWP) are shown in Fig. 2. Production increases slightly in the periods before the policies are put into place as capital is accumulated by the final production firm to smooth profits over future periods. This is a consequence of the assumption of perfect foresight. While the additional capital reduces the cost of the constraint, there are significant reductions to real output induced by each of the policies. Total output does not surpass BAU until at least 48 years after the policies have been imposed.

The eventual aggregate benefits of the policies are delivered through changes in the economy's emissions profile, leading to changes in surface temperature and therefore total factor productivity increases. Cumulative emissions are, by

[11] The model is solved and simulated using Ox Version 4.04 [4].

[12] To test the sensitivity of the results to the choice of T, the BAU economy was solved for $T = 1000$, and changes in the capital accumulation and resource extraction sequences were found to be less than $10^{-3}\%$ over the 160 year analysis sample.

Table 1
Calibrated and fixed parameter values and simulation starting values

Symbol	Description	Value
Fixed parameters, economic sector		
σ	Coefficient of relative risk aversion	1.2213
β	Discount factor	0.96
δ_k	Capital depreciation rate	0.045
α	Production share of capital	0.3
ξ_1	Minimum extraction cost of carbon ($)	1.130×10^2
ξ_2	Linear rate in extraction cost of carbon	7.000×10^2
ξ_3	Exponent in extraction cost of carbon	4.0
Exogenous trends, economic sector		
θ_0	Initial production share of resources	0.05538
γ_θ	Growth in production share of resources	−0.01141
δ_θ	Decay rate of production share of resources	5.510×10^{-4}
ω_0	Initial factor productivity	0.02515
γ_ω	Growth rate of factor productivity	7.626×10^{-3}
δ_ω	Decay rate of γ_ω	1.078×10^{-7}
ϕ_0	Initial emissions intensity of energy	1.307
γ_ϕ	Growth rate of emissions intensity of energy	0.0175
δ_ϕ	Decay rate of γ_ϕ	0.0510
N_{00}	1970 birth cohort	1.017×10^8
γ_n	Growth rate of population	0.02
δ_n	Decay rate of γ_n	0.03
Fixed parameters, climate sector		
δ_m	Carbon cycle transition matrix	$\begin{pmatrix} 0.9602 & 0.03981 & 0 \\ 0.03416 & 0.9516 & 0.01423 \\ 0 & 4.228 \times 10^{-4} & 0.9996 \end{pmatrix}$
$m_{1,b}$	Preindustrial atmospheric CO_2	5.900×10^2
λ_1	AR(1) parameter for temperature deviations	0.9112
λ_3	Rate of mixing for ocean and surface temperature	0.01012
$\dfrac{\lambda_2}{1-\lambda_1-\lambda_3}$	Temperature sensitivity to CO_2 doubling	2.980
λ_4	AR(1) parameter for ocean temperature deviations	2.0×10^{-3}
b_1	Linear component in damages	-4.5×10^{-3}
b_2	Quadratic component in damages	3.35×10^{-3}
Simulation starting values		
K_0	Capital stock (10^{12} 1995 US dollars)	24
N_0	Population (millions)	3.669×10^3
$m_{0,1}$	Atmospheric CO_2 levels (GtC)	6.90×10^2
$m_{0,2}$	Upper strata CO_2 levels (GtC)	7.70×10^2
$m_{0,3}$	Lower strata CO_2 levels, (GtC)	1.918×10^4
G_0	Surface temperature change (°C)	0.295
O_0	Ocean temperature change (°C)	0

construction, lower after the implementation of each of the policies. Fig. 3 shows the changes in atmospheric carbon dioxide concentration induced by each of the policies.[13] None of the policies are sufficiently restrictive to stabilize the atmospheric concentration of carbon within 100 years, but even the least stringent constant cost policy brings about a 15% reduction in concentration by 2100.

The climate change mitigation effects of the policies are shown in Fig. 4. Under BAU, I find a temperature change of 2.91 °C by 2110, which is consistent with IPCC predictions [14]. The policies vary by construction in their levels of climate change mitigation, with the most stringent leading to surface temperature changes of 1.43 °C by 2110, which translates into a doubling of total factor productivity relative to BAU. Even the least stringent policy, the constant emissions cost, results in a 20% increase in 2110 total factor productivity. While climate policy drives increases in total factor productivity these increases are, for a long period of time, offset by decreases in the capital stock induced by the emissions constraints and by

[13] In Fig. 3 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.

