Fiscal Costs of Climate Change in the United States

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Abstract

This paper explores the fiscal impacts of climate change and their policy implications for the United States. First, it builds a dynamic general equilibrium fiscal policy climate-economy model where climate change may affect (i) government consumption requirements (e.g., health care), (ii) transfer payments (e.g., income support), (iii) tax revenues, and where (iv) adaptation (e.g., sea walls) must be publicly provided. Theoretically, the analysis shows that the optimal carbon price must account for government consumption impacts and, if the marginal cost of raising public funds exceeds unity, also for household transfer impacts of climate change. Second, the paper presents a novel bottom-up quantification of fiscal climate impacts based on literature synthesis and data analysis, and a calibration for the United States. Third, the numerical results indicate an optimal carbon price elasticity with respect to government consumption (transfer) impacts per degree warming of around 20 (10). Accounting for fiscal considerations moreover increases the projected domestic U.S. welfare benefits of climate policy by up to a factor of four.

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1 Introduction

Climate change is increasingly recognized as a fiscal risk for many governments.[1] Public finances may be exposed to climate change in numerous ways, including through existing program costs (e.g., disaster assistance, healthcare), the need for publicly funded adaptation (e.g., coastal protective infrastructure), and revenue yields due to climate change impacts on aggregate production. While standard integrated assessment models used to estimate the social cost of carbon (e.g., DICE, Nordhaus, 1992, 2017; FUND, Anthoff and Tol, 2014, etc.) generally do not consider or distinguish fiscal costs as such, they may contribute differentially to the overall costs of climate change. First, governments typically raise revenues with *distortionary* taxes (e.g., payroll levies which make it more expensive for firms to hire workers). Raising or diverting public funds from such taxes is socially costly. Second, fiscal constraints may result in lower adaptation funding - and thus higher climate change vulnerability - than anticipated by standard models. Third, consideration of such impacts may alter optimal climate policy as well.

This paper explores the policy and welfare implications of climate change's fiscal impacts. First, we set up a dynamic general equilibrium climate-economy model with linear distortionary taxes and government spending (building on Barrage, 2020a) and introduce three new channels for climate change to affect public budgets through impacts on (i) government consumption requirements, (ii) government transfers to households, and (iii) endogenous public adaptation expenditures. In addition, revenue impacts arise due to aggregate production impacts of climate change. Theoretically, we show that climate policy must account for fiscal costs. Government consumption impacts ought to be internalized just like output losses in standard climate-economy models. Surprisingly, if governments raise revenues with distortionary taxes, the social cost of carbon must further account for the effects of climate change on government *transfers* to households, and the associated changes in the set of equilibria that can be decentralized as a competitive equilibrium. The theoretical setup also indicates that the welfare costs of raising public revenues distort the optimal provision of adaptation to reduce the direct utility impacts of climate change (e.g., damages to national parks), but not adaptation to reduce production or capital impacts (e.g., protection of infrastructure). Intuitively, while it is costly to raise revenues to fund these adaptation measures, they effectively 'pay for themselves' by increasing aggregate productivity.[2]

Second, this paper presents a novel bottom-up quantification of climate fiscal impacts in the United States. It collects and extends quantitative estimates of climate impacts on the future

[1] For example, the United States Government Accountability Office has placed the federal U.S. government's fiscal exposure to climate change on its "High Risk List" (GAO, 2019). The International Monetary Fund has raised awareness of the fiscal implications climate change (IMF, 2008).

[2] More broadly, this result reflects the well-known property that optimal tax systems should maintain aggregate production efficiency under fairly general conditions (Diamond and Mirrlees, 1971). See also Judd (1999) on public capital inputs to production under distortionary Ramsey taxation.

costs of several government programs, including hurricane-related public spending, crop insurance subsidies, wildfire suppression costs, air quality-related healthcare costs, endangered species protections, and adds an empirical analysis of wildfire impacts on public health expenditures. Public adaptation is quantified based on the costs and benefits of protection against sea level rise damages as revealed by the U.S. Environmental Protection Agency's detailed Coastal Property Model (Neumann et al., 2014a,b). The current benchmark estimate implies an increase in U.S. government consumption of at least 0.39 percentage points per degree Celsius warming, and an increase in transfer payments of at least 0.11 percentage points.

Third, the paper quantifies the broader model for the U.S. economy. The main numerical results are as follows. In the near term, total public expenditures due to climate change are projected to rise from an estimated 10-year total of \$220 billion in the 2020s to \$350 in the 2030s and \$507 billion in the 2040s (\$2012), with the majority coming from existing program cost increases. As these benchmark estimates are subject to fundamental uncertainties, we quantify optimal carbon prices under a range of fiscal cost estimates. The results imply an elasticity of the optimal carbon price with respect to government consumption (transfer) impacts per degree warming of around 20 (10). That is, a one percent increase in government consumption (transfers) per degree warming translates into a +20% (+10%) increase in the optimal carbon price. The domestic welfare benefits of imposing U.S. carbon pricing are found to be substantial, and significantly larger once fiscal considerations are taken into account, rising from \$127 billion (in initial period lump-sum consumption equivalent variaton, \$2012) in the standard first-best setting to up to \$144-\$635 billion in a setting with distortionary taxation. In sum, these results highlight the relevance of fiscal considerations for climate policy design. Indeed, the size of the quantitative effects on the optimal carbon price are on par with prior studies' findings of factors such as climate system tipping points (Lemoine and Traeger, 2014), ambiguity aversion (Lemoine and Trager, 2016), or model uncertainty (Rudik, 2019).

Of course it must be stressed that these results are subject to critical caveats and limitations. Climate change impact quantifications are generally subject to fundamental uncertainties. Here, the fiscal cost estimates are moreover based on a first generation of studies of select programs, subject to many simplifications. Our model's representation of fiscal policy and the economy are also highly stylized. With these caveats in mind, the results nonetheless show that fiscal costs have the potential to be quantitatively important. That is, taking current literature and estimates as given, *adding* fiscal considerations to standard frameworks leads to a significant increase in the estimated welfare effects of climate policy. At the very least, the results thus suggest that fiscal costs warrant further empirical investigation and consideration in integrated assessment models.

Our analysis further relates to the literature as follows. First, this study builds on rich literatures on integrated assessment models (IAMs, e.g. DICE, Nordhaus, e.g., 1992, 2008, 2017; PAGE, Hope, 2011; FUND, Anthoff and Tol, 2014; MERGE, Manne and Richels, 2005; etc.) and macroeconomic climate-economy models (e.g., Golosov, Hassler, Krusell, and Tsyvinski, 2014; van der Ploeg and Withagen, 2014; Acemoglu, Aghion, Bursztyn, and Hemous, 2012; etc.), both of which have generally abstracted from distortionary taxes. A sub-strand of this literature focuses specifically on endogenous adaptation investments in integrated assessment models (e.g., Felgenhauer and Webster, 2013; Agrawala et al., 2010; Bosello, Carraro, and De Cian, 2010; de Bruin, Dellink, and Tol, 2009; Tol, 2007; Hope, 2006.) These frameworks have again generally abstracted from fiscal considerations, as does new work by Fried (2019) which builds and empirically quantifies a detailed macroeconomic model of adaptation to storm events in the United States, but does not distinguish public and private investments.

Second, a large literature[3] in environmental economics has demonstrated the importance of pre-existing taxes for the design of pollution mitigation policies, such as carbon taxes or emissions trading schemes (see, e.g., review by Bovenberg and Goulder, 2002). Numerous studies also use highly sophisticated computable general equilibrium models of the U.S. economy and tax system in order to quantify climate policy interactions with fiscal policy (e.g., Goulder, 1995; Bovenberg and Goulder, 1996; Jorgenson and Wilcoxen, 1996; Babiker, Metcalf, and Reilley, 2003; Carbone, Morgenstern, Williams, Burtraw, 2013; Jorgenson et al., 2013; Goulder, Hafstead, and Williams, 2014; Goulder and Hafstead, 2017; Fried et al., 2018; Goulder et al., 2019; etc.). While this paper's representation of the economy is vastly simplified compared to these studies, it adds an *integrated assessment* representation of climate change and its economic effects, including on government expenditures. In contrast, CGE models commonly assume climate change affects only household utility. This paper also shows how some core insights from this literature extend to optimal *public* adaptation policy.[4]

Finally, we build directly on a small but growing set of quantitative studies on the fiscal impacts of severe weather events and climate change (e.g., Deryugina, 2017; Moore et al., 2020). The remainder of paper proceeds with Section 2, which describes the model and the qualitative results. Section 3 presents our quantification of fiscal impacts and the calibration of the remainder of the model. Section 4 showcases the numerical results, and Section 5 concludes.

[3] These include, inter alia: Sandmo (1975); Bovenberg and de Mooij (1994, 1997, 1998); Bovenberg and van der Ploeg (1994); Ligthart and van der Ploeg (1994); Goulder (1995; 1996; 1998); Bovenberg and Goulder (1996); Jorgenson and Wilcoxedn (1996); Parry, Williams, and Goulder (1999); Goulder, Parry, Williams, and Burtraw (1999); Schwarz and Repetto (2000); Cremer, Gahvari, and Ladoux (2001; 2010); Williams (2002); Babiker, Metcalf, and Reilley (2003); Bernard and Vielle (2003); Bento and Jacobsen (2007); West and Williams (2007); Carbone and Smith (2008); Fullerton and Kim (2008); Parry and Williams (2010); d'Autume, Schubert, and Withagen (2011); Kaplow (2013); Carbone, Morgenstern, Williams and Burtraw (2013); Goulder, Hafstead, and Williams (2014); Barrage (2020a), etc.

[4] See Belfiori (2015) for an analysis of private adaptation in a similar setting.

2 Model

This section presents the model. Our framework builds on the dynamic COMET (Climate Optimization Model of the Economy and Taxation) model of Barrage (2020a), which builds on the climate-economy models of Golosov, Hassler, Krusell, and Tsyvinski (2014) and Nordhaus (2008; 2011) by incorporating a classic dynamic optimal Ramsey taxation framework (see, e.g., Chari and Kehoe, 1999) to incorporate distortionary taxation and government revenue requirements. We here extend this framework in the following four ways. First, we introduce climate change impacts on the costs of providing government services (e.g., health care) and on requisite government transfers to households (e.g., income support). Second, we introduce endogenous public adaptation expenditures. While the quantitative model currently focuses on sea level rise adaptation, the theoretical setup also considers spending to mitigate general climate impacts on production and on household utility. Third, we introduce a sea level rise module, both in terms of the climate dynamics of sea level rise and in making explicit the resulting capital losses. Finally, while the benchmark COMET is a global model, here we develop a version specific to the United States (US-COMET). For a stylized alternative quantification of the model to the global level, see Barrage (2020b).

To briefly preview the model: an infinitely-lived, representative household has preferences over consumption, leisure, and the environment. There are two production sectors. An aggregate final consumption-investment good is produced from capital, labor, and energy inputs. Domestic carbon emissions stem from a carbon-based energy input, which is produced from capital and labor. Rest-of-the-world (ROW) carbon emissions are exogenously given in the benchmark version of the model, although the quantitative analysis also considers a non-zero global emissions response elasticity to U.S. abatement efforts. The government must raise a given amount of revenues for government consumption, transfers, and funding for climate change adaptation through distortionary taxes on labor, capital, intermediate energy inputs, and carbon emissions.[5] Climate change affects the economy through six channels: (i) temperature change alters aggregate productivity, (ii) temperature change enters household utility directly, (iii) sea level rise depreciates the capital stock, (iv) temperature change affects the cost of providing government services (consumption), (v) temperature change affects government transfers to households, (vi) sea level rise affects the government's optimal expenditures on coastal protection efforts, and (vii) temperature change affects the government's optimal adaptation expenditures to mitigate general production and utility damages, respectively.

[5] In particular, lump-sum taxes are assumed to be infeasible, in the Ramsey tradition. It is moreover assumed that the revenues raised from Pigouvian carbon taxes are insufficient to meet government revenue needs, and that the government can commit to a tax series ex-ante (see Barrage (2020a) for further discussion).

