

Optimal Dynamic Carbon Taxes in a Climate-Economy Model with Distortionary Fiscal Policy

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Abstract

How should carbon be taxed as a part of fiscal policy? The literature on optimal carbon pricing often abstracts from other taxes. However, when governments raise revenues with distortionary taxes, carbon levies have fiscal impacts. While they raise revenues directly, they may shrink the bases of other taxes (e.g., by decreasing employment). This paper theoretically characterizes and then quantifies optimal carbon taxes in a dynamic general equilibrium climate-economy model with distortionary fiscal policy. First, this paper establishes a novel theoretical relationship between the optimal taxation of carbon and of capital income. This link arises because carbon emissions destroy natural capital: They accumulate in the atmosphere and decrease future output. Consequently, this paper shows how the standard logic against capital income taxes extends to distortions on environmental capital investments. Second, this paper characterizes optimal climate policy in sub-optimal fiscal settings where income taxes are constrained to remain at their observed levels. Third, this paper presents a detailed calibration that builds on the seminal DICE approach (Nordhaus, 2008) but adds features essential for a setting with distortionary taxes, such as a differentiation between climate change production impacts (e.g., on agriculture) and direct utility impacts (e.g., on biodiversity existence value). The central quantitative finding is that optimal carbon tax schedules are 8% – 24% lower when there are distortionary taxes, compared to the setting with lump-sum taxes considered in the literature.

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1 Introduction

Raising revenues and addressing climate change are two fundamental challenges facing governments. This paper considers these tasks jointly. Specifically, I study the optimal design of carbon taxes both as an instrument to control climate change and as a part of fiscal policy. Many academic¹ and policy² studies of optimal carbon pricing focus on the climate externality as the only distortion in the economy. In such a setting, the optimal carbon tax is *Pigouvian*: it internalizes the full environmental damage costs of carbon emissions.³ However, analyses of this benchmark setting do not account for potential interactions between carbon levies and other taxes.

Carbon pricing, if implemented, will interact with fiscal policy. On the one hand, carbon taxes raise revenues directly. On the other hand, they may decrease revenues indirectly by shrinking the bases of other taxes. For example, if climate policy decreases employment, this will reduce the revenue benefits and exacerbate the welfare costs of labor taxes. Several studies have extended the benchmark setting to quantify these effects in detailed computable general equilibrium models, finding that the welfare costs of carbon taxes' fiscal interactions likely exceed their (non-environmental) revenue benefits (Goulder, 1995; Bovenberg and Goulder, 1996; Jorgenson and Wilcoxon, 1996; Babiker, Metcalf, and Reilly, 2003; etc.). Bovenberg and Goulder (1996) consequently advocate taxing carbon below Pigouvian rates. However, these papers typically model the environmental benefits of climate policy as pure utility gains, abstracting from potential feedback effects between climate change and the production side of the economy.

This paper theoretically characterizes and then quantifies optimal carbon tax schedules in an integrated assessment climate-economy model with distortionary fiscal policy. I combine a dynamic general equilibrium model of the world economy⁴ that includes linear taxes and government expenditures with the seminal representation of the carbon cycle and climate-economy feedbacks based on the DICE framework (Nordhaus, 2008). Indeed, the DICE model is widely applied in the literature, and is one of the three models used by the United States government to value the impacts of carbon dioxide emissions. The main findings of this paper are as follows.

First, I establish a novel theoretical relationship between the optimal taxation of carbon and of capital income. Intuitively, the climate is an environmental capital good used in production (e.g., of agriculture). Carbon emissions accumulate in the atmosphere and change the climate, with adverse effects on future output. Giving up consumption to reduce emissions thus yields a future return of avoided production damages. However, setting carbon taxes below Pigouvian

¹ E.g., Golosov, Hassler, Krusell, and Tsyvinski (2014, "GHKT"), Nordhaus (2008), Anthoff and Tol (2013), Acemoglu, Aghion, Bursztyn, and Hemous (2012), Hope (2011), and Manne and Richels (2005), inter alia.

² E.g., U.S. Interagency Working Group (2010).

³ Specifically, the Pigouvian tax equals the social cost of carbon - the value of marginal damages from another ton of carbon emissions - evaluated at the optimal allocation.

⁴ The implications of heterogeneity in tax systems across countries are formally addressed in Section 6.

rates distorts incentives to invest in this asset, relative to the social optimum. Analogously, capital income taxes create an intertemporal wedge for investments in physical capital. The first main result is as follows: If capital income taxes are optimally set to zero, then the optimal carbon tax fully internalizes production damages at the Pigouvian rate, even if labor markets are distorted. This is because both policies reflect the government’s desire to leave intertemporal decisions undistorted. The literature on optimal dynamic Ramsey taxation has argued for the desirability of undistorted savings decisions in a range of settings (Judd, 1985; Chamley, 1986;⁵ Atkeson, Chari, and Kehoe, 1999; Acemoglu, Golosov, Tsyvinski, 2011, etc.). I show that the logic against capital income taxes extends to distortions on environmental capital investments.

Second, as many countries’ tax codes diverge from the theoretical prescriptions of the benchmark model, I characterize optimal climate policy in a setting where income taxes are constrained to remain at their observed levels. The results indicate that optimal carbon levies in this (third-best) setting are subject to several adjustments whose net effect is theoretically ambiguous. That is, the optimal carbon price could fall above or below the Pigouvian rate.

In order to quantify optimal policies and welfare across fiscal settings, I then present a detailed calibration of the model as the COMET (Climate Optimization Model of the Economy and Taxation). The calibration uses IMF Government Finance Statistics and collects effective tax rate estimates for 107 countries to quantify fiscal baseline parameters. Critically, the COMET distinguishes climate change impacts that affect production possibilities from those that affect utility directly (e.g., biodiversity existence values). Theoretical results in prior literature and this paper demonstrate the necessity of this distinction in a setting with distortionary taxes.⁶ I argue that production impacts account for around 75% of global climate effects at 2.5°C warming.

Third, I compare optimal climate policy in the setting with distortionary taxes to the setting with lump-sum taxes considered in much of the literature and the policy realm. In the benchmark calibration, the presence of distortionary taxes *decreases* the optimal carbon tax schedule by 8-24%. Two effects of distortionary taxes explain this result. One, they decrease the size of the economy and hence the value of marginal damages (i.e., the Pigouvian levy). Two, they alter the optimal carbon tax formulation to no longer equal the Pigouvian levy. In most cases, the optimal tax is below the Pigouvian rate. A sensitivity analysis with respect to key parameters finds optimal carbon price adjustments of -3% to -36% due to distortionary taxes.

The *welfare gains* from carbon taxes in the twenty-first century are nonetheless estimated to be extremely large, ranging from \$21-26 trillion (\$2005 lump-sum consumption equivalent) in the benchmark (\$10-46 trillion in the sensitivity analysis). In fact, these estimated efficiency

⁵ While Straub and Werning (2014) raise questions about these early studies, these focus on different settings such as with an upper bound on capital income taxes. This case is discussed in Section 3.2.

⁶ See, e.g., Bovenberg and van der Ploeg (1994), Williams (2002).

gains are at least as large as those from an idealized global Ramsey income tax reform that would optimally phase out all capital income taxes (\$22 trillion), indicating that a global *failure* to price carbon creates extremely costly (intertemporal) distortions. Finally, I find that policy-makers can increase the welfare benefits of climate policy by considering the interactions of a carbon price with other distortionary taxes.

These results further relate to the literature in the following ways. On the theory side, the described carbon-capital tax link is novel, to the best of my knowledge. While an extensive literature has studied pollution pricing alongside distortionary taxes,⁷ theoretical work in this area has predominantly focused on static settings. This paper analytically characterizes jointly optimal pollution and capital income taxes in an infinite horizon Ramsey second-best economy endogenizing both labor supply and capital accumulation and where government revenues must be raised through distortionary taxes. While previous studies have produced many insights on environmental policy alongside capital income taxes, to the best of my knowledge, these have generally operated in different settings. For instance: First, several studies model pollution and income taxes in endogenous growth models (Fullerton and Kim, 2008; Bovenberg and de Mooij, 1997; Hettich, 1998; Ligthart and van der Ploeg, 1994) but focus on long-run outcomes along a balanced growth path. This paper studies the transition to balanced growth, while taking long-run growth rates as given.⁸ Second, the dynamics of capital income and fossil fuel taxation have been analyzed by several studies focusing on carbon as a rent-generating resource, rather than the climate externality which is the focus of this paper (e.g., Franks, Edenhofer, Lessmann, 2017; Groth and Schou, 2007, etc.).⁹ Third, capital income taxes have been studied as a part of climate policy for reasons unrelated to fiscal needs, such as time-inconsistent preferences (Gerlagh and Liski, 2017) or other considerations (e.g., Sinn, 2008; Dao and Edenhofer, 2018; etc.). Finally, a substantial literature has explored environmental policy in general equilibrium growth models with capital accumulation, but these studies commonly abstract from distortionary taxes.¹⁰

On the quantitative side, the results broadly relate to two branches of the literature. On the one hand, several studies have employed highly detailed multi-sector dynamic computable general equilibrium (CGE) models to assess the welfare impacts of carbon levies in economies with tax

⁷ Including, e.g.: Sandmo (1975); Bovenberg and de Mooij (1994, 1997, 1998); Bovenberg and van der Ploeg (1994); Ligthart and van der Ploeg (1994); Bovenberg and Goulder (1996); Parry, Williams, and Goulder (1999); Schwartz and Repetto (2000); Cremer, Gahvari, and Ladoux (2001; 2010); Williams (2002); Bento and Jacobsen (2007); West and Williams (2007); Carbone and Smith (2008); Fullerton and Kim (2008); Kaplow (2012); Schmitt (2014); d’Autume, Schubert, and Withagen (2016). See also Bovenberg and Goulder (2002).