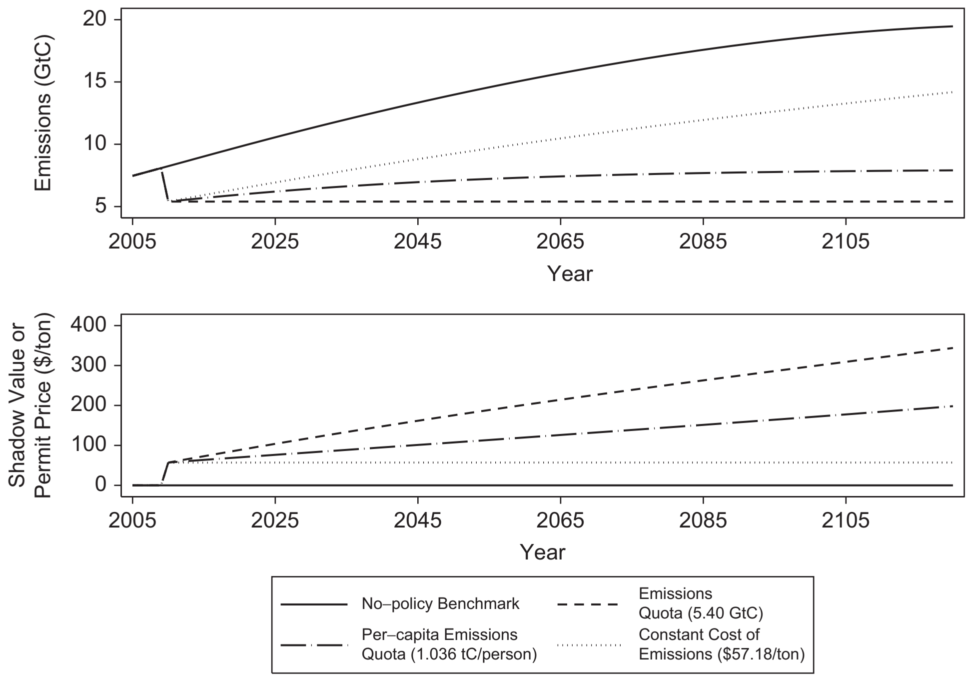

Fig. 1. Shadow prices ($ per ton C) of the constant emissions, constant per-capita emissions, and constant emissions cost constraints. The shadow value of each of the policies is $57.18 per ton in 2010, the first period in which they are imposed, and the emissions in this period are 5.40 GtC.

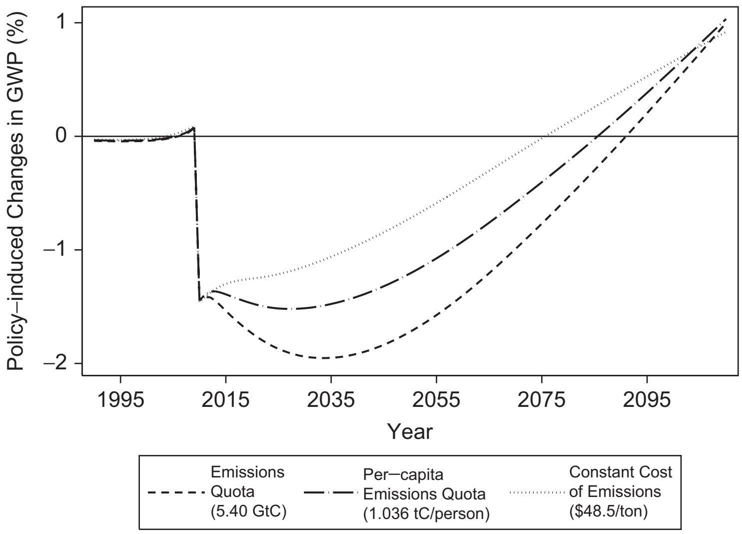

Fig. 2. GWP changes (%) by policy, benchmark (3 °C) climate scenario.

the emissions constraints themselves. While the economy is almost immediately more productive, predicted total output remains below BAU for between 48 and 80 years depending on the stringency of the climate change policy.