Households

A representative household has well-behaved preferences over consumption C_t, labor supply L_t, and the climate, summarized by mean atmospheric surface temperature change T_t. The household's (dis)utility over climate change further depends on society's adaptive capacity to reduce utility damages, Λ_t^u. Lifetime utility U_0 is given by:

$$U_0 \equiv \sum_{t=0}^{\infty} \beta^t U(C_t, L_t, T_t, \Lambda_t^u) \tag{1}$$

Pure utility losses from climate change may reflect domestic non-production impacts, such as damages to national parks and biodiversity existence value losses, or also U.S. household disutility over climate impacts in other countries. We assume additive separability between preferences over consumption, leisure, and the climate, and that adaptive capacity reduces the disutility from climate change via:

$$U(C_t, L_t, T_t, \Lambda_t^u) = v(C_t, L_t) + h[(1 - \Lambda_t^u)T_t] \tag{2}$$

Intuitively, if adaptive capacity was at 100% ($\Lambda_t^u = 1$), climate impacts on utility would be fully neutralized. Each period, the household allocates his income between consumption, the purchase of one-period government bonds B_{t+1} (at price ρ_t), and investment in the capital stock K_{t+1}. The household's income derives from net-of-tax (τ_{lt}) labor income $w_t(1 - \tau_{lt})L_t$, net-of-tax (τ_{kt}) and depreciation ($\delta(SLR_t, \Lambda_t^{slr})$) capital income $\left\{1 + (r_t - \delta(SLR_t, \Lambda_t^{slr}))(1 - \tau_{kt})\right\} K_t$, government bond repayments B_t, profits from the energy production sector Π_t, and government transfers $G_t^T(T_t)$, which are restricted to be non-negative and may be affected by climate change. The capital depreciation rate depends on sea level rise (SLR) SLR_t as well as coastal protection level Λ_t^{slr}. Households take both the climate and adaptive capacities as given. The final consumption good is normalized to be the untaxed good. The household's flow budget constraint each period is thus given by:[6]

$$C_t + \rho_t B_{t+1} + K_{t+1} \leq w_t(1 - \tau_{lt})L_t + \left\{1 + (r_t - \delta(SLR_,, \Lambda_t^{slr}))(1 - \tau_{kt})\right\} K_t + B_t + \Pi_t + G_t^T(T_t) \tag{3}$$

As usual, the household's first order conditions imply that savings and labor supply are governed

[6] As in Barrage (2020a), we assume that (i) capital holdings cannot be negative, (ii) consumer debt is bounded by some finite constant M via $B_{t+1} \geq -M$, (iii) purchases of government debt are bounded above and below by finite constants, and (iv) initial asset holdings B_0 are given.

by the following decision rules:

$$\frac{U_{ct}}{U_{ct+1}} = \beta \left\{ 1 + (r_{t+1} - \delta(SLR_t, \Lambda_t^{slr}))(1 - \tau_{kt+1}) \right\} \tag{4}$$

$$\frac{-U_{lt}}{U_{ct}} = w_t(1 - \tau_{lt}) \tag{5}$$

where U_{it} denotes the partial derivative of utility with respect to argument i at time t.

Production

The final consumption-investment good is produced with a constant returns to scale technology using capital K_{1t}, labor L_{1t}, and energy E_t inputs, and is assumed to satisfy the standard Inada conditions. In addition, output is affected by both the state of the climate T_t and adaptive capacity in final goods production, Λ_t^y :

$$\begin{aligned} Y_t &= (1 - D(T_t)(1 - \Lambda_t^y)) \cdot A_{1t}\widetilde{F_1}(L_{1t}, K_{1t}, E_t) & (6) \\ &= F_1(A_{1t}, T_t, \Lambda_t^y, L_{1t}, K_{1t}, E_t) & (7) \end{aligned}$$

where A_{1t} denotes an exogenous total factor productivity parameter. Once again, if adaptive capacity were at 100% ($\Lambda_t^y = 1$), climate impacts would be neutralized. The modeling of climate production impacts as multiplicative factor was pioneered by Nordhaus (e.g., 1991) and reflects effects in sectors such as agriculture (see Nordhaus and Boyer, 2000). Note that the interpretation of $D(T_t)$ here may differ from standard setups in that it represents damages gross of any (public) adaptation.

Profit maximization and perfect competition imply that marginal products of factor inputs, denoted by F_{1it} for input i at time t, are equated to their prices in equilibrium. Letting p_{Et} denote the price of energy inputs, these conditions imply:

$$\begin{aligned} F_{1lt} &= w_t & (8) \\ F_{1Et} &= p_{Et} \\ F_{1kt} &= r_t \end{aligned}$$

Energy inputs E_t are produced from capital K_{2t} and labor L_{2t} with constant returns to scale:

$$E_t = A_{2t}F_{2t}(K_{2t}, L_{2t}) \tag{9}$$

Energy is generally carbon-based, but producers can provide fraction μ_t of energy from clean or zero-emissions technologies at an additional cost $\Theta_t(\mu_t E_t)$. Given perfect competition, energy sector profits are thus given by:

$$\Pi_t = (p_{Et} - \tau_{It})E_t - [(1-\mu_t)E_t]\tau_{Et} - w_t L_{2t} - r_t K_{2t} - \Theta_t(\mu_t E_t) \quad (10)$$

where p_{Et} represents the price of energy, τ_{It} is an excise intermediate goods tax, and τ_{Et} is an excise tax on carbon *emissions* $E_t^M \equiv (1-\mu_t)E_t$.[7]

Both capital and labor are assumed to be perfectly mobile across sectors, with associated market clearing conditions:

$$\begin{aligned} K_t &= K_{1t} + K_{2t} \\ L_t &= L_{1t} + L_{2t} \end{aligned} \quad (11)$$

Profit maximization thus implies that prices and marginal factors will be equated,

$$\begin{aligned} [p_{Et} - \tau_{It} - \tau_{Et}]F_{2lt} &= w_t \\ [p_{Et} - \tau_{It} - \tau_{Et}]F_{2kt} &= r_t \end{aligned} \quad (12)$$

and that energy producers abate μ_t until its marginal cost equals the carbon price τ_{Et} :

$$\tau_{Et} = \Theta_t'(\mu_t E_t) \quad (13)$$

Government

The government faces the following tasks. First, it must raise revenues to finance a given sequence of public consumption requirements $\{\overline{G}_t^C > 0\}_{t=0}^{\infty}$ and household transfers $\{\overline{G}_t^T \geq 0\}_{t=0}^{\infty}$, and pay off inherited debt B_0^G. One of the main novelties here is that the cost of providing these services may depend on the climate:

$$G_t^C(T_t) = \overline{G_t^C}(1 + \alpha_{C,1}(T_t)^{\alpha_{C,2}}) \quad (14)$$

$$G_t^T(T_t) = \overline{G_t^T}(1 + \alpha_{T,1}(T_t)^{\alpha_{T,2}}) \quad (15)$$

Second, at its discretion, the government can devote resources to produce adaptive capacity. Protection against sea level rise depends on an adaptive capital stock AK_t :

$$\Lambda_t^{slr} = f^{slr}(AK_t) \quad (16)$$

[7] Since producers face two decision margins on energy levels and emissions, we allow for two policy instruments to form a 'complete' tax system in the sense of Chari and Kehoe (1999).

which takes AK_0 as given and follows law of motion:

$$AK_t = AK_{t-1}(1 - \delta^{slr}) + \lambda_t^{slr} \tag{17}$$

Adaptive capacity against other production and utility damages depends on flow expenditures λ_t^y and λ_t^u, respectively:

$$\Lambda_t^i = f^i(\lambda_t^i) \text{ for } i \in \{u, y\} \tag{18}$$

Finally, the government has the following revenue raising instruments at its disposal. It can impose linear taxes on labor and capital income, levy excise taxes τ_{It} on energy inputs and τ_{Et} on carbon emissions, and it can issue new, one-period bonds B_{t+1}^G. The public flow budget constraint is thus given by:

$$G_t^C(T_t)+G_t^T(T_t)+\lambda_t^y+\lambda_t^u+\lambda_t^{slr}+B_t^G = \tau_{lt}w_tL_t+\tau_{It}E_t+\tau_{Et}E_t^M+\tau_{kt}(r_t-\delta(SLR_t,\Lambda_t^{slr}))K_t+\rho_tB_{t+1}^G \tag{19}$$

The market clearing condition for government bonds is given by:

$$B_{t+1}^G = B_{t+1} \tag{20}$$

We note that the benchmark closed model specification (20) captures only the domestic market U.S. government debt. In the quantification of the model, we distinguish domestically owned and foreign-owned U.S. debt to ensure an accurate representation of asset levels currently held by the U.S. public.[8]

One important concept going forward is the *marginal cost of public funds* (MCF_t), which measures the welfare cost of raising an additional dollar of government revenues. If the government could impose lump-sum taxes, then the marginal cost of public funds would be equal to one, as households would give up \$1 in a pure transfer to the government. In contrast, if revenues must be raised through distortionary instruments, the costs of raising \$1 equal \$1 plus the excess burden (or marginal deadweight loss) of taxation. Following the literature, we formally define the MCF_t as the ratio of public to private marginal utility of consumption:

[8] Of course abstracting from foreign demand for U.S. government debt raises additional potential issues. On the one one hand, ignoring the current stock of foreign-held debt may under-estimate the government's future revenue-raising obligations in the intertemporal budget constraint. On the other hand, abstracting from the foreign supply of loanable funds may lead to an over-estimate of the costs of borrowing for the U.S. government.

$$MCF_t \equiv \frac{\lambda_{1t}}{U_{ct}} \tag{21}$$

where λ_{1t} is the Lagrange multiplier on the resource constraint in the planner's problem (see Appendix). The wedge between the marginal utility of public and private incomes thus serves as a measure of the distortionary costs of the tax system.

Climate System

Global temperature change depends on the history of *global* greenhouse gas emissions, that is, the sum of rest-of-world (ROW) emissions $E_t^{M,ROW}$and domestic emissions $\{E_s^M\}_{s=0}^t \equiv \{(1-\mu_s)E_s\}_{s=0}^t$. . Atmospheric temperature change T_t at time t then formally depends on the history of carbon emissions, initial conditions $\mathbf{S}_0$ (e.g., carbon stocks, ocean temperatures, etc.), and exogenous shifters $\{\boldsymbol{\eta}_s\}_{s=0}^t$ (e.g., land-based emissions) via:

$$T_t = F\left(\mathbf{S}_0, E_0^M + E_0^{M,ROW}, E_1^M + E_1^{M,ROW}, ..., E_t^M + E_t^{M,ROW}, \boldsymbol{\eta}_0, ...\boldsymbol{\eta}_t\right) \tag{22}$$

where:

$$\frac{\partial T_{t+j}}{\partial E_t^M} \geq 0 \; \forall j, t \geq 0$$

Sea level rise at time t, in turn, is modeled as a function of the history of global temperature change, along with initial condition SLR_0, following the semi-empirical specification due to Rahmsdorf (2007):

$$SLR_t = G(SLR_0, T_1, T_2, ...T_t) \tag{23}$$

Competitive Equilibrium and Optimal Policy

Competitive equilibrium in this economy is defined in the conventional way. The social planner's problem is to maximize the representative agent's lifetime utility (1) subject to the constraints of (i) feasibility, (ii) the optimizing behavior of households and firms, and (iii) laws of nature (22)-(23). We follow the primal approach of solving for optimal *allocations* after having shown that and how one can construct prices and policies such that the optimal allocation will be decentralized by optimizing households and firms.[9] Solving for optimal allocations, rather than for optimal tax rates, also avoids normalization issues such as documented by Williams (2001).