⁸ Chireleu-Assouline and Fodha (2006) consider pollution taxes in a dynamic model with capital and distortionary taxes, but do not consider capital income taxes and do not focus on optimal policies.

⁹ The cited papers also take labor as exogenous, focusing on capital versus resource taxes.

¹⁰ E.g., van der Ploeg and Withagen (1991, 2014); Bovenberg and Smulders (1996); Leach (2009); Hassler and Krusell (2012); GHKT (2014); Rezai and van der Ploeg (2014); Iverson (2014).

distortions.¹¹ However, as these studies abstract from climate change impacts on production possibilities, this paper’s results indicate that they may underestimate the optimal carbon tax. On the other hand, a rich and growing literature has developed integrated assessment models to quantify the effects of a variety of climate-economy interactions on optimal climate policy.¹² However, these models generally abstract from fiscal considerations. The results of this paper indicate that they may thus overestimate the optimal carbon price, *ceteris paribus*.

There are, of course, many caveats to the present analysis. The model is based on a highly simplified representation of the global economy and fiscal policy. First, I thus also consider a multi-country version of the theoretical model, and derive conditions under which a uniform global carbon tax remains optimal despite cross-country heterogeneity. Second, as the model assumes that the government has access to a commitment technology, I discuss the implications of limited commitment based on recent work by Schmitt (2014) in Section 6. More broadly, however, the model certainly does not match the sectoral and fiscal detail of country-specific CGE models used in prior work on carbon tax interactions with fiscal policy. The analysis also abstracts from other new frontiers in the climate-economy modeling literature, such as different forms of uncertainty (e.g., Lemoine and Traeger, 2014; Cai, Judd, Lontzek, 2015). Instead, this paper presents the first formal integration of distortionary taxes in a dynamic general equilibrium climate-economy model. This paper thus analyzes the *ceteris paribus* implications of tax distortions for optimal climate policy in a transparent setting, building on the seminal DICE model (Nordhaus, 2008, 2010) and Golosov, Hassler, Krusell, and Tsyvinski (2014).

The remainder of this paper proceeds as follows. Section 2 describes the theoretical model. Section 3 provides the theory results. Section 4 details the calibration of the COMET, and Section 5 presents the quantitative results. Section 6 contains the sensitivity analysis as well as model extensions to a multi-country setting. Finally, Section 7 concludes.

2 Model

This section describes the theoretical model. To summarize, the model combines a climate-economy structure based on Golosov, Hassler, Krusell, and Tsyvinski (GHKT) (2014) with an optimal dynamic taxation framework in the Ramsey tradition (see, e.g., Chari and Kehoe, 1999). Following GHKT, I focus on an infinitely-lived, globally representative household. An important difference to GHKT is that agents have preferences not only over consumption, but over leisure

¹¹ E.g.: Goulder (1995); Bovenberg and Goulder (1996); Jorgenson and Wilcoxon (1996); Babiker, Metcalf, and Reilly (2003); Bernard and Vielle (2003); Carbone, Morgenstern, and Williams (2013); Jorgenson et al. (2013); Rausch and Reilly (2015), Williams, Gordon, Burtraw, Carbone, and Morgenstern (2015).

¹² E.g., Manne and Richels (2005); Hope (2011); Acemoglu, Aghion, Bursztyn, and Hemous (2012); Anthoff and Tol (2013); Lemoine and Traeger (2014); Cai, Judd, and Lontzek (2015), etc.

and the climate as well. There are two production sectors. The aggregate final consumption-investment good is produced using capital, labor, and energy inputs. Climate change affects productivity in this sector. A carbon-based energy input is produced from capital and labor. Energy use generates greenhouse gas emissions, which accumulate and change the climate. The central innovation over GHKT is that the government faces the dual task of addressing this externality *and* raising revenues to meet a given expenditure requirement. Importantly, it is assumed that the government must resort to distortionary taxes as lump-sum levies are not available, following the standard Ramsey approach.¹³

Households

An infinitely-lived, representative household has well-behaved preferences over consumption C_t , labor supply L_t , and a climate change variable T_t . Integrated assessment models vary in the climate indicators they consider. I follow the common approach of using *mean global surface temperature change* over pre-industrial levels, T_t , as a sufficient statistic for climate change. Households and firms take temperature change as given. That is, climate change is an externality. Households maximize lifetime utility U_0 :

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

Environmental quality enters preferences additively separably from consumption and leisure:

$$U(C_t, L_t, T_t) = h(C_t, L_t) + v(T_t) \quad (2)$$

The literature on pollution tax interactions with distortionary taxes commonly assumes weak separability. The Online Appendix shows that the main theoretical insights of this paper are robust to relaxing assumption (2).¹⁴ Each period, the representative household faces the following flow budget constraint:

$$C_t + \rho_t B_{t+1} + K_{t+1} \leq w_t(1 - \tau_{lt})L_t + \{1 + (r_t - \delta)(1 - \tau_{kt})\} K_t + B_t + \Pi_t + G_t^T \quad (3)$$

where B_{t+1} denotes one-period government bond purchases, ρ_t the price of one-period bonds, K_{t+1} the household's capital holdings in period $t + 1$, w_t the gross wage, τ_{lt} linear taxes on labor income, τ_{kt} linear taxes on capital income, r_t the return on capital, δ the depreciation

¹³ Pigouvian carbon tax revenues are thus assumed to be insufficient to meet government revenue needs.

¹⁴ Specifically, the optimal internalization of production and utility damages is unchanged. However, non-separability adds terms which could increase or decrease the optimal *total* carbon tax depending on whether T_t is a relative complement or substitute to leisure (as in Schwartz and Repetto, 2000).

rate, Π_t profits from energy production, and G_t^T government transfers to households. These variables are restricted as follows. First, capital holdings cannot be negative. The consumer's debt is bounded by some finite constant M via $B_{t+1} \geq -M$. Similarly, purchases of government debt are bounded above and below by finite constants. Government transfers G_t^T are given and nonnegative. Finally, initial asset holdings B_0 and K_0 are also given.

The household's first order conditions imply that savings and labor supply decisions are governed by the standard rules, respectively:

$$\frac{U_{ct}}{U_{ct+1}} = \beta \{1 + (r_{t+1} - \delta)(1 - \tau_{kt+1})\} \quad (4)$$

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

where U_{it} denotes the partial derivative of utility with respect to argument i at time t . In words, the Euler equation (4) states that households equate their marginal rate of substitution between consumption in periods t and $t + 1$ to the after-tax return on saving between periods t and $t + 1$. Similarly, the implicit labor supply equation (5) states that agents equate their marginal rate of substitution between consumption and leisure to the after-tax return on working.

Final Goods Sector

There are two production sectors: a final consumption-investment good (indexed by "1") and energy (indexed by "2"). The consumption-investment good is produced by a technology \widetilde{F}_1 which features constant returns to scale in energy E_t , labor L_{1t} , and capital K_{1t} inputs, and satisfies the standard Inada conditions. Output Y_t further depends on temperature change T_t and an exogenous technology parameter A_{1t} :

$$Y_t = (1 - D(T_t)) \cdot A_{1t} \widetilde{F}_1(L_{1t}, K_{1t}, E_t) \quad (6)$$

$$= F_1(A_{1t}, T_t, L_{1t}, K_{1t}, E_t) \quad (7)$$

The formulation of climate damages as fraction of output lost in (6) was pioneered by Nordhaus (1991) and is extensively used in the literature.¹⁵ A common approach is to monetize all impacts, including ones that do not affect production possibilities (e.g., biodiversity existence value), and to subtract those costs from output as in (6). However, in a setting with distortionary taxes, distinguishing climate damages that affect production possibilities is necessary. Here, formulation

¹⁵ Climate impacts can, of course, be positive as well (Tol, 2002). The calibration incorporates positive impact estimates where applicable (see Section 4). The theoretical implications of heterogeneity are addressed in Section 6. Finally, while this study maintains a focus on multiplicative impacts, alternative formulations exist (see, e.g., Rezai, van der Ploeg, and Withagen (2012) for an assessment of *additive* damages).

(6) thus represents only actual production effects of climate change. Final goods producers choose factor inputs in competitive markets so as to equate their marginal products with their prices:

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

where F_{1it} denotes the partial derivative of (7) with respect to input i at time t .

Energy Sector

The energy input E_t can be produced from capital K_{2t} and labor L_{2t} inputs through a constant returns to scale technology:

$$E_t = A_{2t}F_2(K_{2t}, L_{2t}) \tag{9}$$

The constant returns to scale formulation (9) assumes that carbon energy is in unlimited supply and therefore earns zero Hotelling profits. As argued by GHKT (2014), this is a reasonable assumption for coal. In addition, the key theoretical results are robust to consideration of non-renewable resource dynamics.¹⁶ Next, energy producers can provide fraction μ_t of energy from clean or zero-emissions technologies, but at additional cost $\Theta_t(\mu_t E_t)$ which is increasing in the *amount* of clean energy or abatement (e.g., carbon capture and storage) that has to be provided ($\mu_t E_t$). This aggregated approach to modeling abatement technologies is based on the DICE framework (Nordhaus, 2008). Profits from energy production are thus given by:

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

where τ_{It} denotes the excise intermediate goods tax on total energy (both clean and carbon-based), and τ_{Et} denotes the excise tax on carbon emissions $E_t^M \equiv (1 - \mu_t)E_t$. That is, since the model features distinct decision margins on energy input levels and emissions, the decentralization includes two policy instruments (as a ‘complete’ tax system in the sense of Chari and Kehoe,

¹⁶ The longer working paper version of this study (Barrage, 2014) formally shows that, with a non-renewable energy resource, the optimal carbon tax formulation is identical to the benchmark case if the government can fully tax away scarcity rents. If 100% profit taxes are not available, a premium is added to the optimal *total* carbon tax to indirectly capture fossil fuel producers’ rents, but the internalization of climate damages remains structurally unchanged (see also Williams, 2002; Bento and Jacobsen, 2007; and Fullerton and Kim, 2008; Franks, Edenhofer, and Lessmann, 2017, for discussions of second-best taxation and untaxed rents).