In order to test the sensitivity of results to the modeling of climate change, low- and high-sensitivity climate change scenarios were introduced which alter the temperature change which occurs from a doubling of atmospheric carbon from the benchmark 3 °C to either a low sensitivity (1.5 °C) or a high sensitivity (4.5 °C). The predicted no-policy temperatures in 2110 are, respectively, 1.47 and 4.34 °C in the low and high-sensitivity scenarios, compared to the benchmark prediction of 2.91 °C. The temperature dynamics under each of the assumptions for the most stringent policy, shown in Fig. 5, confirm that the returns to climate policy will vary significantly with the assumed climate sensitivity.

The effects of policies on future economic performance will follow closely the effects on temperature and therefore are sensitive to the choice of climate change scenario. Consider Fig. 6 which shows the policy-induced output changes under

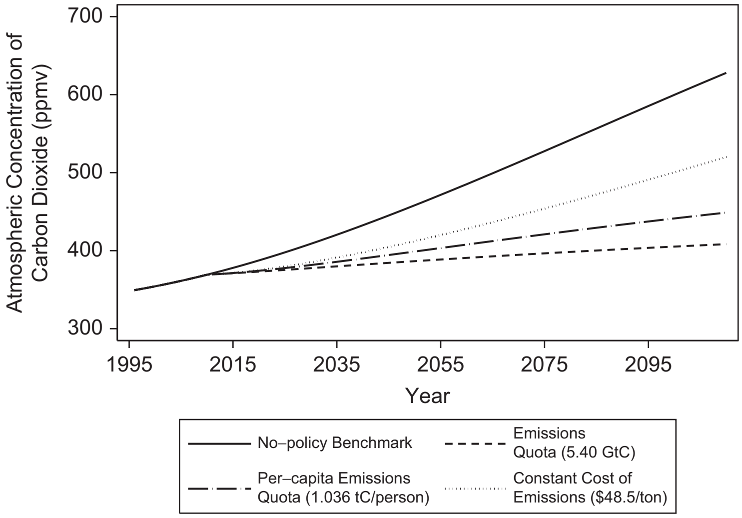

Fig. 3. Atmospheric CO_2 (ppmv) by policy, benchmark (3 °C) climate scenario.

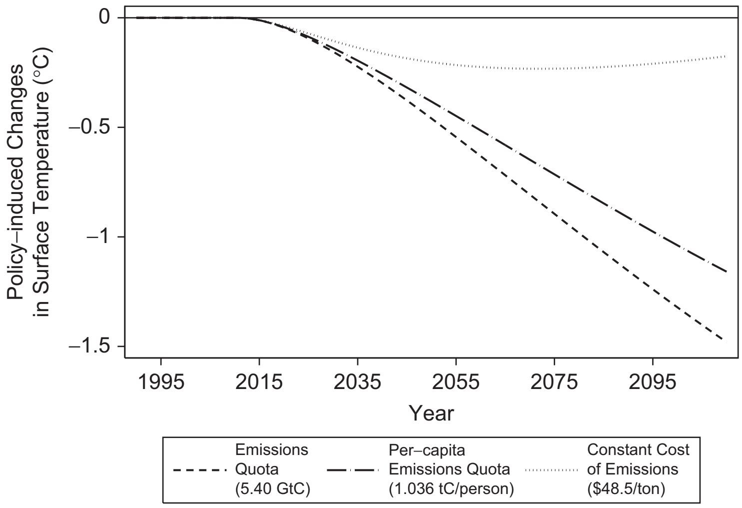

Fig. 4. Temperature changes (°C) by policy, benchmark (3 °C) climate scenario.

the emissions quota for the alternative climate scenarios. When climate change is most severe, total output is higher than under BAU in less than 70 years, in contrast to time periods over 100 years for the benchmark climate assumptions. If climate sensitivity is lower than the benchmark, total output will remain significantly below BAU for much longer. This figure illustrates an important aspect of the climate change policy debate: the costs of climate change policy are much more certain than are the benefits. There is little divergence in the effect of policies on economic growth until up to 20 years after the policies have been imposed, regardless of the severity of climate change.