While the focus of this study is primarily quantitative, we can derive several theoretical results as well. First, we can ask how consideration of fiscal costs affect the optimal carbon price. For

[9] See, e.g., Chari and Kehoe (1999) for a general introduction, and Barrage (2020a) for the relevant proof of the validity of the setup in the benchmark COMET.

notational convenience, first define the discount factor M_j as:

$$M_j \equiv \begin{cases} 1 & \text{if } j = 0 \\ \beta^j \prod_{m=1}^{j} \frac{1}{(1+r_{t+m}-\delta_{t+m})} & \text{o.w.} \end{cases} \tag{24}$$

Result 1 *The optimal carbon tax in period $t > 0$, that is, the carbon tax that can decentralize the optimal allocation along with other taxes set appropriately, is implicitly defined by:*

$$\tau^*_{Et} = \sum_{j=0}^{\infty} M_j \cdot \underbrace{\left[\frac{-\partial Y_{t+j}}{\partial T_{t+j}}\right]}_{\text{Output Impacts}} \cdot \frac{\partial T_{t+j}}{\partial E^M_t} \tag{25}$$

$$+\sum_{j=0}^{\infty} \beta^j (\frac{1}{MCF_t}) \underbrace{\left[\frac{-U_{Tt+j}}{U_{ct}}\right]}_{\text{Utility Impacts}} \frac{\partial T_{t+j}}{\partial E^M_t} \tag{26}$$

$$+\sum_{j=0}^{\infty} \underbrace{\left[\sum_{m=0}^{\infty} M_{j+m} \cdot \frac{\partial \delta K_{t+m}}{\partial SLR_{t+m}} \frac{\partial SLR_{t+m}}{\partial T_{t+j}}\right]}_{\text{Sea Level Rise Impacts}} \frac{\partial T_{t+j}}{\partial E^M_t} \tag{27}$$

$$+\sum_{j=0}^{\infty} M_j \cdot \left[\frac{\partial G^C_{t+j}}{\underbrace{\partial T_{t+j}}}\right]_{\text{Gov't Cons. Impacts}} \frac{\partial T_{t+j}}{\partial E^M_t} \tag{28}$$

$$+\sum_{j=0}^{\infty} \beta^j (\frac{MCF_t - 1}{MCF_t}) \underbrace{\left[\frac{\partial G^T_{t+j}}{\partial T_{t+j}}\right]}_{\text{Gov't Transfer Impacts}} \underbrace{\left(\frac{U_{ct+j}}{[U_{cct}C_t + U_{ct} + U_{lct}L_t - U_{cct}G^T_t(T_t)]}\right)}_{\text{Offer Curve Impacts}} \frac{\partial T_{t+j}}{\partial E^M_t} \tag{29}$$

Intuitively, this expression represents the present discounted vaule sum of marginal damages from another ton of U.S. carbon emissions at time t, adjusted for the fiscal setting. The impacts of emissions on future temperature change are captured by $\frac{\partial T_{t+j}}{\partial E^M_t}$. Each period's temperature change, in turn, contributes to sea level rise, as captured by the additional summation term $\frac{\partial SLR_{t+m}}{\partial T_{t+j}}$ in (27). The economic impacts of these climatic changes are then valued as follows. First, the present discounted value of output impacts in (25) are valued fully, in line with prior literature. Second, and in contrast, utility impacts in (26) are "discounted" by the marginal cost of public funds. That is, in a setting with distortionary taxes where $MCF > 1$, the optimal carbon tax internalizes less than the full Pigouvian cost of marginal utility damages. This result is well known from the literature focusing on the *revenue* impacts of pollution levies alongside distortionary taxes (see Bovenberg and Goulder, 2002). Third, capital losses due to sea level rise are again valued fully in (27), as they fall on the production side of the economy. Fourth, the optimal carbon price should fully internalize government consumption cost increases due to climate change in (28). To the best of our knowledge, this type of impact has not been considered in prior literature. Finally, and perhaps most surprisingly, we find that *the optimal carbon price must account for government transfer impacts of climate change if the marginal cost of public funds exceeds unity* (29). In a standard setting where it is implicitly assumed that governments can raise revenues through lump-sum transfers, $MCF = 1$ and externality effects on transfers would not be included in the calculation of social cost. Here, however, a first-order welfare effect arises due to climate-induced changes in government transfer payments, and the resulting changes in households' offer curves, which may tighten the set of equilibria that can be decentralized as a competitive equilibrium. Importantly, these results showcase that consideration of climate change's fiscal costs may alter the structure of the optimal carbon price, calling for the inclusion of effects - such as on transfer payments - which are generally not considered.

The next theoretical question we can ask is: How does accounting for the welfare costs of raising public funds affect optimal public adaptation expenditures?

Result 2 *Public funding of both (i) flow adaptation inputs to reduce climate impacts on final goods production and (ii) investment in adaptation capital to reduce sea level rise impacts on capital depreciation should remain undistorted regardless of the welfare costs of raising revenues. That is, these adaptation expenditures should be fully provided at the optimum.*

Proof: See Appendix. While the actual dollar amount of optimal spending will differ across fiscal scenarios, Result 2 implies that there is no "wedge" (or distortion) in the optimality condition for adaptation spending to reduce production and capital damages from climate change: the government should invest until the additional benefit of avoided output losses equals the marginal adaptation cost.[10] Intuitively, while it is costly for the government to raise revenues, at the optimal level these expenditures 'pay for themselves' by increasing productivity and thereby expanding the bases of labor and capital income taxes. More broadly, this result follows from the well-known property that optimal tax systems maintain aggregate production efficiency under fairly general conditions (Diamond and Mirrlees, 1971).[11]

Next, and in contrast, consider the adaptation spending to reduce utility impacts of climate change (e.g., beach nourishment to maintain public parks). While these expenditures increase

[10] More formally, the optimal policy equates the marginal rate of transformation between consumption C_t and adaptive capacity Λ_t^y through adaptation expenditures λ_t^y and avoided output losses from climate change in the final goods sector.

[11] By noting that flow adaptation expenditures constitute a public input to production, this result is partly also in the vein of Judd (1999), who shows that public flow productive inputs should always be fully provided, regardless of the distortionary costs of raising revenues.

utility, they do not yield a productivity benefit that could counteract the macroeconomic costs of raising the revenues required to fund them. Consequently, we find that the optimal provision of these adaptation expenditures is distorted in a setting with costly taxation.

Result 3 *Public adaptation funding to reduce direct utility losses from climate change should be distorted proportionally to the marginal cost of raising public funds. That is, provision of the climate adaptation good should be effectively taxed alongside the consumption of other final goods if the government raises revenues with distortionary taxes.*

Proof: See Appendix. Result 3 implies that residual (net-of-adaptation) climate damages may be higher in a setting with distortionary taxes as even optimized public adaptation expenditures may be lower compared to a standard setting without fiscal constraints.

3 Fiscal Costs: Quantitative Estimates

3.1 Existing Programs

This section reviews quantitative evidence related to climate change impacts on the costs of public programs in the United States. We first review prior estimates of specific climate change fiscal impacts. We then conduct an original empirical analysis of wildfire impacts on public health expenditures, and combine this with wildfire risk change projections from the literature to infer future cost changes. Finally, we review prior estimates of the fiscal costs of hurricanes, and couple these with hurricane risk projections under climate change to derive overall impact estimates.

3.1.1 Prior Estimates

Hurricane-related public disaster spending: The Congressional Budget Office (CBO) conducted a careful analysis in 2016 to quantify potential future changes in hurricane damages and their fiscal costs in the United States. Their central estimates imply an increase in expected annual direct hurricane damages from 0.16 percent of GDP at present to 0.22 percent by 2075. Approximately 45 percent of this increase is estimated to be due to climate change, based on state-level sea level rise scenarious coupled with altered future hurricane patterns as simulated under the Intergovernmental Panel on Climate Change's (IPCC) Representative Concentration Pathway ("RCP") 8.5 scenario. The remainder is due to projected increases in coastal development. CBO further estimates that, in recent years, federal spending in response to hurricanes has averaged around 62 percent of the direct damage value, or 0.10 percent of GDP. These expenditures include disaster relief through FEMA and the Department of Housing and Urban Development, as well as repair activities by the Army Corps of Engineers, the Department of Transportation, and the Department of Defense, inter alia. Assuming that the federal aid-damage ratio will remain at 62 percent in the future, CBO thus projects a benchmark increase in federal spending from 0.10 to 0.13 percent of GDP by 2075. We consider the climate-related 45% of this change (+0.0135 percent of GDP) as benchmark impact at the associated global mean surface temperature warming.[12]

Crop-Insurance Subsidies: The U.S. government offers subsidized crop insurance through the Federal Crop Insurance Program. The majority of premium costs - almost two-thirds - are paid for by the government on average according to the Office of Management and Budget (OMB, 2016). In a joint analysis with the U.S. Department of Agriculture (USDA), OMB (2016) projects program costs to increase 40% by 2080 under RCP 8.5, and 23% by 2080 under RCP 4.5 Given the relevant median projections for future global temperature change in each of those scenarios, we infer that impacts are approximately linear at around a +14% increase in costs per degree warming.[13]

Table 1: Crop Insurance Cost Increase by 2080

	RCP 8.5	RCP 4.5	Source
Increase	+40%	+23%	OMB (2016)
Global Temp. Change (by 2075)	$2.85°C$	$1.6°C$	IPCC (2014)
Per $1°C$ impact:	+14.04%	+14.38%	
Regression Coefficient per $1°C$:		+14.05%	

Wildfire Suppression Costs: The OMB (2016) also presents results from a USDA Forest Service (2015) analysis to projected climate change impacts on the wildfire suppression costs incurred by both the Forest Service (FS) and the Department of Interior (DOI). Their central estimates imply annual cost increases of +45% for DOI and 117% for FS by mid-century (2041-2059), and further cost increases of +72% for DOI and +192% for FS by late-century (2081-2099) under the RCP8.5 scenario. Table 2 summarizes these results and the implied cost increases per degree of warming, which again appear close to linear.

12 Mean predicted global temperature changes for RCP 8.5 are $2.0°C$ for 2046-2065, and $3.7°C$ for 2081-2100, above a 1986-2005 baseline (IPCC, 2014). Interpolating linearly yields $2.85°C$ by 2075.

13 One relevant question for the appropriate integration of these costs into an IAM is whether this program's benefits are already reflected in agricultural output loss projections included in climate-economy models. To the extent that agricultural impact estimates are based on studies that use private return measures such as land prices (e.g., Nordhaus, Mendelsohn, and Shaw, 1994), they should already reflect net-of-subsidy costs, so that subsidies can be added to the model without modification to the private damage function. Of course we note that this approach ignores potential moral hazard effects of crop insurance on incentives for climate adaptation as documented by Annan and Schlenker (2015).

Table 2: Wildfire Suppression Cost Increases

	RCP 8.5		Source
	2041-59	2081-99	
Global Temp. Change	$2.0°C$	$3.7°C$	IPCC (2014)
Forest Service	+117%	+192%	OMB (2016), USDA FS (2015)
Per $1°C$ impact:	+58.5	+51.9	
Regression coefficient per $1°C$		+52.1%	
DOI	+45%	+72%	OMB (2016), USDA FS (2015)
Per $1°C$ impact:	+22.5%	+19.5%	
Regression Coefficient per $1°C$:		+19.6%	

Urban Drainage Infrastructure: Climate change is projected to alter the costs of maintaining current levels of service in urban infrastructure drainage systems. The U.S. Environmental Protection Agency (EPA, 2017) has produced estimates of these costs across 100 major cities in the Unitd States. Assuming that cities will want to remain prepared for 50-year storm events, the estimated cost increases are presented in Table 3.