1999). Labor and capital are mobile across sectors, implying market clearing conditions:

$$\begin{aligned} L_t &= L_{1t} + L_{2t} \\ K_t &= K_{1t} + K_{2t} \end{aligned} \tag{10}$$

This assumption is in line with GHKT (2014). Due to the 10 year time step used in the empirical model, formulation (10) is also more realistic than in an annual formulation. An important implication of (10) is that factor prices will be equated across sectors in equilibrium. Competitive energy producers thus equate marginal factor products and prices:

$$\begin{aligned} [p_{Et} - \tau_{It} - \tau_{Et}]F_{2lt} &= w_t \\ [p_{Et} - \tau_{It} - \tau_{Et}]F_{2kt} &= r_t \end{aligned} \tag{11}$$

Note that, at the optimum, the abatement term μ_t drops out of the firm's profit-maximizing conditions (11) as the marginal benefit of avoided tax payments per unit of E_t ($\mu_t \tau_{Et}$) is equated to the marginal increase in abatement costs per unit of E_t ($\Theta'_t(\mu_t E_t)\mu_t$). Formally, this is because profit-maximization yields the standard condition that firms engage in emissions reductions until the marginal abatement cost equals the carbon price τ_{Et} :

$$\tau_{Et} = \Theta'_t(\mu_t E_t) \tag{12}$$

Government

Following standard approaches in the literature (e.g., Chari and Kehoe, 1999; Jones, Manuelli, and Rossi, 1993), the government needs to finance an exogenously given sequence of public consumption (G_t^C) and household transfers $\{G_t^T > 0, G_t^T\}_{t=0}^\infty$, and to pay off inherited debt B_0^G . The government can issue new, one-period bonds B_{t+1}^G and levy linear taxes on labor and capital income. In addition, the government can impose excise taxes τ_{It} on energy inputs and τ_{Et} on carbon emissions. The consumption good serves as the untaxed numeraire. The government's flow budget constraint is given by:

$$G_t^C + G_t^T + B_t^G = \tau_{lt}w_tL_t + \tau_{It}E_t + \tau_{Et}E_t^M + \tau_{kt}(r_t - \delta)K_t + \rho_t B_{t+1}^G \tag{13}$$

Market clearing requires that consumer demand and government supply for bonds be equated:

$$B_{t+1}^G = B_{t+1} \tag{14}$$

The analysis assumes that the government can commit to a tax policy sequence at time zero.

Though common, this assumption is not innocuous. I discuss its implications in Section 6.

Carbon Cycle

Atmospheric temperature change T_t at time t is assumed to depend on the history of carbon emissions $\{E_s^M\}_{s=0}^t = \{(1 - \mu_s)E_s\}_{s=0}^t$, initial conditions \mathbf{S}_0 (e.g., atmospheric carbon stocks, deep ocean temperatures, etc.), and exogenous shifters $\{\boldsymbol{\eta}_s\}_{s=0}^t$ (e.g., land-based emissions):

$$T_t = F(\mathbf{S}_0, E_0^M, E_1^M, \dots, E_t^M, \boldsymbol{\eta}_0, \dots, \boldsymbol{\eta}_t) \quad (15)$$

where:

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

Competitive Equilibrium

Competitive equilibrium in this economy can now be formally defined as follows:

Definition 1 *A competitive equilibrium consists of an allocation $\{C_t, L_{1t}, L_{2t}, K_{1t+1}, K_{2t+1}, E_t, \mu_t, T_t\}$, a set of prices $\{r_t, w_t, p_{Et}, \rho_t\}$ and a set of policies $\{\tau_{kt}, \tau_{lt}, \tau_{Et}, \tau_{It}, B_{t+1}^G\}$ such that:*

- (i) *the allocations solve the consumer's and the firms' problems given prices and policies,*
- (ii) *the government budget constraint is satisfied in every period,*
- (iii) *temperature change satisfies the carbon cycle constraint in every period, and*
- (iv) *markets clear.*

The Ramsey framework assumes that the government seeks to maximize the household's lifetime utility (1) subject to the constraints of (i) feasibility and (ii) the optimizing behavior of households and firms, for a given set of initial conditions. I characterize the optimal allocations using the primal approach. By solving for optimal *allocations*, rather than for optimal tax rates, this method avoids normalization issues (see, e.g., Williams, 2001). Intuitively, optimal tax rates depend on the choice of numeraire, whereas optimal allocations do not. The validity of the primal approach setup in this context requires the following proposition:

Proposition 1 *The allocations $\{C_t, L_{1t}, L_{2t}, K_{1t+1}, K_{2t+1}, E_t, \mu_t, T_t\}$, along with initial bond holdings B_0 , initial capital K_0 , initial capital tax $\overline{\tau_{k0}}$, initial carbon concentrations S_0 and climate shifters $\{\boldsymbol{\eta}_t\}$ in a competitive equilibrium satisfy:*

$$F_1(A_{1t}, T_t, L_{1t}, K_{1t}, E_t) + (1 - \delta)K_t \geq C_t + K_{t+1} + G_t^C + \Theta_t(\mu_t E_t) \quad (\text{RC})$$

$$T_t \geq F(\mathbf{S}_0, (1 - \mu_0)E_0, (1 - \mu_1)E_1, \dots, E_t, \boldsymbol{\eta}_0, \dots, \boldsymbol{\eta}_t) \quad (\text{CCC})$$

$$E_t \leq A_{2t} F_2(K_{2t}, L_{2t}) \quad (\text{ERC})$$

$$L_{1t} + L_{2t} \leq L_t \quad (\text{LC})$$

$$K_{1t} + K_{2t} \leq K_t \quad (\text{KC})$$

$$\sum_{t=0}^{\infty} \beta^t [U_{ct} C_t + U_{lt} L_t - U_{ct} G_t^T] = U_{c0} [K_0 \{1 + (F_{1k0} - \delta)(1 - \bar{\tau}_{k0})\} + B_0] \quad (\text{IMP})$$

In addition, given an allocation that satisfies (RC)-(IMP), one can construct prices, debt holdings, and policies such that those allocations constitute a competitive equilibrium.

Proof: Online Appendix. This proposition and its proof differ from the setup in Chari and Kehoe (1999) mainly through the addition of the energy production sector and the carbon cycle constraint. In words, Proposition 1 ensures that any allocation satisfying conditions (RC)-(IMP) can be decentralized as a competitive equilibrium. I assume that the solution to the Ramsey problem is interior and that the planner's first order conditions are both necessary and sufficient. Formally, the government's problem is thus to maximize household lifetime utility (1) subject to (RC)-(IMP). Let λ_{1t} denote the Lagrange multiplier on the resource constraint (RC) in period t .

Before describing the results, define the following concepts. First, the *marginal cost of public funds* (*MCF*) measures the welfare cost of raising an additional unit of government revenue. As lump-sum taxes are pure transfers, their *MCF* is unity. In contrast, transferring one unit via distortionary taxes costs households said unit *plus* the marginal deadweight loss of the associated tax increase. I follow the standard approach of defining the *MCF* as follows:

Definition: Let the *Marginal Cost of Public Funds* (*MCF*) be defined as the ratio of the public marginal utility of consumption to the private marginal utility of consumption:

$$MCF_t \equiv \frac{\lambda_{1t}}{U_{ct}} \quad (16)$$

Next, letting $\frac{\partial Y_{t+j}}{\partial T_{t+j}}$ denote the marginal output change from temperature increase T_{t+j} at time $t+j$, letting $U_{T_{t+j}}$ denote the marginal disutility of temperature change at time $t+j$, and $\frac{\partial T_{t+j}}{\partial E_t^M}$ the change in temperature at time $t+j$ caused by a marginal increase in today's carbon emission E_t^M , define the following terms:

Definition: Both the *Pigouvian carbon tax* and the *social cost of carbon* (*SCC*) are defined as the present value of marginal damages valued at the agent's marginal utility of consumption. *Pigouvian taxes to internalize damages to production and utility, respectively, are defined by:*

$$\text{Production damages: } \tau_{Et}^{\text{Pigou}, Y} \equiv (-1) \sum_{j=0}^{\infty} \beta^j \frac{U_{ct+j}}{U_{ct}} \left[\frac{\partial Y_{t+j}}{\partial T_{t+j}} \frac{\partial T_{t+j}}{\partial E_t^M} \right] \quad (17)$$

$$\text{Utility damages: } \tau_{Et}^{Pigou,U} = (-1) \sum_{j=0}^{\infty} \beta^j \frac{U_{Tt+j}}{U_{ct}} \left[\frac{\partial T_{t+j}}{\partial E_t^M} \right] \quad (18)$$

The total Pigouvian carbon tax is defined as fully internalizing marginal damages (the SCC):

$$\tau_{Et}^{Pigou,T} \equiv \tau_{Et}^{Pigou,U} + \tau_{Et}^{Pigou,Y} \quad (19)$$

Finally, the level of the Pigouvian tax in each fiscal scenario is given by (19) evaluated at the optimal allocation (i.e., the solution to the planner's problem) in that particular fiscal scenario. These definitions are standard. Focusing on production impacts, GHKT (2014) show that (17) defines the optimal carbon price in the first-best setting. The next section characterizes optimal carbon tax design alongside other, distortionary taxes.