Two results are important to take away from these aggregate measures; the distribution over time and the sensitivity to climate change assumptions of costs and benefits of mitigation policies. First, costs and benefits of the respective constraints are clearly separated in time, with present-day economic slowdown costs being traded off against future benefits in the form of increased productivity and cheaper resources. Second, while the near-term costs are largely invariant to the model's assumptions about climate change dynamics, the future benefits vary significantly across possible climate scenarios. Each of these suggests the potential for significant inter-generational inequity resulting from climate policy.

4.2. The individual welfare effects of climate policy

As a result of imposing the overlapping generations demographics, I am able to use the distribution of costs and benefits of policies across age-cohorts as a measure of policy evaluation, something which is not possible in a representative agent

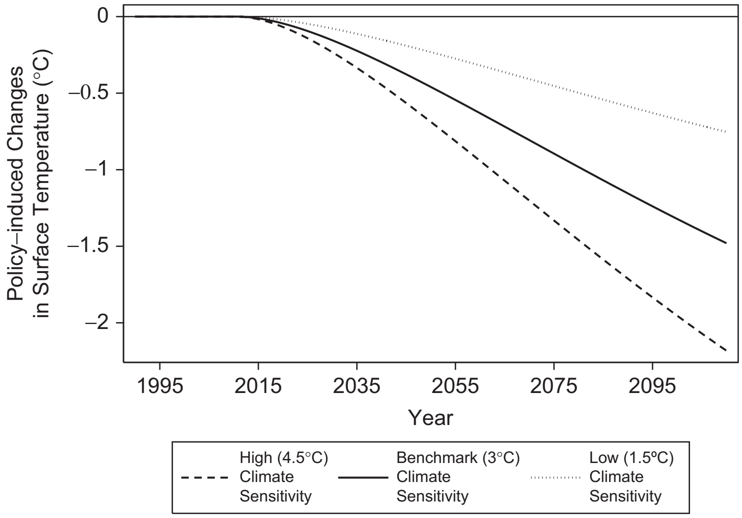

Fig. 5. Temperature changes (°C) for the 5.40 GtC emissions quota by climate scenario.

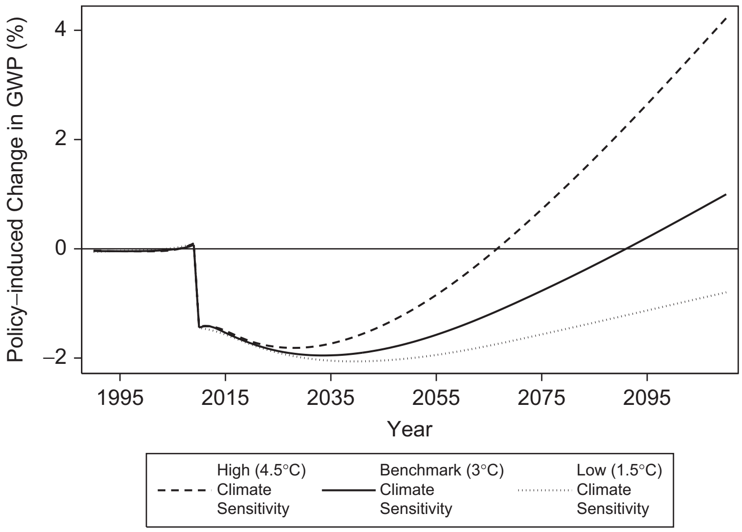

Fig. 6. GWP changes (%) for the 5.40 GtC emissions quota by climate scenario.

model. Below, I first define a measure of welfare, and then examine the welfare effects of the considered policies under the assumption that present-day production firms own the rights to emissions. I then alter the allocation rule to one where the agents alive in each period own the rights to that period's emissions, and therefore collect policy-induced scarcity rents. I present results for each of the climate change scenarios.