Table 3: Urban Drainage Infrastructure Costs

	RCP 8.5		RCP 4.5		Source
	2050	2090	2050	2090	
Global Temp. Change	$2.0°C$	$3.7°C$	$1.4°C$	$1.8°C$	IPCC (2014)
Annual Cost ($2015 bil)	4.3	5.6	3.7	4.1	EPA (2017)
Per $1°C$ impact:	2.2	1.5	2.6	2.3	
Regression coefficient per $1°C$				+$1.83 bil./yr	

Endangered Species Act (ESA): As climate change is predicted to significantly increase the number of species at risk of extinction, it may also increase the number of species listed under the ESA. Protected species incur significant government expenditures at both state and federal levels, for activities ranging from enforcement to research, and at agencies ranging from the U.S. Fish and Wildlife Service to the Army Corps of Engineers. Moore et al. (2020) combine a careful empirical analysis of the determinants of species listings and expenditures with projections of species extinction risk under warming to estimate the associated fiscal costs. Their benchmark results imply that the present value of ESA-related expenditures will increase 12.5% due to $2°C$ of warming, and 47.5% due to $5°C$ warming, implying an average per degree increase of +7.9%. We apply this increase to base year total government ESA expenditures (FWS, 2017) to infer annual spending impacts.

West Nile Neuroinvasive Disease: Climate change may expand the ranges of vectors for diseases such as the West Nile virus. The EPA (2017) projects increases in cases of West Nile neuroinvasive Disease (WNND) due to climate change across the United States. WNND is a severe condition resulting from West Nile Virus infection which typically requires hospitalization and carries a 6.5% mortality rate (EPA, 2017). Table 4 presents EPA projections of WNND case increases due to a changing climate (that is, excluding population change effects).

Table 4: West Nile Neuroinvasive Disease Cases

	RCP 8.5		RCP 4.5		Source
	2050	2090	2050	2090	
Global Temp. Change	$2.0°C$	$3.7°C$	$1.4°C$	$1.8°C$	IPCC (2014)
Additional Cases	720	2200	510	800	EPA (2017)
Per $1°C$ impact:					
Regression coefficient per $1°C$				+513 cases/yr	

Typical hospitalization costs for WNND are $41k ($2015) per case (EPA, 2017). National Health Expenditure Accounts suggest that *public* spending has consistently accounted for around 50% of hospitalization expenditures since the 1970s (CMS, 2020). We consequently assume a public cost of $20.5k per case, implying a cost increase of $10.5 million/year/$°C$.[14]

Air Quality-Related Healthcare: Garcia-Menendez et al. (2015) use coupled earth systems and a global atmospheric chemistry model to study climate change impacts on concentrations of fine particulate matter (PM2.5) and ground-level ozone across the United States. A changing climate is projected to alter these pollutants' concentrations through mechanisms such as water vapor and temperature effects on atmospheric chemistry and ventilation. While their published study focuses on resulting mortality impacts, OMB (2016) obtained further results from the authors on several morbidity outcomes (e.g., respiratory hospital admissions), and uses these to quantify associated changes in federal health care costs. Their central estimates are modest, corresponding to an extra *$1.2 billion per year* in today's terms in a 'no policy' baseline (leading to $6°C$ global mean surface temperature change by end of century) compared to a mitigation scenario (limiting warming to $1.5°C$). Importantly and as noted by OMB, as these estimates do not capture climate impacts through changes in wildfire frequencies. We consequently attempt a separate quantification of these impacts below.

[14] Assuming that hospitalization costs remain constant in the future is arguably conservative in that it implicitly assumes productivity growth in health care to match that of the aggregate economy. In reality, substantial evidence suggests that productivity growth has been lower in the health care sector (Sheiner and Malinovskaya, 2016) implying cost increase over time.

3.1.2 Wildfires and Healthcare

The estimates presented thus far do not account for the potential public healthcare costs of future changes in wildfire activity. This section focuses on this channel, motivated by two considerations. First, wildfire risk is projected to increase rather severely in many parts of the United States (Vose et al., 2012). Table 5 summarizes key estimates from the literature by presenting averages of standardized projections for the most wildfire-vulnerable states. Some states are projected to experience average annual burn area increases of over 200 percent per degree of global warming.

Table 5: Review of Wildfire Burning Change Estimates

State	%ΔWildfire Activity per $1^{\circ}C$ global warming	Sources:
AZ	241	McKenzie et al. (2004), Littell et al. (2009), Liu et al. (2009)
NM	237	McKenzie et al. (2004), Littell et al. (2009), Liu et al. (2009)
UT	240	McKenzie et al. (2004), Littell et al. (2009), Liu et al. (2009)
NV	98	McKenzie et al. (2004), Littell et al. (2009), Liu et al. (2009)
CA	82	Lenihan et al. (2003), McKenzie et al. (2004), Littell et al. (2009)
ID	84.7	Littell et al. (2010), Liu et al. (2010)
OR	72.1	Rogers et al. (2011), Littell et al. (2010), Liu et al. (2010)
WA	72.1	Rogers et al. (2011), Littell et al. (2010), Liu et al. (2010)
TX	14.0	Liu et al. (2010) (SW region estimate)
OK	14.0	Liu et al. (2010) (SW region estimate)
FL	28.2	Liu et al. (2010) (SE region estimate)
AK	43.3	Liu et al. (2010) (US overall estimate)

Table presents average of projections of percentage changes in acres burned per year or, for Liu et al. (2010), annual wildfire potential as measured by the Keetch-Byram Drought Index, normalized across future climate scenarios to a change per $1^{\circ}C$ global warming. We infer linearity in temperature based on Liu et al. (2010).

The second motivation is that wildfires have been linked to both poor air quality and increased healthcare utilization. For example, Ahman et al. (2012) document increases in emergency department visits and hospitalizations for respiratory and cardiovascular outcomes during the June 2012 wildfires in Colorado. Similarly, Gan et al. (2017) link 2012 wildfires in Washington State to both higher PM2.5 concentrations and increased cardiopulmonary hospital admissions. A national analysis by Fann et al. (2018) combines a chemical transport model to project PM2.5 increases from wildfire episodes between 2008-2012 across the United States with exposure response functions to estimate health impacts. Their central estimates imply +11,300 extra hospital admissions in 2008 due to wildfires.

Data: For the purposes of this study, we need estimates of the marginal effect on public healthcare expenditures associated with wildfire activity. To this end, we collect data from the following sources. First, we obtain information on total government transfer values for medical benefits, populations, and incomes at the county-year level from the Bureau of Economic

Analysis' (BEA) Reginal Economic Accounts ("REA", following Deryugina's (2017) analysis of hurricanes as described below). These data are available from 1969-2018. We also consider more detailed data on Medicare utilization and beneficiary demographics from the Centers for Medicare & Medicaid Services (CMMS). Though also at the county-year level, these data are only available from 2007-2017. Next, we use the National Oceanic and Atmospheric Administration's (NOAA) Storm Events Database, which provides information on a wide range of events including wildfires from 1996-2018. We process these data by computing, for each county-year, the number of days during which an event of interest occurred.[15] Our primary focus is on wildfires and dense smoke events, however we later also consider controls for winter weather events (blizzards, sleet, high snow, etc.), rain- and thunderstorm events (heavy rain, thunderstorms, tropical depression, etc.), extreme heat and cold episodes, and strong wind events. We also consult the National Interagency Fire Center to obtain information on the number of acres burned by state-year (2002-2018), which we use to identify the top quartile of states in terms of wildfire risk, measured by average acres burned per year relative to state land area. These are the states listed in Table 5. Following analogous logic to Deryugina (2017), we restrict our empirical analysis to counties in these high risk states as the more appropriate control group. State land areas are obtained from the U.S. Census Bureau, and population age and race profiles by county-year are obtained from the National Center for Health Statistics. Finally, we collect air quality information from the U.S. Environmental Protection Agency, again at the county-year level for 1996-2018.

Analysis: We present two sets of regressions. The first considers wildfires directly as a covariate of public healthcare spending. The second is a two-stage least squares specification that first links wildfires to poor air quality, and then considers the impact of these air quality changes on public health costs. The first follows a standard panel specification:

$$\ln Y_{j,t} = \gamma_j + \delta_t + (\theta_s \cdot t) + \beta_1 \ln \text{FireDays}_{j,t} + \mathbf{X_{j,t}}'\boldsymbol{\beta} + \epsilon_{j,t} \tag{30}$$

Here, $\ln Y_{j,t}$ denotes the natural logarithm of outcome Y in county j in year t. The γ_j are county fixed-effects, which absorb cross-sectional differences in public medical expenditures across counties. Year fixed-effects δ_t capture aggregate (national) shocks to public medical spending in a given year. We further include *state-specific trends* $(\theta_s \cdot t)$ that allow our outcome variables to follow different trends in different states. The coefficients of interest thus measure the association between wildfires and counties' deviations in outcomes relative to their local means and state-trends (conditional on the other covariates). This coefficient of interest is β_1, the elasticity of outcome $\ln Y_{j,t}$ with respect to the number of fire and smoke days in a county-year. The

[15] The Storm Events Database maps events into counties or "zones". We translate zone events into underlying counties based on the National Weather Service's zone-county correlation file. [https://www.weather.gov/gis/ZoneCounty]

vector $\mathbf{X_{j,t}}$ represents other control variables. For regressions using REA data, "Demo./Inc. Controls" includes the natual logarithm of counties' populations, of the population 65 years and older, and of real per capita income; controls for prior year to current population and per capita income growth, and the fraction of non-hispanic whites in the county population. For regressions using CMMS Medicare data, "Medicare Controls" further adds the natural logarithm of the number of Medicare beneficiares, the percentages female and non-hispanic white among beneficiares, the percentage enrolled in Medicare Advantage plans, average beneficiary age, and average Hierarchical Condition Category scores in the county-year. Standard errors $\epsilon_{j,t}$ are heteroskedasticity-robust and clustered at the county level. Finally, we estimate (30) both as is and with observations weighted by county populations.[16]

Table 6 presents the results. The association between wildfires and public medical expenditures appears small, but it is positive and precisely measured across several specifications. Taken at face value, the results suggest that a 1% increase in the number of wildfire or smoke days in a vulnerable county increases public Medicaid and other expenditures that year by 0.0007%. Though not directly comparable,[17] we can consider this order of magnitude vis-à-vis Fann et al.'s (2018) estimate that U.S. wildfires caused an additional 11,300 hospital admissions in 2008. Given that national hospital admissions resulting from emergency department visits were 15 million in 2008, the implied percentage increase is 0.00075%.

[16] This is both to account for the higher number of 'observations' underlying each county-year in populous counties, and, similarly, to reduce the weight given to very small counties that may easily appear as outliers for our outcomes measured in growth terms.

[17] Fann et al. (2018)'s estimates represent (i) a total effect, (ii) on hospital admissions, (iii) at a national level, whereas our estimates represent (i) marginal effects (ii) on total expenditures, but (iii) in the most vulnerable states, which we would expect to be smaller on account of (i) and (ii) but larger on account of (iii).

Table 6: Public Medical Expenditures (REA Data)

Dep. Var.:	ln(Public Medical Expenditures)						
	Medicaid plus (Veterans etc.)			Medicare			
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
ln(FireSmokeDays)	0.0007**	0.0007**	0.0007**	0.0001	0.0006*	0.0001	0.0006*
	(0.0004)	(0.0004)	(0.0004)	(0.0002)	(0.0003)	(0.0002)	(0.0003)
ln(WinterEventDays)			0.0011***			0.0005**	0.0002
			(0.0004)			(0.0002)	(0.0003)
ln(RainThunderDays)			-0.0003			0.0004**	0.0002
			(0.0002)			(0.0002)	(0.0002)
ln(HeatEventDays)			0.0008*			0.0001	-0.0003
			(0.0004)			(0.0002)	(0.0002)
ln(ColdEventDays)			-0.0002			0.0001	0.0002
			(0.0004)			(0.0003)	(0.0003)
Obs.	15,289	15,289	15,289	15,302	15,302	15,302	15,302
Adj. R-Sq.	0.994	0.997	0.994	0.997	0.999	0.997	0.999
#Counties	701	701	701	701	701	701	701
Demo./Inc. Controls:	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Pop. Weights:	No	Yes	No	No	Yes	No	Yes
County F.E.s:	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year F.E.s:	Yes	Yes	Yes	Yes	Yes	Yes	Yes
State-Trends:	Yes	Yes	Yes	Yes	Yes	Yes	Yes
S.E. Cluster	County	County	County	County	County	County	County

Analogous results to Table 6 using the CMMS Medicare data are generally noisy, as may be expected given that the sample size is only half (10 years) of the REA data. Both in order to improve precision and further illustrate the underlying mechanism of the wildfire-healthcare expenditure link, we thus next present a two-stage least squares analysis. The first stage seeks to isolate changes in air quality - specifically the number of days with "unhealty" air as per EPA classification - associated with wildfires. The second stage links these air quality changes to public healthcare expenditures. Table 7 presents results for three outcomes: (i) total public medical expenditures from the REA data, (ii) emergency department visits per 1,000 Medicare beneficiares from the CMMS data, and (iii) standardized (for reimbursement rate differences) Medicare expenditures from the CMMS data. All specifications include county fixed effects, year fixed effects, state-specific trends, demographic and income controls, and, where applicable, further Medicare controls. The results confirm a positive and significant association between both wildfire days and unhealthy air days, and between unhealthy air and public medical costs. As a placebo check, we also consider dialysis events per 1,000 Medicare beneficiaries, for which we find a negative point estimate that is statistically indistinguishable from zero (see Appendix).