3 Theory Results

This section first describes theoretically optimal policy in a setting where the planner has access to an unrestricted set of policy instruments (aside from lump-sum taxes). Given that the resulting policy prescriptions do not necessarily align with observed fiscal policy, the second part describes optimal climate policy in a (third-best) setting where the planner faces additional constraints on capital and labor income taxes. In the COMET calibration, these constraints are set to effective tax rates observed in reality. These analytic results thus provide additional conceptual underpinnings for the quantitative analysis.

3.1 Climate Policy with Optimized Distortionary Taxes

This section first presents the fully optimal carbon tax formulation in the general case, and then develops intuition and implications for two special cases where climate change affects only utility or production possibilities. Combining the planner's first order conditions and comparing them with the energy producer's profit-maximizing conditions (11), it is straightforward to show (see Appendix A) the following: Provided that capital and labor income taxes are set appropriately, the optimal intermediate goods tax on energy inputs is zero ($\tau_{1t}^* = 0 \forall t > 0$), whereas the optimal carbon tax for $t > 0$ is implicitly defined as follows:

$$\tau_{Et}^* = \underbrace{\sum_{j=0}^{\infty} \beta^j \left[\frac{-U_{Tt+j}}{U_{ct}} \frac{1}{MCF_t} \right] \left[\frac{\partial T_{t+j}}{\partial E_t^M} \right]}_{\text{Utility Damages}} + \underbrace{\sum_{j=0}^{\infty} \beta^j \left[\frac{-\partial Y_{t+j}}{\partial T_{t+j}} \frac{\lambda_{1t+j}}{\lambda_{1t}} \right] \left[\frac{\partial T_{t+j}}{\partial E_t^M} \right]}_{\text{Production Damages}} \quad (20)$$

Expression (20) shows that the optimal carbon price consists of two components: one to inter-

nalize the discounted sum of future utility damages associated with an increase in time t carbon emissions, and one to internalize the sum of future production impacts. Importantly, however, *distortionary taxes drive a wedge between the planner's and the household's valuations of these impacts*. Utility damages are divided by the contemporaneous marginal cost of public funds MCF_t : If taxes are distortionary ($MCF_t > 1$), then the optimal policy does not fully internalize utility damages from carbon emissions. In contrast, the planner's valuation of production damages depends on the evolution of the public marginal utility of income λ_{1t+j} over time. While it is difficult to derive concrete insights on this term in the general case, restricting preferences to two commonly used CES forms leads to the following result:

Proposition 2 *If preferences are of either commonly used constant elasticity form,*

$$U(C_t, L_t, T_t) = \frac{C_t^{1-\sigma}}{1-\sigma} + \vartheta(L_t) + v(T_t) \quad (21)$$

$$U(C_t, L_t, T_t) = \frac{(C_t L_t^{-\gamma})^{1-\sigma}}{1-\sigma} + v(T_t) \quad (22)$$

and direct government transfers to households are either zero or account for a constant fraction of consumption, then, for $t > 0$:

- 1) *the optimal capital income tax is zero: $\tau_{kt+1}^* = 0$*
- 2) *the optimal intermediate goods tax on energy inputs is zero: $\tau_{It}^* = 0$*
- 3) *the optimal carbon emissions tax is implicitly defined by:*

$$\tau_{Et}^* = \frac{\tau_{Et}^{Pigou,U}}{MCF_t} + \tau_{Et}^{Pigou,Y} \quad (23)$$

Alternatively, letting $\theta_t^u \equiv (\tau_{Et}^{Pigou,U} / \tau_{Et}^{Pigou,T})$ denote the share of utility impacts in marginal damages from period t emissions, the optimal carbon tax for $t > 0$ is implicitly defined by:

$$\tau_{Et}^* = \tau_{Et}^{Pigou,T} \left[1 + \theta_t^u \frac{(1 - MCF_t)}{MCF_t} \right] \quad (24)$$

Proof: See Appendix A. In words, Proposition 2 shows that, for preferences (21)-(22) and given some (commonly implicitly assumed) conditions on government expenditures, the optimal policy fully internalizes output damages from carbon emissions, but does not fully internalize utility impacts if the tax code is distortionary ($MCF > 1$).¹⁷ Both Bovenberg and van der Ploeg (1994) and Williams (2002) derive analogous expressions to (23) in a static setting. Proposition 2 thus provides conditions under which their result generalizes to a dynamic economy. More generally, it

¹⁷ Note that the MCF cannot be expressed in closed-form here. Even on a balanced growth path, long-run tax rates are endogenous to the history of taxes and revenues collected. See Barrage (2014).

is clear from (20) that (23) will continue to hold for flow pollutants which dissipate rapidly from the environment (e.g., sulfur dioxide). On the other hand, however, for accumulative pollutants such as carbon, expression (20) may not reduce to (23) depending on intertemporal distortions in the economy. In order to elucidate and contextualize this result, the remainder of this section analyzes output and utility damages separately.

Special Case 1: Climate Change Affects Only Utility

The literature on environmental policy alongside other taxes commonly assumes that pollution affects only utility. In this case, the optimal carbon tax expression (20) reduces to:

$$\tau_{Et}^* = \sum_{j=0}^{\infty} \beta^j \left[\frac{-U_{Tt+j}}{U_{ct}} \frac{1}{MCF_t} \right] \left[\frac{\partial T_{t+j}}{\partial E_t^M} \right] = \frac{\tau_{Et}^{Pigou,U}}{MCF_t} \quad (25)$$

where the second equation follows from the definition of $\tau_{Et}^{Pigou,U}$ (18). Expression (25) extends to a dynamic setting the classic result from static models that $(\tau_E^* = \tau_E^{Pigou}/MCF)$ (Bovenberg and van der Ploeg, 1994; Bovenberg and Goulder, 1996, etc.). The intuition is as follows. Utility damages reflect the value of the climate as a final consumption good (e.g., amenity value). Expression (25) implies that the optimal allocation leaves a wedge between the household's marginal rate of substitution (*MRS*) and the marginal rate of transformation (*MRT*) between the climate and the final consumption good. The provision of the climate good is thus distorted, along with the general consumption-leisure margin.

Intuitively, if climate change affects only utility, imposing a carbon tax provides no productivity benefits. To the contrary, carbon taxes will decrease the real returns to labor, as higher energy prices increase the cost of the consumption good relative to leisure. By decreasing employment, carbon pricing can thus exacerbate the welfare costs of labor income taxes. In order to account for these tax interactions, the optimal carbon price discounts utility damages by the MCF_t . This is the "tax interaction effect" that has been extensively studied in the literature (see, e.g., Bovenberg and Goulder, 2002).

Special Case 2: Climate Change Affects Only Production

Consider now climate change impacts that only affect production possibilities (e.g., in agriculture, fisheries, etc.). In this case, the optimal tax expression (20) reduces to:

$$\tau_{Et}^* = \sum_{j=0}^{\infty} \beta^j \left[\frac{-\partial Y_{t+j}}{\partial T_{t+j}} \frac{\lambda_{1t+j}}{\lambda_{1t}} \right] \left[\frac{\partial T_{t+j}}{\partial E_t^M} \right] \quad (26)$$

This term represents the discounted sum of marginal output changes $\left(\frac{-\partial Y_{t+j}}{\partial T_{t+j}}\right)$, as in the standard setting (GHKT, 2014). However, with distortionary taxes, the public value of output λ_{1t} differs from the household's ($\lambda_{1t+j} \neq U_{ct+j}$, see (16)). Whether (26) matches the Pigouvian tax (17) thus depends critically on how the planner's relative valuation of output *over time* ($\frac{\lambda_{1t+j}}{\lambda_{1t}}$) compares to the household's, leading to the following result:

Proposition 3 *If the government optimally chooses to set capital income taxes to zero from period $t+1$ onwards, then the optimal carbon tax to internalize production damages at time $t > 0$ is the Pigouvian tax.*

Proof. First, for all $j \geq 1$, multiply the $t + j^{\text{th}}$ term in the sum of (26) by:

$$\left(\prod_{m=1}^{j-1} \frac{\lambda_{1t+m}}{\lambda_{1t+m}}\right) = 1$$

Each term $\frac{\lambda_{1t+j}}{\lambda_{1t}}$ can then be rearranged to equal $\left(\frac{\lambda_{1t+j}}{\lambda_{1t+j-1}} \frac{\lambda_{1t+j-1}}{\lambda_{1t-2}} \dots \frac{\lambda_{1t+1}}{\lambda_{1t}}\right)$. Second, combine the planner's optimality conditions for consumption C_t , aggregate capital savings, K_{t+1} , and final goods production capital K_{1t} to show that the optimal allocation for all $t > 0$ satisfies:

$$\frac{\lambda_{1t}}{\lambda_{1t+1}} = \beta [F_{1kt+1} + (1 - \delta)] \quad (27)$$

Third, combining households' (4) and firms' (8) optimality conditions shows that, in equilibrium,

$$\frac{U_{ct}}{U_{ct+1}} = \beta \{1 + (F_{1kt+1} - \delta)(1 - \tau_{kt+1})\} \quad (28)$$

Comparing (27) and (28) immediately shows that, if the government optimally chooses to set capital income taxes in period $t + 1$ to zero, then:

$$\frac{\lambda_{1t}}{\lambda_{1t+1}} = \frac{U_{ct}}{U_{ct+1}} \quad (29)$$

If the government optimally sets capital income taxes to zero from period $t + 1$ onwards, this implies that condition (29) must be satisfied for all $t + j$, $j \geq 1$. Finally, repeatedly substituting $\frac{\lambda_{1t+j}}{\lambda_{1t+j-1}} = \frac{U_{ct+j}}{U_{ct+j-1}}$ into (26) yields the desired result:

$$\tau_{Et}^* = \sum_{j=0}^{\infty} \beta^j \left[\frac{U_{ct+j}}{U_{ct}} \frac{-\partial Y_{t+j}}{\partial T_{t+j}} \right] \left[\frac{\partial T_{t+j}}{\partial E_t^M} \right] = \tau_{Et}^{\text{Pigou}, Y} \quad \blacksquare. \quad (30)$$

The intuition for this result is straightforward: The climate is an asset used in production, analogous to physical capital. However, as the climate is a public good, the private sector's incentives

to invest in it through emissions reductions are distorted in the absence of a properly set carbon tax. That is, without a Pigouvian carbon tax, a wedge remains between the intertemporal MRS and MRT between present and future consumption based on investments in climate protection.¹⁸ Analogously, capital income taxes drive a wedge between private and social returns to investments in physical capital, also leading to a divergence between the intertemporal MRS and the social MRT . Consequently, the economic factors that make it desirable for the government to leave households' physical capital investments undistorted likewise make it desirable for environmental investment incentives to be undistorted. This requires precisely a Pigouvian tax. Given that the optimal capital income tax in the setting of Proposition 2 is zero, Proposition 3 therefore also explains why output damages are then internalized by a Pigouvian levy in (23) even if labor markets are distorted.