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:

$$W \equiv \sum_{t=0}^{T} \rho^t N_{1,t} \sum_{l=1}^{L} \beta^{l-1} U(c_{l,t+l-1}) = \sum_{t=0}^{T} \rho^t N_{1,t} V(t). \tag{16}$$

The discounted summation over L defines the private welfare from consumption for an agent born in time t. Since 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 each cohort, $N_{1,t}$, and discounted by a social discount factor, ρ. The social discount factor has no impact on the transition of the decentralized economy, and only determines the value placed on the distribution of consumption to particular cohorts, *ex post*. Where the social discount factor is set to 1, social welfare

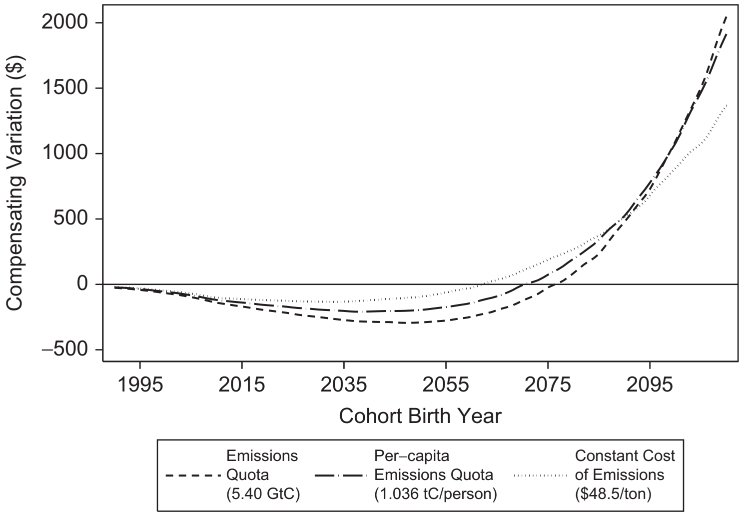

Fig. 7. Cohort compensating variation ($\$US_{1995} \times 10^9$) by policy, benchmark (3 °C) climate scenario.

is the sum of the indirect utility 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 formulation of a measure of compensating or equivalent variation is complicated by the dynamic, general equilibrium nature of the model. An infinite number of potential sequences of transfers over time which would make an agent indifferent between the policy and the BAU transition path exist. In the results reported below, I use a compensating variation in first period consumption. 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 through changes in equilibrium rates of return, the measure serves to translate the values from utility units into more informative real dollar units.

I use the following definition of compensating variation of a policy choice. Denote by $V_{\mathrm{B}}(t)$ and $V_{\mathrm{P}}(t)$ the indirect utility for an agent born at time t under the BAU and policy simulation, respectively. Similarly, denote by $U(c^{\mathrm{P}}_{1,t})$ the utility from first period consumption under the policy. I can therefore derive the compensating variation for cohort t, κ_t, by solving the following:

$$V_{\mathrm{B}}(t) - V_{\mathrm{P}}(t) = U(\kappa_t c^{\mathrm{P}}_{1,t}) - U(c^{\mathrm{P}}_{1,t}). \tag{17}$$

Thus, $(\kappa_t - 1)c^{\mathrm{P}}_{1,t}$ is the compensating variation in consumption units.

Fig. 7 shows the compensating variation for agents born in each time period of the model for each of the policies when the production firm owns the rights to emit. Recall that the economic slowdown was very abrupt, as shown in Fig. 2. Fig. 7 shows that welfare costs are faced by generations born both before and long after the policies are imposed. Agents have perfect foresight so the NPV of quota rents will be captured by the first generation of agents in the model—the initial shareholders of the firm. Younger agents will be able to purchase shares in the firm for savings, but the share prices will already reflect the future scarcity rents.[14]All agents alive when the policies are introduced and not holding shares in the firm when the policies are announced as well as those born for up to 60 years afterwards will be made worse-off by them.

Allocating valuable emissions rights to agents allows younger agents who have not accumulated equity holdings to benefit from a transfer at the point where their consumption would have been most affected by the policies. The time series of compensating variations under the most stringent policy considered for each of the two quota-attribution rules is shown in Fig. 8. The results are qualitatively similar for other considered policies. The attribution of a portion of the created scarcity rents to agents has a positive effect on the welfare evaluation of the policies, as each cohort of agents in the analysis sample is made better off than they would be under grandfathered permits.