Table 7: Two-Stage Analysis: Wildfires, Unhealthy Air Days, and Public Medical Expenditures

	(1)	(2)	(3)	(4)	(5)	(6)
	First Stage	Second Stage	First Stage	Second Stage	First Stage	Second Stage
	ln(Unhealthy Days)	ln(Public Medical Expend.)	ln(Unhealthy Days)	ln(Emergency Dep. Visits/ 1000 Ben.)	ln(Unhealthy Days)	ln(Stnd. Medicare Exp. p.c.)
ln(FireDays)	0.0728***		0.0798***		0.0798***	
	(0.0166)		(0.0222)		(0.0222)	
ln(UnhealthyDays)		0.0082**		0.0069*		0.0012
		(0.0033)		(0.0041)		(0.0018)
Obs.	4,704	4,704	2,320	2,320	2,320	2,320
#Counties	282	282	237	237	237	237
Demo./Inc. Controls:	Yes	Yes	Yes	Yes	Yes	Yes
Medicare Controls:	-	-	Yes	Yes	Yes	Yes
County F.E.s:	Yes	Yes	Yes	Yes	Yes	Yes
Year F.E.s:	Yes	Yes	Yes	Yes	Yes	Yes
State-Trends:	Yes	Yes	Yes	Yes	Yes	Yes
S.E. Cluster	County	County	County	County	County	County
Adj. R-Sq.		0.973		0.203		0.764
Kleibergen-Paap Wald F. Stat.	19.3		12.98		12.98	

We ultimately combine the benchmark elasticity estimate of 0.007 from Tabel 6 with the state-specific wildfire risk increase projections from Table 5 to gauge potential future cost increases due to climate change. This approach is conservative in that it sets cost changes in other states to zero, including in states such as Colorado which are generally also projected to suffer significant wildfire risk increases due to climate change.

3.1.3 Hurricanes: Healthcare and Transfers

Deryugina (2017) presents a detailed empirical analysis of hurricane strike impacts on fiscal transfers in the United States. She shows that non-disaster transfers, such as public medical payments and unemployment insurance, increase significantly in response to storms, and that those transfers are generally of much higher value than direct disaster aid. Deryugina (2017) presents several disaggregations of impacts by transfer type and hurricane category. For our purposes, we first utilize her data and code to construct estimates of the average annual per capita spending impact on a county struck by a hurricane in the ten years following the storm for total medical and income support payments, respectively.[18] Table 8 displays the resulting

[18] We specifically create outcome variables that are either (i) the log of the sum of Medicare and non-Medicare public medical expenditures per capita, or (ii) the log of the sum of unemployment benefits, income maintenance transfers (e.g., Supplemental Nutrition Assistance Program), and retirement and disability insurance benefits, and re-run the "Wind Speed Regressions" "Event study" specification for these outcomes, which yields impact estimates for the 10 years following the storm. Table 6 presents the average annual impact by

estimates.

Table 8: Hurricanes' Fiscal Costs

Hurricane Saffir-Simpson Category:	Public Medical	Transfers
Cat. 1	3.7%	1.2%
Cat. 2	3.6%	1.8%
Cat. 3+	4.8%	6.76%

Avg. *annual* per capita effect across estimated coefficients for years 0-10

Second, we combine these results with predictions of changes in U.S. hurricane patterns to infer climate impacts. We specifically use the current and future U.S. hurricane probability density functions estimated by Bakkensen and Barrage (2019) based on synthetic hurricane tracks under current and future climates from Emanuel et al. (2008), along with historical storm track data from the International Best Track Archive for Climate Stewardship (Knapp et al., 2010). The predicted increases in U.S. storm risk are substantial, implying, for example, an increase in the expected number of Category 3+ storms making landfall from 0.45 per year in the current climate to 2.6 per year by the end of the century under a business-as-usual warming scenario.[19] We divide these aggregate risk increases across space in the 21 hurricane-vulnerable states considered in Deryugina's analysis by assuming future cyclone tracks will remain geographically distributed as historical ones, and compute expected medical expenditure increases for each county in the data. Deryugina finds that government spending increases persist for 10 years following a storm. Our benchmark estimate thus uses the present discounted (at an interest rate of 5 percent) expenditure over a decade as expense impact measure. The resulting estimates imply that a ceteris paribus increase in hurricane risk associated with $1°C$ warming increases total annual public medical expenditures in affected sample counties by $4.9 billion ($2016), and income support transfers by $3.0 billion.

3.1.4 Overall Impacts

We combine the quantitative estimates described in this section utilizing data on base year (2015 or 2016) program expenditures, global temperature changes associated with the underlying climate scenarios (IPCC, 2014), and overall (federal plus local) U.S. government consumption from the National Income and Product Accounts of the BEA. Table 9 summarizes the estimates, which imply an overall U.S. government consumption increase of +0.39 percentage points and a transfer increase of +0.11 percentage points per $1°C$ global temperature change.

hurricane category.

[19] Specifically for 2080-2100 under the IPCC's A1B SRES emissions scenario.

Table 9: Fiscal Costs Summary

	%ΔCost per 1°C	
Government Consumption		
Program	Program	Gov't Cons.
Hurricane response*	+5%	+0.04%
Crop-insurance subsidies	+14%	+0.04%
Wildfire suppression - FS	+52%	+0.04%
Wildfire suppression - DOI	+20%	+0.004%
Fed. healthcare - Air quality		+0.01%
Healthcare - Wildfires	varies by state	+0.008%
Healthcare - Hurricanes	varies by county	+0.19%
Urban drainage infrastructure		+0.03%
West Nile Neuroinvasive Disease		+0.0002%
Endangered Species Act	+7.9%	+0.004%
Total		+0.39%
Government Transfers		
Income support - Hurricanes	varies by county	+0.11%

*Includes FEMA aid, HUD, Army Corps of Engineers, DOD, DOT

On the one hand, these estimates almost certainly *understate* the fiscal costs of climate change for numerous reasons. For example, we only consider a limited set of public programs and climate impact channels for which some quantification was possible. Even for those programs, estimates may be lower bounds. For West Nile virus infections, only hospitalization costs for the most severe cases are included; for fire suppression, only federal expenditures are included; for urban infrastructure, only 100 cities are included, etc. Our analysis also considers only the most vulnerable states for wildfire and hurricane healthcare cost estimates, and thus implicitly assigns zero cost changes to other areas (e.g., zero wildfire cost increases in Colorado). On the other hand, however, there are also potential fiscal benefits of climate change which are not currently reflected. For example, two specifications in Table 6 suggest a positive and significant association between winter weather events and public healthcare expenditures, as may be expected due to, e.g., increases in automobile accidents. To the extent that global warming will decrease winter weather episodes in the United States, healthcare and other public costs (e.g., road clearing) may thus decrease, ceteris paribus. Interestingly, however, global warming may actually be increasing extreme snowstorms in certain parts of the United States,[20] highlighting the fact that both the estimated magnitudes and their potential biases remain highly uncertain. We nonetheless use

[20] See, e.g., NOAA News "Climate Change and Extreme Snow in the U.S.", ULR (accessed December 2019): [https://www.ncdc.noaa.gov/news/climate-change-and-extreme-snow-us]

this as currently available evidence to gauge the plausible orders of magnitude of the implications of climate change's fiscal costs for welfare and policy design.

3.2 Sea Level Rise Impacts and Public Adaptation

We quantify both gross damages and the costs and benefits of adaptation to sea level rise based on modeling results of the EPA's Coastal Property Model runs for the Climate Change Impacts and Risk Analysis project (EPA, 2017). The Coastal Property Model (Neumann et al., 2014a,b) considers detailed locally differentiated property values and vulnerabilities, sea level rise effects (based on Kopp et al., 2014; and NOAA, 2017), and tropical cyclone surge impacts of climate change (building on Emanuel et al., 2008). It estimates costs resulting both from increased storm surge damages and property abandonement. Importantly, the model also considers and optimizes adaptation responses to sea level rise in the forms of either beach nourishment, shoreline armoring (e.g., sea walls), or property elevation.

First, in order to construct a gross-of-adaptation SLR damage function, we utilize model results from 'no adaptation' runs for both RCP scenarios 4.5 and 8.5[21] Total gross damages appear approximately linear in global mean sea level rise (see Appendix Figure A1). We translate these level damages into depreciation rates by (i) deflating future values into base year property value equivalents, and (ii) dividing by the base year capital stock. Regressing the resulting observations of depreciation rates on global sea level rise values yields a benchmark estimate of 0.0186% capital loss per decade per centimeter SLR (over 2000 base period values). Letting $\overline{\delta}$ denote baseline capital depreciation, we consequently set:

$$\begin{aligned} \delta(SLR_t, \Lambda_t^{slr}) &= \overline{\delta} + \delta^{SLR} \cdot SLR_t \cdot (1 - \Lambda_t^{slr}) \\ &= \overline{\delta} + 0.000186 \cdot SLR_t \cdot (1 - \Lambda_t^{slr}) \end{aligned} \tag{31}$$

Second, in order to quantify adaptation costs and effectiveness, we utilize model results from the 'adaptation' runs, again for RCP scenarios 4.5 and 8.5. These provide information on both annual expenditures on different coastal protection measures, and residual damages incurred. As per (17), we assume that adaptive capital at time t is given by:

$$AK_t \equiv \sum_{s=0}^{t-1} (\lambda_s^{slr}(1 - d^{slr})^s) + \lambda_s^{slr} \tag{32}$$

We further assume that adaptive capacity depends on the protective capital stock relative to

[21] We are extremely grateful to Jeremy Martinich for sharing both model results and input assumptions.

gross damages (i.e., capital at risk) via:

$$\Lambda_t^{SLR} = \left(\gamma_1 \frac{AK_t}{(\delta^{SLR} \cdot SLR_t \cdot K_t)}\right)^{\gamma_2} \tag{33}$$

We quantify adaptation cost parameters γ_1, γ_2, and d^{slr} by minimizing the sum of squared deviations between equations (32), (33), and an intra-temporal optimality condition for adaptation expenditures,[22] and the 'observations' of Λ_t^{SLR}, AK_t, and gross damages obtained from the EPA's Coastal Property Model, all aggregated to the decadal level.[23] That is, we effectively fit parameters to create a reduced-form aggregate representation for the detailed EPA model results. The deviation-minimizing parameters are $\gamma_1 = 10.1752$, $\gamma_2 = 0.0945$, and $d^{slr} = 0.2462$, implying an *annual* protective capital depreciation rate of 2.79%.