The literature on optimal dynamic Ramsey taxation has found that capital income taxes are undesirable in a broad range of models and settings (see, e.g., Judd, 1985; Chamley, 1986; Atkeson, Chari, and Kehoe, 1999; Acemoglu, Golosov, and Tsyvinski, 2011). A number of studies have explored the implications of this result for human capital taxation (Judd, 1999; Jones, Manuelli, and Rossi, 1993, 1997). Proposition 3 demonstrates that the logic against capital income taxes further extends to distortions on investments in environmental capital.

3.2 Climate Policy with Constrained Distortionary Taxes

In reality, most countries tax capital income in various forms. A natural follow-up question to Proposition 3 is thus: What is the optimal structure of carbon taxes in an economy where capital income *is* taxed? Perhaps surprisingly, the answer can depend on the underlying reason why capital income levies are positive.

For example, if the capital tax rate is constrained by agents' ability to hold capital without renting it out to firms, the government optimally sets capital income levies at this upper bound for a finite number of periods and eventually decreases them to zero (Atkeson, Chari, and Kehoe, 1999). Adding this constraint in the present setting, one can then show that carbon taxes to internalize output damages are lower than Pigouvian rates for as long as capital income taxes remain positive (see Barrage, 2014).

In contrast, with an exogenous constraint that capital income levies be fixed at some positive level $\bar{\tau}_k \in (0, 1)$ (due to, e.g., unmodeled political constraints preventing efficiency-maximizing tax reform from being fully implemented), the carbon price is subject to several adjustments. Since it is empirically of interest to solve for optimal carbon prices in a fiscal 'business as usual' scenario that maintains capital or labor income taxes at current rates, Corollaries 1 and 2 pro-

¹⁸ See Barrage (2014) for a formal illustration of this point in a two-period framework.

vide an analytic characterization of optimal climate policy in two of the settings analyzed in the COMET. Only one income tax constraint is considered at a time so as to leave the other instrument free to help meet the government budget constraint.

Corollary 1 *If the government is constrained to maintain capital income taxes at $\bar{\tau}_k \forall t > 0$:*

$$\frac{U_{ct}}{\beta U_{ct+1}} = 1 + (1 - \bar{\tau}_k)(F_{1kt+1} - \delta) \quad (31)$$

then, letting Ψ_t denote the planner's Lagrange multiplier on (31) in period t , the optimal carbon tax for $t > 0$ is implicitly defined by:

$$\tau_{Et}^* = (-1) \left[\underbrace{\sum_{j=0}^{\infty} \beta^j \frac{U_{Tt+j}}{U_{ct}} \frac{1}{MCF_t} + \frac{\lambda_{1t+j}}{\lambda_{1t}} \frac{\partial Y_{t+j}}{\partial T_{t+j}}}_{\text{Utility + Production Impacts}} + \underbrace{\frac{\Psi_{t-1+j}}{\lambda_{1t}} \frac{1}{\beta} \frac{\partial F_{1kt+j}}{\partial T_{t+j}} (1 - \bar{\tau}_k)}_{\text{Fiscal Constraint Interaction}} \right] \left[\frac{\partial T_{t+j}}{\partial E_t^M} \right] \quad (32)$$

where the government's discounting of output damages for $t \geq 0$ is defined by:

$$\frac{\beta \lambda_{1t+1}}{\lambda_{1t}} = [F_{1kt+1} + (1 - \delta) + \frac{\Psi_t}{\lambda_{1t+1}} \frac{1}{\beta} \frac{\partial F_{1kt+1}}{\partial K_{1t+1}} (1 - \bar{\tau}_k)]^{-1} \quad (33)$$

Corollary 2 *If the government is constrained to maintain labor income taxes at $\bar{\tau}_l \forall t > 0$:*

$$\frac{-U_{lt}}{U_{ct}} = (1 - \bar{\tau}_l) F_{1lt} \quad (34)$$

then, letting Λ_t denote the planner's Lagrange multiplier on (34) in period t , the optimal carbon tax for $t > 0$ is implicitly defined by:

$$\tau_{Et}^* = (-1) \left[\sum_{j=0}^{\infty} \beta^j \frac{U_{Tt+j}}{U_{ct}} \frac{1}{MCF_t} + \frac{\lambda_{1t+j}}{\lambda_{1t}} \frac{\partial Y_{t+j}}{\partial T_{t+j}} + \frac{\Lambda_{t+j}}{\lambda_{1t}} \frac{\partial F_{1lt+j}}{\partial T_{t+j}} (1 - \bar{\tau}_l) \right] \left[\frac{\partial T_{t+j}}{\partial E_t^M} \right] \quad (35)$$

Utility + Production Impacts Fiscal Constraint Interaction

where the government's discounting of output damages for $t \geq 0$ is defined by:

$$\frac{\beta \lambda_{1t+1}}{\lambda_{1t}} = [F_{1kt+1} + (1 - \delta) + \frac{\Lambda_{t+1}}{\lambda_{1t+1}} \frac{\partial F_{1lt+1}}{\partial K_{1t+1}} (1 - \bar{\tau}_l)]^{-1} \quad (36)$$

Proofs: See Online Appendix. In a third-best setting with limited potential for tax reform, the optimal carbon tax thus differs from (20) for several reasons. First, the marginal cost of funds MCF_t may be different. Second, the government's discounting of future output damages changes, as shown in (33) and (36). In particular, the opportunity cost of capital is now adjusted to reflect

the efficiency costs of the income tax constraints defining the fiscal setting. For example, if the government would like to set lower capital income taxes $\tau_{kt+1}^* < \overline{\tau}_k$ (implying that $\Psi_t > 0$), then the opportunity cost of investing in capital in (33) is adjusted *downward*, ceteris paribus, to reflect the fact that additional capital would reduce marginal returns further away from their social optimum (as $\frac{\partial F_{1kt+1}}{\partial K_{1t+1}} < 0$), exacerbating the constraint (31). At the same time, the planner's future output valuation ($\frac{\beta \lambda_{1t+1}}{\lambda_{1t}}$) also differs from the household's ($\frac{\beta U_{ct+1}}{U_{ct}}$) through the capital income tax itself, which lowers the former relative to the latter, ceteris paribus. The third difference is that climate damages now interact with the fiscal constraints. For example, consider again the case where the optimal capital tax is below $\overline{\tau}_k$. As climate change decreases the marginal product of capital ($\frac{\partial F_{1kt+j}}{\partial T_{t+j}} < 0$), it effectively exacerbates the capital income tax constraint by lowering returns further from their social optimum. In sum, the net impacts of fiscal policy constraints (31) and (34) on optimal climate policy are thus theoretically ambiguous, and therefore quantified in Section 5.

Before proceeding, two remarks are in order. The first is that decentralizing the optimal allocation in the third-best may require non-zero intermediate energy input taxes τ_{It} in addition to carbon levies. Intuitively, energy usage of all types - including clean energy - alters the marginal products of capital and labor, and therefore interacts with the fiscal constraints. The Online Appendix provides an analytic characterization and further discussion of optimal intermediate goods taxes τ_{It}^* in this setting. The second point to note is that Corollaries 1 and 2 only speak to carbon tax design in a setting with exogenous income tax constraints. In the literature, there are numerous extensions of the basic Ramsey setup as well as alternative models of optimal taxation that imply the desirability of capital income taxes (see review by Sorensen, 2007; also, e.g., Piketty and Saez, 2013; Golosov, Kocherlakota, and Tsyvinski, 2003; Klein and Rios-Rull, 2003; etc.). Integrating climate capital and exploring optimal carbon levies in those frameworks is beyond the scope of this study but an interesting area for future research.¹⁹

4 Calibration of the COMET

This section describes the calibration of the Climate Optimization Model of the Economy and Taxation (COMET) outlined above. The calibration adopts many parameters and functional forms directly from the seminal DICE climate-economy model by Nordhaus (e.g., 2008) in order to maintain close comparability with this benchmark. At the same time, the calibration presents quantifications for the novel features of the model, such as tax policy, government spending, and

¹⁹ For example, Cremer, Gahvari, and Ladoux (2001) study pollution taxes in a Mirrleesian optimal taxation model with informational frictions. It would be interesting to extend their work to the dynamic setting. See also discussion below of Schmitt (2014), who studies optimal carbon taxes with time-consistent fiscal policy.

separate representations of production and utility damages. The calibration matches data on world GDP, energy consumption, labor supply, government expenditures, etc. for the year 2005 as a base period ($t = -1$), and begins simulations in 2015 ($t = 0$). In line with DICE and other literature (e.g., GHKT), the model’s time step is set to a decade.²⁰ The computational procedure is described in Appendix B, and the details of the calibration are as follows.