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. Fig. 9 shows the magnitude of the welfare effects of the most stringent policy across generations for the considered climate scenarios. The fact that the costs of climate change mitigation are much more certain than benefits is again highlighted, only here in welfare terms rather than in measures of economic growth. While future agents might be willing to pay substantial amounts for emissions reduction today if climate change is severe (represented by the upper curve in the graph), the policy maker must weigh this against the fact that under more optimistic forecasts (illustrated by the lowest curve) both present and future generations bear a

[14] Since the first cohorts of agents are dropped from the analysis sample, the figure shows all agents as being made worse-off by the policy.

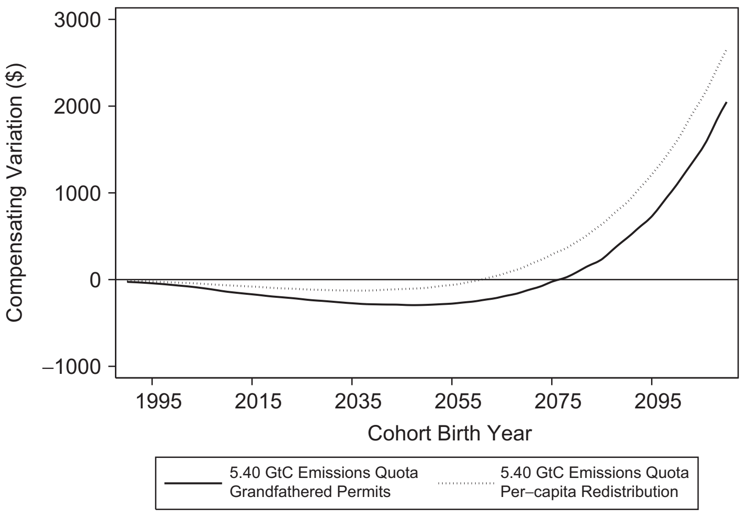

Fig. 8. Cohort compensating variation ($\$US_{1995} \times 10^9$) by rent redistribution rule for the 5.40 GtC emissions quota and benchmark (3 °C) climate scenario.

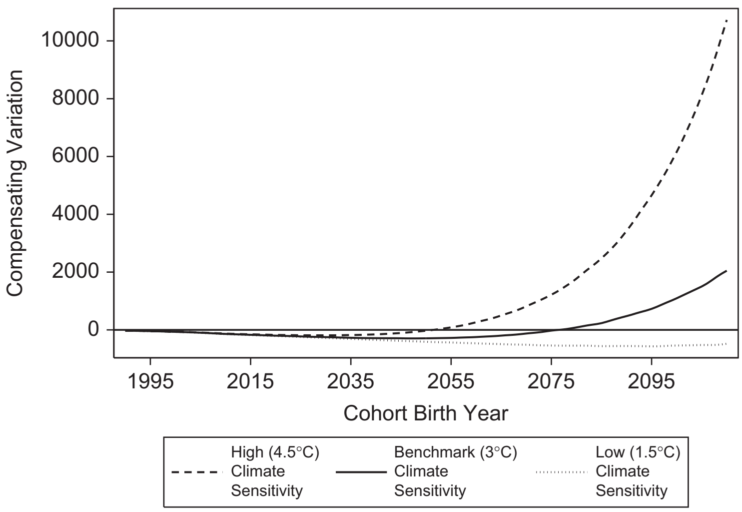

Fig. 9. Cohort compensating variation ($\$US_{1995} \times 10^9$) for the 5.40 GtC emissions quota by climate scenario.

cost of climate policies. Current generations see the certain costs, and uncertain benefits, and these are likely to dissuade them from acting.