3.3 Other Public Adaptation

While there are many examples and some quantifications of public adaptation measures beyond coastal protection, mapping out these potential expenditures and their corresponding benefits at a systemic level is difficult and fraught with uncertainties. For utility damages, relevant examples range from expenditures to protect and repair national parks from climate damages to public funding for mental health support after disasters (e.g., FEMA Crisis Counseling Assistance and Training Program). For production and capital damages, examples range from research funding on climate-resilient crops to public expenditures on inland flood protection infrastructure. While Barrage (2020b) uses a stylized representation of public adaptation efforts at a global level based on prior literature (Argawal et al., 2010), for the present analysis we currently abstract from quantifications of Λ_t^y and Λ_t^u and focus on Λ_t^{slr} for which higher quality and U.S.-specific estimates are available as outlined in the prior section.

3.4 General Calibration

The remainder of the calibration can be described as follows.

[22] The intra-temporal optimality condition for minimizing the sum of gross damages and adaptation costs is that $\frac{\partial \Lambda_t^{slr}}{\partial \lambda_t^{slr}} = \frac{1}{\text{GrossDamages}_t}$.

[23] We further add one assumption-based moment, namely that spending only 50% of prescribed adaptation funds in the base 2010-2020 period would achieve 60% of the benchmark adaptation effectiveness. This moment was added as the Coastal Property Model results imply very high levels of optimal adaptation effectiveness, around 95% or higher, across all periods, thus limiting the range of 'observations' available to quantify the full curvature of the adaptation cost function.

3.4.1 Production

First, as is standard in the literature, we assume a Cobb-Douglas aggregate production technology for the final good in (6):

$$\widetilde{F_1}(K_{1t}, L_{1t}, E_t) = K_{1t}^{\alpha} L_{1t}^{1-\alpha-v} E_t^{v}$$

Expenditure shares are set at standard values $\alpha = 0.3$ and $v = 0.03$ (e.g., GHKT, 2014). Base year total factor productivity (TFP) A_{10} in (6) is inferred by matching initial output ($17.4 trillion in $2012, Source: FRED) given initial capital, labor, and energy inputs. Base year energy input E_0 is set at 1.375 gitatons of carbon (GtC, Source: EPA, 2017). Normalizing available work time per annum to unity, L_0 is set at initial labor time share 0.2324 based on OECD data for the United States in 2015 (OECD, 2020), times the initial population of 320 million. This aggregate labor is distributed between the final good and energy sectors based on profit maximization and initial energy production.[24] The initial aggregate private capital stock K_0 is inferred assuming a real interest rate of 5% and a depreciation rate of 10%, and this capital stock is distributed across sectors to be consistent with profit maximization and initial energy production.[25] Future productivity growth is taken as exogenous and quantified based on the 2010 RICE Model parameters for the United States (Nordhaus, 2011). The base year savings rate is set to match 20.258% of GDP as per World Bank data for the United States in 2015.

Both fossil fuel-based and clean energy are produced with Cobb-Douglas technology:

$$E_t = A_{2t}(K_{2t}^{1-\alpha_E} L_{2t}^{\alpha_E}) \tag{34}$$

The labor share is set to $\alpha_E = 0.403$ based on Barrage (2020a). The quantification of abatement cost function $\Theta_t(\mu_t E_t)$ structurally follows the same approach as the global COMET but for the United States, that is, it converts the RICE model's U.S. abatement cost estimates into a per-ton cost measure through a logistic approximation (see Appendix and Barrage, 2020a).

Climate change impacts on production are structurally modeled as in the seminal DICE and RICE models (Nordhaus, 2011):

$$(1 - D_t(T_t)) = \frac{1}{1 + \alpha_y T_t^2} \tag{35}$$

Our quantification of $D(T_t)$ uses U.S. estimates from the RICE model as a basis, but makes two important adjustments. First, given that sea level rise impacts are modeled explicitly (31), we remove them from the RICE damages to avoid double counting. Second, the DICE/RICE model family aggregates all impacts - both production and non-market - into an output-*equivalent*

[24] The labor share in final goods production is $(1-\alpha-v)/(\alpha_E \cdot v + 1 - \alpha - v) = 98.23\%$ at benchmark values.
[25] The capital share in final goods production is $(\alpha)/((1-\alpha_E)v + \alpha) = 94.37\%$ at benchmark values.

damage function $D(T_t)$. In a setting with distortionary taxes, the distinction between these two damages becomes welfare-relevant. We therefore disaggregate the sectoral impact estimates underlying the U.S. RICE damage function into production and utility damages following the delineation of Barrage (2020a), which, for the United States, implies around 70% of damages from 2.5°C warming in the production sector, and 30% affecting utility directly. The parameter θ_1 in (35) is set to match the resulting production loss estimate of 0.616 percent output loss due to 2.5°C warming, yielding $\alpha_y = 0.00099171$.

3.4.2 Government

Base year effective tax rates: According to OECD estimates, the average effective labor tax wedge in the United States between 2010-2018 has fluctuated between 29.6% and 31.8% with an average value of 30.8778%. The average effective consumption tax has been estimated at 6.1% (Carey and Tchilinguirian, 2000), implying an overall effective labor-consumption wedge of 35.09%.[26] For tax burdens on capital, a detailed review by the Congressional Budget Office (2014) estimates a 29% effective marginal rate on business capital.[27]

Government Expenditures: According to U.S. National Income and Product Accounts data (BEA, 2019), total U.S. government expenditures in 2015 included $2.7 trillion in transfer payments and $2.7 trillion in consumption and subsidies ($2015). We set base year $\overline{G_t^T}$ and $\overline{G_t^C}$ values accordingly. In future years, we assume that total baseline (i.e., without climate change) government expenditures grow at the rates of population and productivity growth (as in, e.g., Goulder, 1995), and that the consumption share remains at its base year value (49.7 percent). For climate change impacts, following Table 8, we set the parameters in (14) to match a 0.39 and 0.11 percentage point increase in consumption and transfers per degree warming, respectively, yielding $\alpha_{C,1} = 0.00389$, $\alpha_{C,2} = 1$, $\alpha_{T,1} = 0.0011$, and $\alpha_{T,2} = 1$.

Government Debt: The benchmark calibration sets B_0 based on the 2015 federal debt held by the domestic public at 41.1% of base year GDP (FRED, 2020).

3.4.3 Preferences

The specification of preferences is as in the benchmark COMET but with quantitative adjustments for the U.S. setting. Utility is defined over per-capita consumption $c_t \equiv C_t/N_t$, where N_t is the period t population and labor supply is $l_t \equiv L_t/N_t$. The dynastic household maximizes the

[26] Following Carey and Tchilinguirian (2002), the labor-consumption wedge is computed as $\tau_{cl} = \tau_l + (1-\tau_l)\tau$.
[27] CBO (2014) also estimate a lower rate of 18% if owner-occupied housing is included, but this figure does not account for local property taxes, leading us to prefer the more self-contained estimate for business capital.

population-weighted lifetime utility:

$$\sum_{t=0}^{\infty} \beta^t N_t U(c_t, l_t, T_t)$$

The U.S. population grows from 320 million in 2015 to 417.5 million by 2105 and asymptotes towards 448 million, matching projections from RICE (Nordhaus, 2011).

The utility function is specified as follows:

$$U(c_t, l_t, T_t) = \frac{\left[c_t \cdot (1 - \varsigma l_t)^{\gamma}\right]^{1-\sigma}}{1-\sigma} + \frac{(1 + \alpha_u T_t^2)^{-(1-\sigma)}}{1-\sigma} \tag{36}$$

Preference parameters are set to jointly match base year labor supply $l_{2015} = 0.2324$ and a Frisch elasticity of labor supply of 1.83, which is the average between the benchmark micro and macro estimates identified by Chetty et al. (2011), given initial tax rates[28] and assumed values of $\sigma = 1.5$ and a decadal utility discount factor of $\beta = (.985)^{10}$. In the benchmark model, the climate disutility parameter α_u is chosen to match an aggregate global consumption loss-equivalent of disutility from climate change at $2.5°C$ of 0.26% of output (for further discussion see Barrage, 2020a).

3.4.4 Carbon Cycle and Climate Model

At present, the COMET adopts the carbon cycle and climate model from the DICE model (Nordhaus, 2010, 2016). An update to incorporate revisions in line with recent climate science evidence as described by Dietz et al. (2020) is in progress.

Given the U.S. focus of the model, we consider three possibilities for rest-of-world emissions: (i) ROW-B assumes business-as-usual emissions in the rest of the world (taken from the 2010 RICE Model, Nordhaus, 2011), (ii) ROW-O assumes optimized rest of the world emissions (also taken from Nordhaus, 2011), and, finally (iii) ROW-E assumes a positive response elasticity of global emissions reductions to U.S. abatement. We specifically consider an elasticity of 0.5, implying that for every percent of U.S. abatement, the rest of the world abates 0.5 percent of emissions.

[28] Initial tax rates are set to zero in the lump-sum taxation (theoretical first-best) scenarios.

4 Quantitative Results

4.1 Main Results

We present model results across four income tax and five climate policy scenarios. The income tax scenarios are as follows:

1. "First-Best": The government can levy non-distortionary lump-sum taxes. This assumption is standard in IAMs in the literature.

2. "Optimized Distortionary": The government can fully optimize its revenue-raising taxes, but cannot impose lump-sum levies.

3. "Fixed Labor, Variable Capital Income Taxes": Labor taxes are held fixed at business-as-usual levels $\overline{\tau_l} = 35.1\%$ but the government can raise additional revenues by raising capital income taxes. Depending on the scenario, the planner can also tax carbon and energy.

4. "Fixed Capital, Variable Labor Income Taxes": Capital income taxes are held fixed at business-as-usual levels $\overline{\tau_k} = 29\%$ but the government can raise additional revenues by raising labor income taxes. Depending on the scenario, the planner can also tax carbon and energy.

For U.S. carbon and energy taxation, two scenarios are considered:

1. "No": This business-as-usual scenario assumes no carbon or energy taxes throughout the 21st Century (until 2115).

2. "Opt." The government freely optimizes carbon and energy taxes.

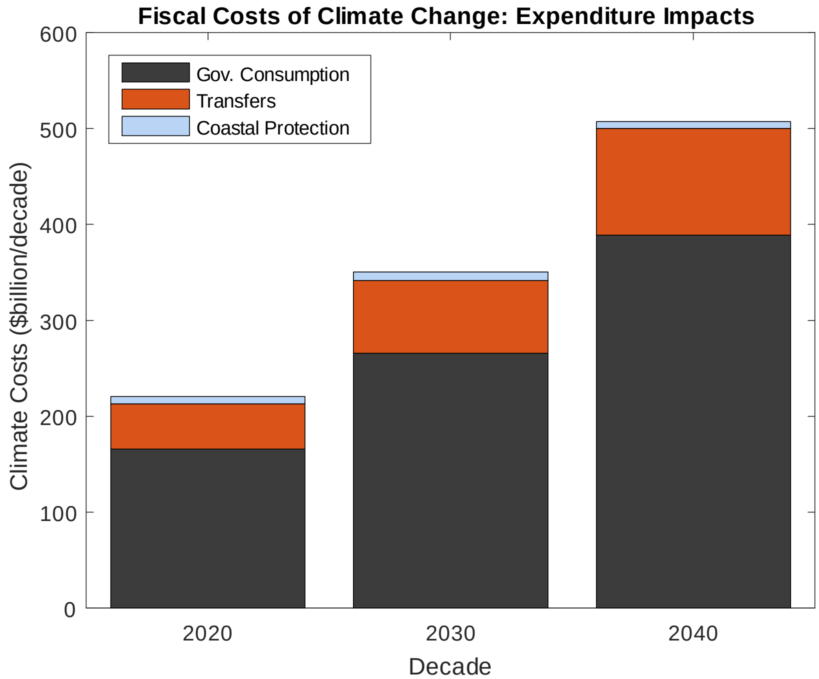
Finally, for rest-of-the-world (ROW) carbon emissions, three scenarios are considered:

1. "No": ROW emissions follow the RICE model's BAU scenario (Nordhaus, 2011).