4.1 Carbon Cycle and Climate Model

The relationship between carbon emissions and temperature change (15) is adopted from DICE (Nordhaus, 2010). The calibration keeps track of two exogenous climate shifters $\boldsymbol{\eta}_t$: land-based greenhouse gas emissions E_t^{Land} and exogenous radiative forcings χ_t^{Ex} (e.g., aerosols). The final relationship between temperature and emissions (15) is composed of several steps. First, emissions flow through three carbon reservoirs: the atmosphere (S_t^{At}), the upper oceans and biosphere (S_t^{Up}), and the deep oceans (S_t^{Lo}):

$$\begin{pmatrix} S_t^{\text{At}} \\ S_t^{\text{Up}} \\ S_t^{\text{Lo}} \end{pmatrix} = \begin{pmatrix} \phi_{11} & \phi_{21} & 0 \\ \phi_{12} & \phi_{22} & \phi_{32} \\ 0 & \phi_{23} & \phi_{33} \end{pmatrix} \begin{pmatrix} S_{t-1}^{\text{At}} \\ S_{t-1}^{\text{Up}} \\ S_{t-1}^{\text{Lo}} \end{pmatrix} + \begin{pmatrix} E_t^{\text{M}} + E_t^{\text{Land}} \\ 0 \\ 0 \end{pmatrix} \quad (37)$$

Second, increases in atmospheric carbon lead to higher radiative forcings χ_t :²¹

$$\chi_t = \kappa \left\{ \ln \left(\frac{S_t^{\text{At}}}{S_{1750}^{\text{At}}} \right) / \ln(2) \right\} + \chi_t^{\text{Ex}}$$

Finally, increased forcings raise atmospheric temperatures T_t . The model also tracks heat exchange with the ocean T_t^{Lo} in order to capture warming delays:

$$\begin{pmatrix} T_t \\ T_t^{\text{Lo}} \end{pmatrix} = \begin{pmatrix} (1 - \zeta_1 \zeta_2 - \zeta_1 \zeta_3) & \zeta_1 \zeta_3 \\ (1 - \zeta_4) & \zeta_4 \end{pmatrix} \begin{pmatrix} T_{t-1} \\ T_{t-1}^{\text{Lo}} \end{pmatrix} + \begin{pmatrix} \zeta_1 \chi_t \\ 0 \end{pmatrix} \quad (38)$$

Given a set of initial conditions $\mathbf{S}_0 = \{S_0^{\text{At}}, S_0^{\text{Up}}, S_0^{\text{Lo}}, T_0, T_0^{\text{Lo}}\}$, shifters $\{\boldsymbol{\eta}_0\}_{s=0}^t$, and emissions $\{E_s^{\text{M}}\}_{s=0}^t$, iteratively combining (37)-(38) thus defines the emissions-temperature relationship (15). The parameters match an equilibrium temperature change due to a doubling of carbon concentrations (i.e., a climate sensitivity) of 3.2°C , and are listed in the Online Appendix.

²⁰ The calibration values are adjusted from annual to decadal values through compounding or linearly, following the DICE approach and as described both below and in the Online Appendix (Table A1).

²¹ Radiative forcings measure the net change in the earth’s radiation energy balance (in watts/ m^2).

4.2 Damages

The theoretical results demonstrate the importance of distinguishing production and utility damages in a setting with distortionary taxes. The literature commonly aggregates climate damages into pure production losses (e.g., Nordhaus, 2008; GHKT, 2014), pure utility losses (e.g., Acemoglu, Aghion, Bursztyn, and Hemous, 2012), or distinguishes market and non-market impacts (*PAGE*, Hope, 2006, 2011; *MERGE*, Manne and Richels, 2005; *FUND*,²² Tol, 1995, 1997). However, the differentiation of production vs. utility damages requires a different approach.

In order to maintain comparability with DICE, I use the regional-sectoral damage estimates underlying the DICE/RICE models (Nordhaus, 2007; Nordhaus and Boyer, 2000). These models present estimates of eight types of climate change impacts in each of twelve regions.²³ I first split and then re-aggregate these impacts according to the classification scheme presented in Table 1.

Impact Category	Classification
Agriculture	Production
Other vulnerable markets (energy services, forestry, etc.)	Production
Sea-level rise coastal impacts	Production
Amenity value	Utility
Ecosystems	Utility
Human (re)settlement	Utility
Catastrophic damages	Mixed
Health	Mixed

Table 1: Climate Damage Categorization

While the classification of some impacts is straightforward (e.g., agriculture), three categories warrant further explanation. First, sea-level rise coastal impacts represent damages to capital. Extending the benchmark model to incorporate climate-dependent depreciation ($\delta(T_t)$), one can easily show that the optimal carbon tax internalizes these losses identically to production damages.²⁴ Second, the catastrophic impact costs in DICE are based on expected damages from events equivalent to a permanent loss of 30% of global GDP. However, this reduction represents both actual output losses and disutility of non-production damages. For each region, I thus split catastrophic damages into production and utility components according to each region's share

²² Current versions of FUND do not focus on this distinction and provide disaggregated output for damages across sectors such as agriculture, sea-level rise, and health (see, e.g., Anthoff and Tol, 2013).

²³ The United States, Western Europe, Russia, Eastern Europe/former Soviet Union, Japan, China, India, Middle East, Sub-Saharan Africa, Latin America, other Asian countries, and other high income countries.

²⁴ With a single investment-consumption good and capital malleability, both increased depreciation $\delta(T_t)$ and output losses $D(T_t)Y_t$ reduce the amount of the final good left over at the end of period t .

of non-catastrophic impacts affecting production and utility, respectively.^{25,26}

Third, while human health impacts are typically classified as "non-market" effects, they can alter production possibilities, such as by decreasing time endowments and labor productivity (Williams, 2002). In the literature, a common approach is to value projected years of life lost from climate-sensitive diseases based on the value of statistical life literature (DICE, Nordhaus, 2008; FUND 3.7, Anthoff and Tol, 2013). In contrast, in order to capture labor market impacts of climate change, I use projected years of life lost to separately estimate (i) the global labor time endowment reduction and corresponding output loss and (ii) the disutility from lost leisure time. In addition, as labor productivity impacts have not generally been included in climate-economy models (Tol, 2011), I use available evidence in the literature to compute labor productivity losses associated with malaria - one of the most climate-sensitive diseases (WHO, 2009).²⁷

Accurately characterizing climate change impacts is notoriously difficult and fraught with uncertainties, such as adaptation. However, it should be noted that the DICE damage estimates account for several forms of adaptation. For example, impacts are modeled with different income elasticities to reflect, e.g., decreased disease vulnerability or higher amenity values as income levels grow (Nordhaus and Boyer, 2000). Similarly, they use agricultural impact estimates from Ricardian models that incorporate adaptation (see Mendelsohn, Nordhaus, and Shaw, 1994). They also assume some amount of necessary migration due to sea-level rise, and compute an associated disutility of re-settlement. However, considerable uncertainty remains over factors such as trade, migration, and future changes in technology or even preferences (see, e.g., Atkin, 2013). One of the literature's frontiers is to formalize the effects of such factors (e.g., Desmet and Rossi-Hansberg, 2015). However, as this paper seeks to isolate the effects of distortionary taxes, I focus on standard DICE estimates to maintain comparability to this benchmark.

The results suggest that production impacts account for 74% of aggregate (output-weighted) global climate damages at the calibration point of 2.5°C warming. Applying this estimate back

²⁵ In contrast, some studies categorize catastrophic impacts as 'non-market' because they are difficult to monetize (e.g., Manne and Richels, 2006).

²⁶ Note that (i) damage shares are measured relative to the *absolute value* of total non-catastrophic impacts in order to account for regions with both positive and negative impacts, and that (ii) climate amenity values are excluded from the damage share calculation as they are unlikely to be important for catastrophic impacts.

²⁷ This calculation combines estimates of labor productivity losses from malaria due to Bleakley (2003), with World Bank malaria prevalence data and impact estimates from Tol (2008). See Barrage (2014).

to the 2010-DICE model’s aggregate impacts yields the following moments:²⁸

$$\begin{aligned}
\text{Share of output damages} & : 74\% & (39) \\
\text{Total damages from } 2.5^\circ C \text{ warming} & : 1.74\% \text{ of output} \\
\text{Total } \mathbf{production} \text{ damages} & : 1.29\% \text{ of output} \\
\text{Total } \mathbf{direct} \text{ utility damages} & : 0.46\% \text{ of output}
\end{aligned}$$

The COMET also adopts the functional form for output damages from DICE:

$$(1 - D_t(T_t)) = \frac{1}{1 + \theta_1 T_t^2} \quad (40)$$

Solving (40) for (39) yields $\theta_1 = 0.0021$ for output damages.

4.3 Households

Household preferences are quantified over per-capita consumption $c_t \equiv C_t/N_t$, where N_t is the population at time t (exogenously given), and labor supply $l_t \equiv L_t/N_t$. The dynastic household (and the planner) thus maximize the population-weighted lifetime utility:

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

Global population projections $\{N_t\}_{t=2005}^{t \geq 2255}$ are taken from DICE (Nordhaus, 2010). The relevant adjustments to the model setup are standard (see Online Appendix). The utility discount factor is set to 1.5% per year, or $\beta = (.985)^{10}$ in the decadal model, in line with DICE.