The first measure I use to evaluate the set of considered climate policies is the date at which the first future generation made better off by the policy is born, or the point at which the compensating variation schedule crosses the zero line. This result will be affected by the combination of the marginal product of labour over agents' lifespans as well as the sequences of resource and policy rents they receive. It will also be affected by the equilibrium rates of return, which determine the cost of consumption smoothing. I present the results of policy evaluation on this basis in Table 2. Under the benchmark climate scenario and with permits allocated to firms, the first cohort made better off by the least stringent of policies, the constant price policy, is the generation born in 2061, 51 years after the policy is instituted. 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. The more stringent is the policy or the less severe is climate change, the longer is the period before any cohort is made better off.

Table 2 presents the important role for policy rent allocation in determining welfare effects. The most stringent policy considered, the fixed emissions quota, with a per-capita allocation rule has a shorter period before a birth cohort is made better off than does the least stringent policy with a grandfathering rule in place. More importantly, the first cohort made better off is born 15–25 years earlier in all cases when permit rents are allocated per-capita versus the same policy with a grandfathering of emissions permits to firms. The allocation of permits (equiv. carbon tax revenues) to agents on a

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

Policy	Low-sensitivity scenario (1.5 °C)		Benchmark scenario (3 °C)		High-sensitivity scenario (4.5 °C)	
5.40 GtC quota						
Issued to firms	NA	(6)	2075	(6)	2051	(6)
Issued per-capita	2115	(4)	2060	(3)	2036	(3)
Per-capita quota						
Issued to firms	NA	(5)	2069	(5)	2046	(5)
Issued per-capita	2103	(2)	2051	(2)	2030	(2)
Constant shadow value						
Issued to firms	2108	(3)	2061	(4)	2041	(4)
Issued per-capita	2080	(1)	2042	(1)	2025	(1)

*Policy rankings in brackets. NA implies that, within the sample period, no cohort is better off under the policy than under the BAU transition. In this case, ranking is by compensating variation for the 2120 birth cohort.

Table 3
Net present (2007) value, by discount rate, of compensating variation transfers in 10^{12} 1995 US dollars by allocation of emissions rights

	Social discount rate (ρ)											
	0			1.4%			10%			Market rate of return[a]		
	Climate change scenario			Climate change scenario			Climate change scenario			Climate change scenario		
	1.5 °C	3 °C	4.5 °C	1.5 °C	3 °C	4.5 °C	1.5 °C	3 °C	4.5 °C	1.5 °C	3 °C	4.5 °C
5.40 GtC quota												
Issued to firms	3.8	1085.6	7662.9	−17.1	188.3	1356.0	−7.5	−7.2	−6.7	−10.8	−10.5	−9.9
Issued per-capita	68.0	1202.9	8186.2	2.9	220.1	1465.7	−3.6	−3.4	−2.9	−5.4	−5.0	−4.3
Per-capita quota												
Issued to firms	32.9	905.4	4767.8	−7.5	186.1	863.0	−6.3	−6.1	−5.6	−9.2	−8.9	−8.3
Issued per-capita	87.1	997.5	5052.6	10.0	160.2	927.2	−3.0	−2.8	−2.3	−4.4	−4.1	−3.5
Constant shadow value (*$57.18/ton*)												
Issued to firms	44.7	419.3	1183.4	0.5	77.5	252.3	−5.3	−5.1	−4.7	−7.8	−7.5	−6.7
Issued per-capita	76.1	457.3	1234.5	11.6	90.4	235.8	−2.4	−2.2	−1.7	−3.6	−3.3	−2.6

[a] Compensating variations are discounted at agents' endogenously determined values of consumption over time under the no-policy benchmark for each climate scenario.

per-capita basis provides a benefit to agents born after the policies are implemented, but before the full effects of climate change mitigation are felt.

The second measure of policy performance I use is the NPV relative to the BAU, using a range of social discount factors $0<\rho\leqslant 1$. The social discount factor only has an *ex post* role, and so it is possible to test the sensitivity of policy evaluation to the social discount rate without distorting agent behaviour. I calculate the NPV of each policy and report these in Table 3.[15]

I choose to report NPV for discount rates of 1.4% and 10% given the recent debate over the conclusions of the Stern Review on the Economics of Climate Change [30]. While models such as Nordhaus and Boyer have derived optimal policies based on social discount rates in the range of 10% per year, the Stern Review uses a real rate of return on capital of 1.4% [21]. The degree to which the chosen discount rate affects the magnitude of policy NPV, and thus the choice of an appropriate response to the threat of climate change, is immediately obvious from Table 3. Using a 10% rate of discount, none of the climate policies considered have positive NPV even in the worst-case scenario. Conversely, under the 1.4% rate of discount, even the most stringent policy may have positive NPV under the least severe scenario for climate change.