2. "Opt.": ROW emissions follow the RICE model's globally optimized climate policy scenario (Nordhaus, 2011).

3. Responsive: ROW emissions are initially at BAU levels but follow U.S. emissions reductions at a given elasticity.

To begin, Figure 1 presents the projected government expenditure impacts of climate change in the near-term, which increase from around \$220 billion in the 2020-2030 period to over \$500 billion in the 2040-2050 period.[29] Increases in existing program costs are projected to account for the majority of these costs.



Next, Table 10 presents policy and welfare results for the benchmark model with and without U.S. climate policy. ROW emissions are fixed at business-as-usual levels in this table, but Appendix Table A2 shows that the main results are similar with fixed optimized climate policy in other countries. In the first-best setting - the standard in climate-economy models - labor and capital income taxes are both zero, and the MCF is equal to unity. Introducing the optimal U.S. carbon price sequence in this setting yields a domestic welfare gain of $127 billion dollars ($2015 in terms of initial period equivalent variation consumption transfer). Second, in a setting with optimized distortionary taxes, the government raises most revenues from the labor-consumption wedge, with an equilibrium marginal cost of public funds of 1.10. In this setting, while the optimal carbon price level is slightly lower, the welfare gains associated with U.S. climate policy are over 20% higher than in the standard setting, estimated at $155 billion. Third, in a more realistic 'business as usual' fiscal setting where labor income taxes are fixed at current levels, the government raises additional revenues in part from capital income taxes. Without a carbon price, the average effective capital income tax is 35.2% at a marginal cost of funds of 1.54.

[29] These figures are from the "Optimized Distortionary" income tax scenario with optimized domestic carbon taxes in the face of business-as-usual global emissions. Expenditures in the near term are not too different in other climate policy scenarios due to delays in the climate system assumed in the DICE model and the stock nature of sea level rise. The former may change with a switch to a climate system representation as recommended by Dietz et al. (2020).

Introducing climate policy could lower capital income tax rates to 33.8% on average, thus also lowering the MCF to 1.51, and, importantly, yielding overall welfare gains of $635 billion. That is, in a fiscally constrained setting, the welfare gains associated with carbon pricing are over *four times higher* than in the first-best setting generally assumed in the literature. Fourth, if capital income taxes remain fixed and the government raises additional revenue mainly through labor income taxes, the marginal cost of funds is again low at 1.10. The optimal carbon price in this setting nonetheless yields a welfare gain of $144 billion, again higher than in a first-best world.

Table 10: Benchmark Results

Scenario: Income	Scenario: Carbon & Energy	Labor Tax	Capital Tax	MCF	Carbon Tax ($/mtC)	ΔWelfare EV ΔC_{2015} ($2015 bil.)
		Avg. 2025-2215			2015-25	
First-Best	No	0	0	1.00	0	
First-Best	Opt.	0	0	1.00	11.3	127
Opt.	No	40.3	4.6	1.10	0	
Opt.	Opt.	40.2	4.7	1.10	8.7	155
BAU $\overline{\tau_l}$,	No	$\overline{35.1}$	35.2	1.54	0	
vary τ_k	Opt.	$\overline{35.1}$	33.8	1.51	7.1	635
BAU $\overline{\tau_k}$,	No	39.6	$\overline{29.0}$	1.10	0	
vary τ_l	Opt.	39.5	$\overline{29.0}$	1.10	8.4	144

Rest-of-world emissions exogenous at BAU levels.

Table 10 assumes that global emissions are fixed at business-as-usual level ('No' global climate policy). We next consider a responsive setting with a *positive* response elasticity of global emissions reductions to U.S. abatement, motivated by, e.g., technology spillovers or climate agreement cooperation. We specifically consider a value of 0.5, meaning that ROW emissions decrease by 0.5% for every percent of U.S. abatement. The results, shown in Table 11, indicate that the optimal carbon price is considerably higher in this setting, ranging from $35.8 to $46.1 per metric ton. The corresponding welfare gains are higher as well. Importantly for this paper's focus, however, it is still the case that the welfare gains associated with carbon pricing are 20-240% higher in a setting with distortionary taxes.

Table 11: Main Results with ROW Mitigation Response Elasticity 0.5

Scenario Income	Scenario Carbon & Energy	Labor Tax (Avg. 2025-2215)	Capital Tax (Avg. 2025-2215)	MCF (Avg. 2025-2215)	Carbon Tax ($/mtC) 2015-25	ΔWelfare EV ΔC_{2015} ($2015 bil.)
First-Best	No	0	0	1.00	0	
First-Best	Opt.	0	0	1.00	46.1	502
Opt.	No	40.3	5.0	1.10	0	
Opt.	Opt.	40.2	5.0	1.10	40.1	651
BAU $\overline{\tau_l}$,	No	$\overline{35.1}$	35.3	1.54	0	
vary τ_k	Opt.	$\overline{35.1}$	33.7	1.50	35.8	1,216
BAU $\overline{\tau_k}$,	No	39.6	$\overline{29.0}$	1.09	0	
vary τ_l	Opt.	39.5	$\overline{29.0}$	1.09	39.8	612

Rest-of-world emissions respond 0.5% per each 1% increase in U.S. abatement.

As previously noted, the benchmark model's quantification of fiscal climate impacts is subject to significant uncertainty and very likely presents a lower bound. Figure 1 thus showcases how the optimal U.S. carbon price in the initial decade (2015-2025) varies as a function of the fiscal cost changes per degree warming. The results indicate that, even at seemingly small values, fiscal costs can have significant implications for the social cost of carbon. Each percentage point increase in government consumption (transfers) per degree warming translates into optimal carbon price increases of around 19% (10%). Even at our benchmark values, the estimated implications of fiscal costs for climate policy are thus quantitatively on par with the importance of factors such as climate tipping points (Lemoine and Traeger, 2014), ambiguity aversion (Lemoine and Trager, 2016), or model uncertainty (Rudik, 2019) documented in prior studies.

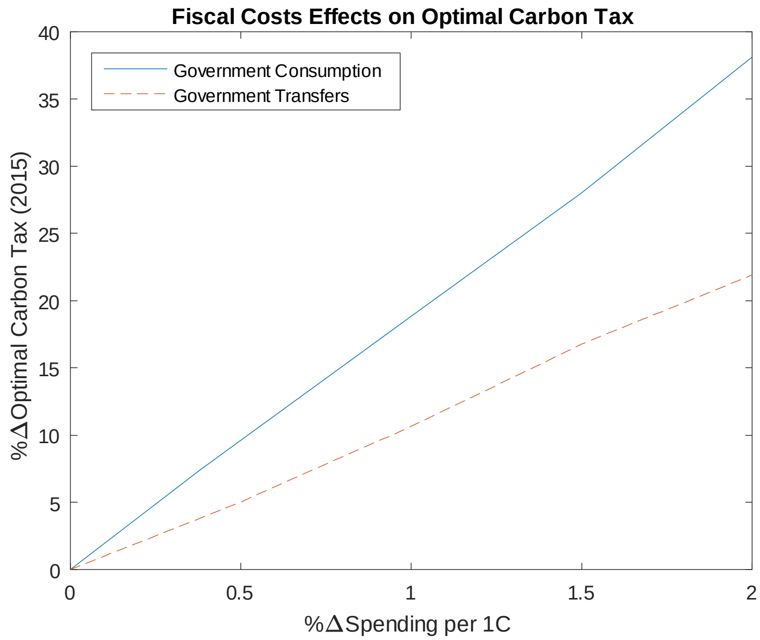


Figure 1

5 Conclusion

Climate change is increasingly being recognized as a potential threat to fiscal sustainability. Both policy and academic studies have documented numerous channels through which a changing climate may alter public budgets (e.g., Egenhofer et al., 2010; Moore et al., 2020). This paper presents what is to the best of our knowledge a first systematic integration of these channels into a macroeconomic integrated assessment model. The analysis first demonstrates that fiscal costs have *qualitative* implications for climate policy: the social cost of carbon must account for climate impacts on both government consumption and, surprisingly, transfer payments to households when the marginal cost of raising public funds exceeds unity. We then present a novel bottom-up quantification of climate impacts on government expenditures in the United States. The quantification synthesizes and extends prior studies, and adds an empirical analysis of public health expenditures and wildfires. *Quantitatively*, while our estimates are obviously subject to fundamental uncertainties, we find large potential effects of both public expenditure impacts and fiscal interactions of climate policy more broadly. For example, the domestic benefits of U.S. climate policy may be under-estimated by up to a factor of four by conventional climate-economy models that abstract from distortionary taxes and government expenditure requirements.

The analysis makes important simplifying assumptions. For example, local, state, and federal finances are all aggregated into a central fiscal authority. In reality, the distribution of climate change's fiscal impacts across levels of government may be important. Certain costs - such road elevation to protect against flooding - may fall disproportionately on local governments which also face a higher cost of raising public funds. Indeed, recent empirical work has found significantly higher long-term municipal bond issuance costs in U.S. counties more vulnerable to climate change (Painter, 2020), consistent with less-than-complete risk sharing. Consideration of regional heterogeneity also raises distributional questions which are currently outside the scope of the analysis. More broadly, our framework does not account for income inequality and redistribution as important aspects of the tax system. Indeed, very little work to date has considered climate policy in dynamic heterogeneous agent economies in general, let alone with tax policy. These are all critical areas for future research. Importantly, however, we conjecture that consideration of factors such as higher local fiscal exposure to climate risks would likely serve to increase the potential relevance of climate fiscal costs for policy design.

At the time of this writing, the United States faces significant fiscal challenges. Due to the COVID-19 pandemic and response, the U.S. federal debt held by the public has risen from 79 to 105 percent of GDP between the first and second quarters of 2020 (FRED, 2020). The U.S. Congressional Budget Office moreover projects continued increases in U.S. debts under current policy (CBO, 2020). This paper's results suggest that climate change may exacerbate these trends. Importantly, however, the analysis also finds that appropriately designed domestic climate policy and international climate agreements may allow for lower tax burdens and yield large net economic benefits for the U.S. economy.

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6 Appendix

6.1 Climate Impacts Quantification

6.1.1 Placebo: Dialysis Events

Table A1 presents results for the two-stage least squares analysis of Section 3 with the number of outpatient dialysis events per 1,000 Medicare beneficiaries as outcome variable. We fail to detect a significant impact of wildfire-induced unhealthy air days on dialysis events.