Next, the utility function $U(c_t, l_t, T_t)$ is chosen based on three criteria: (i) consistency with balanced growth, (ii) matching the DICE model’s consumption elasticity ($\sigma = 1.5$), and (iii) jointly matching Frisch elasticities of labor supply from the literature ($= 0.78$ based on Chetty, Guren, Manoli, and Weber, 2011) and base year labor supply ($l_{2005} = 0.227$ from OECD data) at base year effective labor tax rates ($\tau_{l,2005} = 36.09\%$ for distortionary tax scenarios, and $\tau_{l,2005} = 0$ for first-best scenarios). Though theoretically convenient, the utility functions from Proposition 1 (21)-(22) do not satisfy all of these criteria. For example, specification (21) is only consistent with balanced growth for logarithmic utility ($\sigma = 1$) (King, Plosser, Rebelo, 2001). Consequently, I adopt a modified version of (22) building on other quantitative dynamic Ramsey taxation models

²⁸ Due to the different aggregation across sectors and countries, production and utility damages in my calculation sum to aggregate impacts of only 1.44% of output at 2.5°C warming. I apply the estimated production damage share (0.74) back to the DICE aggregate damage estimates to maintain comparability.

(e.g., Jones, Manuelli, and Rossi, 1993):^{29,30}

$$U(c_t, l_t, T_t) = \frac{[c_t \cdot (1 - \varsigma l_t)^\gamma]^{1-\sigma}}{1-\sigma} + \frac{(1 + \alpha_0 T_t^2)^{-(1-\sigma)}}{1-\sigma} \quad (41)$$

The formulation of preferences over climate change in (41) ensures that the temperature risk aversion coefficient (Weitzman, 2010) is the same for utility damages and equivalent consumption losses. The parameter α_0 is set so that the aggregate global consumption loss-equivalent of disutility from climate change at $2.5^\circ C$ equals 0.46% of output as per (39). The Appendix provides further details of this calibration, and the parameters are summarized in Table 3.

4.4 Production

Production of the final consumption-investment good is modeled as:

$$\widetilde{F}_1(K_{1t}, L_{1t}, E_t) = K_{1t}^\alpha L_{1t}^{1-\alpha-v} E_t^v \quad (42)$$

with expenditure shares $\alpha = 0.3$ and $v = 0.03$, following GHKT (2014).³¹ Projections of production growth are taken from DICE (2010) and listed in the Online Appendix.

The energy sector produces both fossil fuel-based and clean (zero-emissions) energy. Both are perfectly substitutable in final goods production, but clean energy production entails an additional cost. Both types of energy are produced with a Cobb-Douglas technology:

$$E_t = A_{2t}(K_{2t}^{1-\alpha_E} L_{2t}^{\alpha_E}) \quad (43)$$

Paired with the assumption of perfect competition, formulation (43) permits inferring the output elasticity α_E from observed expenditure shares. Using U.S. Bureau of Economic Analysis data, I estimate a labor share in the energy sector of $\alpha_E = 0.403$ (see Online Appendix). Next, the calibration of the clean energy production premium $\Theta_t(\mu_t E_t)$ converts the DICE model's abatement cost estimates into a per-ton cost measure through a logistic approximation:

$$\Theta_t(\mu_t E_t) = \frac{\bar{a} P_t^{backstop}}{1 + a_t \exp(b_{0t} - b_{1t}(\mu_t E_t))^{b_2}} \cdot (\mu_t E_t) \quad (44)$$

²⁹ Specification (41) adds ς as an additional degree of freedom to calibrate to the desired moments. It is easy to show that (41) is consistent with balanced growth at the desired parameters (see Barrage, 2014).

³⁰ While (41) does not deliver the same unambiguous theoretical prediction of zero capital income taxes for all periods $t \geq 1$ as (21)-(22), quantitatively, the optimal policy path is almost identical (see Online Appendix 'Calibration Details'). Theoretically, it is moreover easy to show that labor supply convergence to a steady level is a sufficient condition for (41) to yield the same theoretical results as (21)-(22) thereafter.

³¹ While the Cobb-Douglas specification has been shown to be a poor representation of energy input use in the short-run, in the long run, a unit elasticity appears plausible (Hassler, Krusell, and Olovsson, 2012).

Here, $P_t^{backstop}$ denotes the backstop technology price in year t , taken directly from DICE, and the remaining parameters are estimated to minimize the sum of squared errors of abatement costs implied by (44) versus DICE (see Online Appendix for details).

4.5 Government

The COMET distinguishes government spending on consumption G_t^C and social transfers G_t^T (e.g., disability insurance), line with other quantitative Ramsey tax models (Jones, Manuelli, and Rossi, 1997, 1993; Lucas, 1990). Expenditures are calibrated based on IMF Government Finance Statistics for all available countries in the model base year (2005).³² The data yield the following PPP-adjusted GDP-weighted expenditure breakdown:

	% of GDP	% of Government Spending
Government Consumption	17.75	57
Social Benefits	13.32	43
Total	31.07	

Data sources: IMF Government Finance Statistics, IMF International Financial Statistics.

Table 2: Government Expenditure Shares (2005)

The *level* of total public spending is thus set to 31.07% of base decade GDP, and assumed to grow at the rates of labor productivity and population growth, in line with prior studies (Goulder, 1995; Jones, Manuelli, and Rossi, 1993). The spending shares allocated to government consumption and transfers remain at 57% and 43%, respectively.

Lastly, the model requires a specification of baseline taxes. From the literature estimating effective tax rates, I obtain one or more tax wedge estimates for 107 countries (see Online Appendix), yielding the following base year GDP-weighted average rates:

Effective Capital Tax (τ_k)	33.40%
Effective Labor Tax	28.10%
Effective Consumption Tax	11.11%
\Rightarrow Labor-Consumption Tax (τ_l)	36.09%

While I adopt these values to calibrate initial tax rates (i.e., $\tau_{k,2015} = 0.3340$), they are insufficient to meet projected government revenue requirements going forward. The forward-looking business as usual tax rates are thus calibrated at slightly higher and mutually consistent values of $\overline{\tau}_l = 38.25\%$ and $\overline{\tau}_k = 34.57\%$ (see Table 4).

³² The countries in the data account for 71% of world GDP (in 2005 PPP-adjusted dollars) in 2005.

4.6 Summary

Table 3 summarizes the key parameters and calibration strategies. It is important to reiterate that the re-calibration of utility parameters between the first-best and distortionary settings serves to make the model runs *more* comparable (by rationalizing the same baseline labor supply in the two settings). While it might appear from the climate disutility parameters (α_0) that this re-calibration biases the optimal carbon tax downward in the distortionary setting, the opposite is true: Without re-calibration, first-best labor supply and thus output would be 16% higher, leading to a correspondingly higher first-best carbon tax (see Online Appendix ‘Additional Sensitivity’). Re-calibration thus mitigates the effect of distortionary taxes on carbon prices.

5 Quantitative Results

This section first presents optimal policy and welfare for a set of benchmark model runs comparing outcomes across fiscal scenarios. Second, this section presents a decomposition of the drivers of optimal climate policy change across scenarios. Sensitivity is discussed in Section 6.

5.1 Quantitative Results: Summary

Table 4 summarizes the main results for the following COMET runs:

1. A ‘*business as usual*’ (BAU) scenario with no carbon tax throughout the twenty-first century.³³ Variant (1a) holds labor income taxes fixed at $\bar{\tau}_l = 38.25\%$ (as in (31)) and adjusts the capital income tax to meet the government budget constraint. Variant (1b) holds capital income taxes fixed at $\bar{\tau}_k = 34.57\%$ (as in (34)) and adjusts the labor tax. Income taxes are moreover restricted to remain constant over time.
2. An *income tax reform* scenario where capital and labor taxes are fully optimized but there are no carbon taxes in the twenty-first century. This scenario measures the welfare gains from conventional tax reform (as in, e.g., Lucas, 1990).
3. A *green tax reform* scenario which adds "wrong" *first-best* carbon taxes to the BAU scenarios (1). Variant (3a) again holds labor taxes at $\bar{\tau}_l = 38.25\%$ and thus uses carbon tax revenues to reduce the capital income tax. Variant (3b) holds capital income taxes at $\bar{\tau}_k = 34.57\%$ and recycles revenues to reduce the labor income tax. These scenarios measure the welfare gains from environmental tax reform with the "wrong" carbon tax.

³³ I permit carbon taxes as of 2115 in all scenarios in order to avoid estimating welfare effects of climate change well in excess of $4^\circ C$, as would occur without carbon taxes. This is done because the smooth damage function employed does not reflect discontinuities that may occur at high temperature change.