The time structure of benefits and costs of climate change policy is such that the choice of discount rate dampens the effect of uncertainty over the severity of climate change in policy evaluation. While the costs of imposing climate change policy are felt with relative certainty in the near term, while the relatively more uncertain benefits are felt further into the

[15] Reported measures of NPV are sensitive to the truncation of the economy. Truncation introduces a downward bias in most cases, as long as the benefits to climate change mitigation policies are increasing in time and eventually positive. There may also be a bias for policies which have significant benefits or costs to older agents born before 1970, who are not included in the NPV calculations.

future. Comparing the range of benefits of any policy across climate change scenarios for the 10% and 1.4% discount rates powerfully illustrates this point. More severe climate change increases the benefits of the 5.4 GtC quota by an order of magnitude relative to the benchmark climate assumptions when I use a 1.4% discount rate, while the same change increases the NPV by less than 10% with a 10% discount rate. This motivates continued consideration of optimal climate policies derived using IAMs to the choice of social discount factor and the characterization of uncertain future events.

Table 3 highlights the importance of rent allocation rules in determining welfare effects. Holding the discount factor and climate scenario constant, the per-capita allocation of permit rents always dominates the grandfathering of emissions rights in NPV terms.[16] Discounting at market rates of return, I find that the most stringent quota policy considered with per-capita allocation of permits dominates the least stringent (constant shadow value) policy with grandfathered permits. Through per-capita allocation, young agents receive a transfer of scarcity rents which partially compensates them for having to live in a period of policy-induced economic slowdown. Whether or not one believes that climate change is a serious problem, the total abatement costs, in welfare terms, are reduced significantly by a per-capita allocation of policy rents. This suggests that both the optimal level of emissions and the cost of reaching a given target level of emissions or atmospheric carbon concentration will be lower under a per-capita allocation of climate policy rents.

5. 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 in the relatively short term, these effects may be tempered by lasting effects of emissions constraints on economic growth. 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 shown are in terms of the welfare implications of revenue recycling and discounting of future benefits. While most policies implemented or considered so far world-wide have grandfathered rights based on previous emissions, I show that the NPV of a policy such as the Kyoto protocol may be more than twice as high if the scarcity rents are captured on a per-capita basis rather than by firms. Perhaps more important still, I show that stringent climate change mitigation policies may be rejected on the basis of having a negative NPV where firms or older agents capture the rents, while the same emissions constraints would have positive NPV were the rents they generate allocated to the population as a whole. Regardless of the chosen policy or the severity of climate change, total abatement costs, in welfare terms, are reduced significantly by a per-capita allocation of rents. On the issue of discounting, my results show that when using the 10% rate of discount common in the IAM literature, none of the climate policies considered have positive NPV even in the worst-case scenario for climate change. Conversely, using a 1.4% rate of discount comparable to that used in the Stern Review, even the most stringent policies considered may have positive NPV under the least severe scenario for climate change.

While the current application of the model examines the question of rent allocation, the decentralized, generational model of climate and economy I propose provides a framework in which to examine other important climate change policy issue. Since the model characterizes the dynamic interaction between self-interested firms, agents, and resource owners, the environment is well suited to examine issues of voting and endogenous climate policy, research and development under technology competition, the interaction of climate policy and market power in the resource sector, and the examination of secondary benefits to climate change mitigation, where the reduction in other pollutants is likely to have age-specific impacts.

Certainly 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. As discussed in the paper, 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, as explored in the literature on induced technological progress. 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 allocation 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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[16] This can be seen by comparing the values in the first, third, and fourth rows of Table 3 with the values directly beneath.

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Appendix A. Supporting Information

Supplementary data associated with this article can be found in the onlin version at doi:10.1016/j.jeem.2007.11.006.

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