Table A1: Two-Stage Analysis: Dialysis Events

	(1)	(2)
	First Stage	Second Stage
	ln(Unhealthy Days)	ln(Outp. Dialysis Events/1000 Ben.)
ln(FireDays)	0.0761***	
	(0.0222)	
ln(UnhealthyDays)		-0.0020
		(0.0057)
Obs.	2,298	2,298
#Counties	233	233
Demo./Inc. Controls:	Yes	Yes
Medicare Controls:	Yes	Yes
County F.E.s:	Yes	Yes
Year F.E.s:	Yes	Yes
State-Trends:	Yes	Yes
S.E. Cluster	County	County
Adj. R-Sq.		0.558
Kleibergen-Paap Wald F. Stat.	11.70	

6.1.2 Sea Level Rise Costs

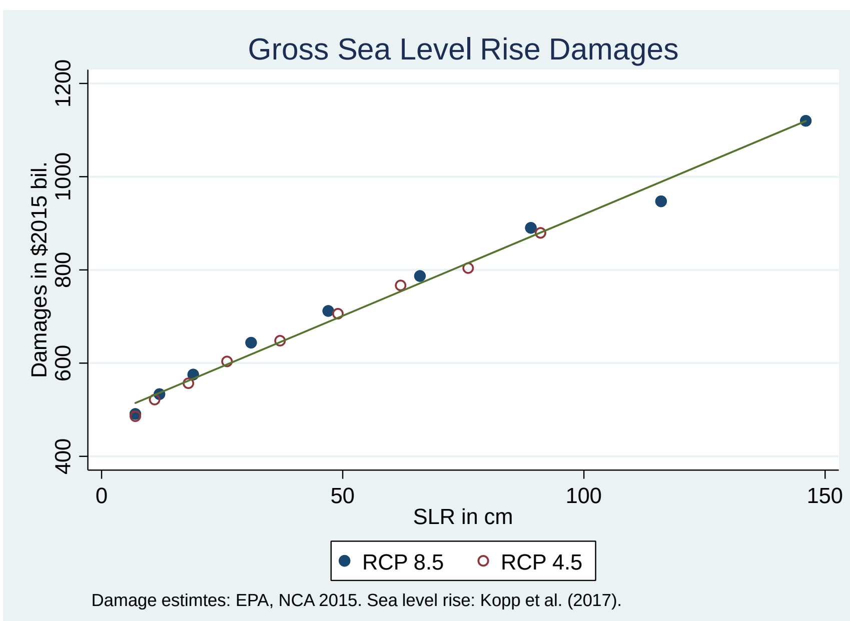

Figure A1: Gross Sea Level Rise Costs from EPA (2017)

6.2 Theory Setup and Results

It is straightforward to show (following an analogous derivation to the one in Barrage, 2020a) that the primal social planner's problem for our framework is as follows:

$$\max \sum_{t=0}^{\infty} \beta^t \underbrace{[[v(C_t, L_t) + h[T_t] + \phi\left[U_{ct}C_t + U_{lt}L_t - U_{ct}G_t^T(T_t)\right]]}_{\equiv W_t}$$
$$+\sum_{t=0}^{\infty} \beta^t \lambda_{1t} \left[\begin{array}{c} \left\{[1-D(T_t)] \cdot A_{1t}\widetilde{F_{1t}}(L_{1t}, E_t, K_{1t})\right\} + (1-\delta(SLR_t, \Lambda_t^{slr})K_t \\ -C_t - K_{t+1} - G_t^C(T_t) - \lambda_t^y - \lambda_t^u - \lambda_t^{SLR} - \Theta_t(\mu_t E_t) \end{array} \right]$$
$$+\sum_{t=0}^{\infty} \beta^t \xi_t [T_t - F\left(\mathbf{S}_0, (1-\mu_0)E_0, (1-\mu_1)E_1, ..., (1-\mu_t)E_t, \boldsymbol{\eta}_0, ...\boldsymbol{\eta}_t\right)] \tag{37}$$
$$+\sum_{t=0}^{\infty} \beta^t \zeta_t [SLR_t - f^{slr}(T_0, T_1, ...T_t)] \tag{38}$$
$$+\sum_{t=0}^{\infty} \beta^t \lambda_{lt} \left[L_t - L_{1t} - L_{2t}\right]$$
$$+\sum_{t=0}^{\infty} \beta^t \lambda_{kt} \left[K_t - K_{1t} - K_{2t}\right]$$
$$+\sum_{t=0}^{\infty} \beta^t \omega_t \left[F_{2t}(A_{Et}, K_{2t}, L_{2t}) - E_t\right]$$
$$+\sum_{t=0}^{\infty} \beta^t \eta_{St} \left[f^{SLR}(AK_t) - \Lambda_t^{SLR}\right] \tag{39}$$
$$+\sum_{t=0}^{\infty} \beta^t \eta_{akt} [AK_t(1-\delta^{slr}) + \lambda_t^{slr} - AK_{t+1}] \tag{40}$$
$$-\phi\left\{U_{c0}\left[K_0\left\{1 + (F_{1k0} - \delta)(1 - \overline{\tau_{k0}})\right\} + B_0\right]\right\}$$

6.2.1 Result 1

To derive our optimality conditions of interest, first combine the planner's first-order conditions for $t > 0$ with respect to SLR_t and T_t to express the social cost of carbon emissions in utility terms, ξ_t :

$$(-U_{Tt}) + \phi U_{ct}\frac{\partial G_t}{\partial T_t} - \lambda_{1t}\frac{\partial Y_t}{\partial T_t} + \lambda_{1t}\frac{\partial G_t^c}{\partial T_t} + \sum_{m=0}^{\infty}[\beta^m \lambda_{1t+m}\frac{\partial \delta}{\partial SLR_{t+m}}K_{t+m}]\frac{\partial SLR_{t+m}}{\partial T_t} = \xi_t \tag{41}$$

Next, the first order condition with respect to mitigation μ_t for $t > 0$ implies that, at the optimum, marginal abatement costs are equated to the present value of future marginal damages:

$$\Theta_t'(\mu_t E_t) = \sum_{j=0}^{\infty} \frac{\xi_{t+j}}{\lambda_{1t}} \beta^j \frac{\partial T_{t+j}}{\partial E_t^M} \tag{42}$$

Combining (41) and (42) yields an expression for the optimal carbon price τ^*_{Et} in equilbrium as per (13). In order to derive the expression of Result 1 in the paper, one needs to substitute out for the public marginal utility of income λ_{1t} and for the Lagrange multiplier on the implementability constraint, ϕ. With regards to the former, the planner's optimality condition with respect to the aggregate private capital stock $[K_{t+1}]$ for $t > 0$ implies that:

$$\frac{\lambda_{1t}}{\beta\lambda_{1t+1}} = [F_{Kt+1} + (1 - \delta(.))] \tag{43}$$

Substituting the equilibrium condition for capital returns (8) into (43) links to the rate of return term in M_j (24). With regards ot the latter, taking the first order condition with respect to $[C_t]$ for $t > 0$ reveals that:

$$\phi = \frac{\lambda_{1t} - U_{ct}}{[U_{cct}C_t + U_{ct} + U_{lct}L_t - U_{cct}G^T_t(T_t)]} \tag{44}$$

Substituting (44) into (41), multiplying by $\frac{U_{ct}}{U_{ct}}$, invoking the definition of the $MCF_t = \frac{\lambda_{1t}}{U_{ct}}$, and rearranging yields the expression for the optimal carbon price τ^*_{Et} in Result 1.

6.2.2 Result 2

Production adaptation In order to demonstrate that the optimal provision of general production adaptation Λ^y_t is undistorted, we note that combining the first order conditions with respect to $[\Lambda^y_t]$ and $[\lambda^y_t]$ for $t > 0$ yields optimality condition (45):

$$\underbrace{(-\widetilde{F_{1Tt}}D(T_t))}_{\text{MRT}^{F_{1t}}_{C_t,\Lambda^y_t}} = \underbrace{\frac{1}{f^y_{\lambda_t}}}_{\text{MRT}^{f^y_t}_{C_t,\Lambda^y_t}} \tag{45}$$

Here, $\widetilde{F_{1Tt}}$ denotes the marginal output losses due to a change in temperature at time t, and $D(T_t)$ is the damage function from (6). The left-hand side of (45) thus measures the increase in the final consumption good available due to a marginal increase in adaptive capacity in the final goods sector (Λ^y_t). Conversely, the right-hand side represents the marginal rate of transformation between the consumption good C_t and adaptive capacity through adaptation expenditures λ^y_t. While condition (45) will be evaluated at different allocations depending on the tax system, it demonstrates that there is no wedge distorting adaptation provision at the optimum, as indicated in Result 2.

Sea level rise protection With regards to public sea level rise adaptation, combining the planner's first order conditions with respect to adaptive capacity $[\Lambda^{slr}_t]$, capital $[AK_{t+1}]$, and investment $[\lambda^{slr}_t]$ yields an Euler equation governing optimal public investment in coastal protection:

$$\frac{\lambda_{1t}}{\beta\lambda_{1t+1}} = \frac{\partial\Lambda^{SLR}_{t+1}}{\partial AK_{t+1}}\frac{\partial\delta}{\partial\Lambda^{slr}_{t+1}}K_{t+1} + (1 - \delta^{slr}) \tag{46}$$

The right-hand side captures the intertemporal marginal rate of transformation between the consumption-investment good today and in the future through investments in sea level rise adaptation capital. The left-hand side denotes the social planner's intertemporal marginal rate of substitution. Comparison of (23) to (43) demonstrates that, at the optimum, the planner equates the marginal rates of transformation between sea level rise and general capital, indicating that there is again no distortion in the provision of this asset even if it is funded through distortionary taxation.

6.2.3 Result 3

Finally, for Result 3, combining the planner's first order conditions with respect to $[\Lambda_t^u]$ and $[\lambda_t^u]$ for $t > 0$ yields the optimality condition for public provision of utiliy adaptation:

$$\begin{aligned} \frac{-U_{Tt}T_t}{\lambda_{1t}} &= \frac{1}{f^u_{\lambda_t}} \\ \frac{(-U_{Tt}T_t)/U_{ct}}{MCF_t} &= \frac{1}{f^u_{\lambda_t}} \end{aligned} \tag{47}$$

Multiplying the left-hand side of (47) by U_{ct}/U_{ct} and invoking the definition of the MCF_t in (21) then yields the following optimality condition governing public utility adaptation expenditures for $t > 0$:

$$\underbrace{\frac{(-U_{Tt}T_t)}{U_{ct}}}_{\text{MRS}_{C_t,\Lambda_t^u}}\underbrace{\frac{1}{MCF_t}}_{\text{wedge}} = \underbrace{\frac{1}{f^u_{\lambda_t}}}_{\text{MRT}^{f_t^u}_{C_t,\Lambda_t^u}} \tag{48}$$

The first term on the left-hand side of (48) is the household's marginal rate of substitution (MRS) between consumption and adaptive capacity to reduce climate change utility impacts. The right-hand side equals the marginal cost of increasing this adaptive capacity, or the marginal rate of transformation (MRT) between consumption and adaptive capacity (through λ_t^u). Importantly, there is a wedge between the MRS and MRT at the optimum, demonstrating that the provision of the public utility adaptation good is distorted as stated in Result 3.

6.3 Further Calibration Details

6.3.1 Clean Energy Costs

The production of clean energy, in addition to (), has costs $\Theta_t(\mu_t E_t)$ which approximate the RICE model's (Nordhaus, 2011) estimates of a U.S. abatement cost curve from per-percentage into a per-ton cost measure through a logistic approximation:

$$\Theta_t(\mu_t E_t) = \frac{\overline{a} P_t^{backstop}}{1 + a_t \exp(b_{0t} - b_{1t}(\mu_t E_t))^{b_2}} \cdot (\mu_t E_t)^{bx} \tag{49}$$

where $P_t^{backstop}$ is the backstop technology price in year t, taken directly from RICE (Nordhaus, 2011). We note that $P_t^{backstop} = 0$ for $t > 2255$. The remaining parameters minimize the sum of squared errors of abatement costs implied by (49) versus RICE (see Barrage, 2020a for details), namely:

$\overline{a}$	0.0662
a_t	$= 49.8896{+}0.8551 \log(t)$
b_{0t}	$= 14.3338{-}6.4698 \log(t)$
b_{1t}	$= 15.1937{-}6.6864 \log(t)$
b_2	$9.4680e-04$
bx	2.6931

6.4 Further Quantitative Results

Table A2 presents analogous resluts to Table 10 but assuming rest-of-the-world emissions are fixed at globally optimal levels, declining over the Century.

Table A2: Main Results with Optimal ROW Emissions

Scenario: Income	Scenario: Carbon & Energy	Labor Tax	Capital Tax	MCF	Carbon Tax ($/mtC)	ΔWelfare EV ΔC_{2015} ($2015 bil.)
		Avg. 2025-2215			2015-25	
First-Best	No	0	0	1.00	11.1	154
First-Best	Opt.	0	0	1.00	0	
Opt.	No	40.1	5.2	1.10	8.6	177
Opt.	Opt.	40.1	5.9	1.10	0	
BAU $\overline{\tau_l}$, vary τ_k	No	$\overline{35.1}$	32.7	1.47	7.2	604
	Opt.	$\overline{35.1}$	34.0	1.50	0	
BAU $\overline{\tau_k}$, vary τ_l	No	39.4	$\overline{29.0}$	1.09	8.3	170
	Opt.	39.6	$\overline{29.0}$	1.09	0	

Rest-of-world emissions exogenous at globally optimal levels.