Parameter	Value	Sources and Notes
Preferences: $U(c_t, l_t, T_t) = \frac{[c_t \cdot (1-\zeta l_t)^\gamma]^{1-\sigma}}{1-\sigma} + \frac{(1+\alpha_0 T_t^2)^{-(1-\sigma)}}{1-\sigma}$		
σ	1.5	Nordhaus (2010)
β	$(.985)^{10}$	Nordhaus (2010)
ζ	$\begin{cases} 2.2381 & \text{if distortionary} \\ 2.0785 & \text{if first-best} \end{cases}$	Jointly match Frisch elasticity (0.78) and rationalize base labor supply ($l_{2005} = .2272$) at base year marginal product of labor w_{2005} with $\tau_{l,2005} = 0.3609$ or $\tau_{l,2005} = 0$, resp.
γ	$\begin{cases} 0.7178 & \text{if distortionary} \\ 1.2985 & \text{if first-best} \end{cases}$	
α_0	$\begin{cases} .00023808 & \text{if distortionary} \\ .00027942 & \text{if first-best} \end{cases}$	Match disutility from $2.5^\circ C$ warming equiv. to 0.46% output loss given the relevant ζ, γ
Production Damages: $(1 - D_t(T_t)) = \frac{1}{1+\theta_1 T_t^2}$		
θ_1	0.0021	Match 1.29% output loss from $2.5^\circ C$ warming
Final Goods Production: $F_1(A_{1t}, T_t, L_{1t}, K_{1t}, E_t) = (1 - D_t(T_t)) A_{1t} (K_{1t}^\alpha L_{1t}^{1-\alpha-v} E_t^v)$		
α	0.3	GHKT (2014)
v	0.03	GHKT (2014)
δ	0.6513	Match annual $\delta^{Yr} = 10\%$ (in % per decade)
Energy Good Production: $E_t = A_{2t} (K_{2t}^{1-\alpha_E} L_{2t}^{\alpha_E})$		
α_E	0.403	U.S. Bureau of Economic Analysis Data (2000-10)
Abatement Costs: $\Theta_t(\mu_t E_t) = \frac{\bar{a} P_t^{backstop}}{1+a_t \exp(b_{0t}-b_{1t}(\mu_t E_t)^{b_2})} \cdot (\mu_t E_t)$ for $t \leq 2250$, = 0 afterwards		
\bar{a}	0.9245	Minimize sum of squared errors in difference to DICE abatement costs
a_t	$= 49.9096 + 1.0995 \log(t)$	
b_{0t}	$= 15.5724 + 3.4648 \log(t)$	
b_{1t}	$= 13.0210 + 1.5725 \log(t)$	
$P_t^{backstop}$	$= 0.63(1 + \exp(-0.05 \cdot t))$	Nordhaus (2010), \$1000/mtC (\$2005)
Government:		
$\tau_{l,2005}$	$\begin{cases} 36.09\% & \text{if distortionary} \\ 0\% & \text{if first-best} \end{cases}$	GDP-weighted global avg. effective rate
$\tau_{k,2015}$	$\begin{cases} 33.4\% & \text{if distortionary} \\ 0\% & \text{if first-best} \end{cases}$	GDP-weighted global avg. effective rate
G_{2005}^C	98.395 \$trillion	$= (.331)(.57)(GDP_{2005}^{World} \cdot 10)$ (\$2005)
G_{2005}^T	73.713 \$trillion	$= (.331)(.43)(GDP_{2005}^{World} \cdot 10)$ (\$2005)
B_0	34.659 \$trillion	$= (.6263)(GDP_{2005}^{World})$ (\$2005), World Bank WDI
See Online Appendix for full parameter listing and further details.		

Table 3: Summary of Key Calibration Parameters

Fiscal Scenario		Carbon Tax τ_{Et}^*				T_t		$\Delta \text{Welfare}^2$			
Labor	Capital	Carbon & Energy	τ_l^*	τ_k^*	MCF	2015	2025	%Adjust. ¹ from FB (6)	max	ΔC_{2015} (\$tril.)	$\% \Delta C_t \forall t$
Variable	$\bar{\tau}_k=34.6\%$	None (until 2115) ³	38.3%	avg. 2025-2255		\$/mtC	0	0	4.31	-	-
1a.	Variable	None (until 2115) ³	38.3%		1.06	0	0		4.31	-	-
1b.	$\bar{\tau}_l=38.3\%$	Variable		34.3%	1.43	0	0		4.30	\$0.05	0.00%
2.	Optimized	None (until 2115)	42.1%	2.8% ⁴	1.06	0	0		4.31	\$22.42	0.82%
3a.	$\bar{\tau}_l=38.3\%$	Variable		31.9%	1.37	71	105		2.78	\$24.88	0.90%
4a.	Variable	Optimized ⁵		31.1%	1.35	49	77	-24%	3.03	\$26.21	0.95%
3b.	Variable	'Wrong' (First-Best)	37.9%		1.05	71	105		2.82	\$21.27	0.78%
4b.	Variable	Optimized ⁶	37.9%		1.06	58	91	-11%	3.01	\$22.03	0.80%
5.	Optimized		41.9%	2.8%	1.06	58	92	-8%	3.00	\$45.77	1.63%
6.	First-Best		0	0	1.00	71	105	-	2.97	\$96.81 ⁷	3.25%

Table 4: Main Results

¹Average adjustment of optimal vs. first-best carbon tax during twenty-first century.
²Relative to BAU scenario (1a). Equivalent variation change in aggregate initial consumption ΔC_{2015} or permanent change in consumption $\% \Delta C_t \forall t$.
³Carbon taxes are allowed after 2115 so as to keep the analysis in an appropriate range for the (smooth) damage function.
⁴Consists of high initial tax followed by $\sim 0\%$ tax (see Online Appendix for graph of τ_{kt}^* over time).
⁵Includes non-zero intermediate input tax on clean and dirty energy ($\tau_I^* = \$35/\text{mtC}$ -eq in 2025). See Online Appendix for derivation and alt. results with $\bar{\tau}_l=0$.
⁶Includes non-zero intermediate input tax on clean and dirty energy ($\tau_I^* = \$3/\text{mtC}$ -eq in 2025). See Online Appendix for derivation and alt. results with $\bar{\tau}_l=0$.
⁷Calculation uses utility parameters from second-best model to compare both first- and second-best allocations. However, these are not strictly comparable as leisure preferences are actually calibrated to $\tau_{l0}=0$ in the first-best but $\tau_{l0}=36.09\%$ in the second-best.

4. An *optimized green tax reform* scenario which is identical to (3) except that carbon and energy taxes are optimized. The differences in welfare between (4) and (3) reflect the value of adjusting environmental policy to the fiscal setting. Variant (4a) again holds labor taxes at $\bar{\tau}_l = 38.25\%$, whereas variant (4b) holds capital income taxes at $\bar{\tau}_k = 34.57\%$.
5. A *fully optimized* scenario that optimizes all taxes.
6. A *first-best* scenario with lump-sum taxation and optimized climate policy.

Several findings emerge from Table 4. First, optimal carbon levies are consistently lower when there are distortionary taxes. Figure 1 displays carbon tax schedules from the optimized climate policy scenarios for the twenty-first century. Throughout the century, optimal carbon taxes are

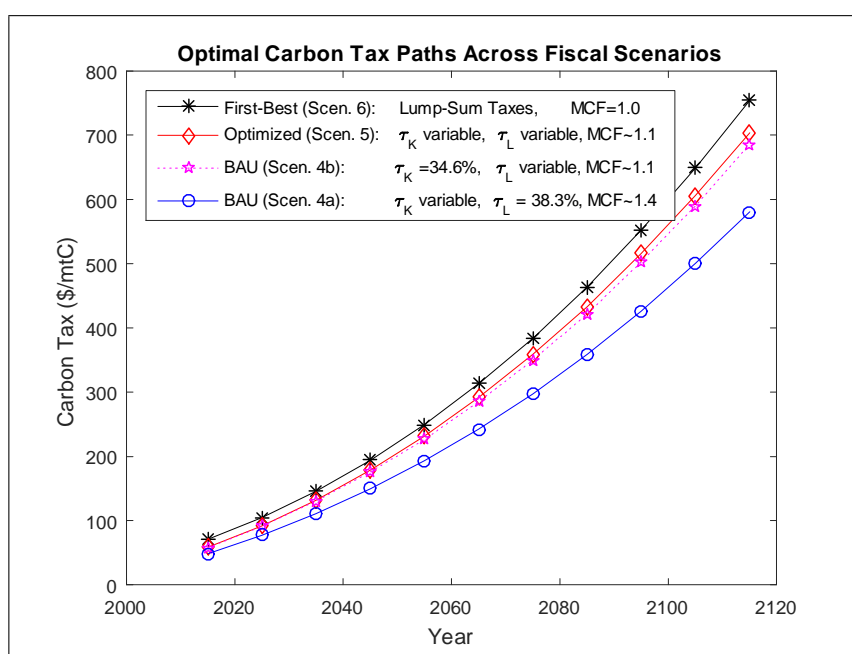


Figure 1

8-24% lower when levied alongside distortionary taxes, depending on the scenario. The reasons for these change are analyzed below.

The second main result is that a carbon tax yields much larger efficiency gains if its revenues are used to reduce capital income taxes (\$26 trillion initial or 0.95% permanent consumption increase) than labor income tax rates (\$22 trillion or 0.80%). Intuitively, this is because capital income taxes have a much higher marginal cost of funds than labor income taxes. Consequently, offsetting the former creates larger efficiency gains than the latter. This finding is firmly in line with previous studies such as Goulder (1995), who finds that the non-environmental welfare costs of carbon taxes in the U.S. economy are lower with capital- rather than personal labor income tax revenue recycling (see also Jorgenson et al., 2013).

The third result is that adjusting carbon taxes to the fiscal setting can create large welfare improvements. I compare the efficiency gains from imposing optimized carbon prices in the BAU income tax scenarios (4a and 4b) to those from carbon levies estimated in a model that abstracts from distortionary taxes, corresponding to common practice (runs 3a and 3b). The *additional* welfare gains from adjusting climate policy to the fiscal setting ranges from \$760 billion to \$1.33 trillion. While these efficiency gains are large, they are modest compared to the overall potential welfare gains of adopting carbon taxes in the twenty-first century (\$21-\$26 trillion or a 0.78%-0.95% permanent consumption increase). Within the context of the model, adopting a carbon tax thus yields efficiency gains that are at least as large as those from an idealized global Ramsey income tax reform that would optimally phase out all capital income taxes (\$22 trillion or 0.82%).³⁴ These results again highlight that a global *failure* to price carbon appropriately creates extremely costly (intertemporal) distortions.

5.2 Quantitative Results: Decomposition

The changes in optimal carbon taxes in the presence of distortionary fiscal policy are broadly driven by two factors. On the one hand, the size of the economy is smaller. As a result, the social cost of carbon - and hence the Pigouvian tax - are lower. On the other hand, if there are distortionary taxes, the optimal carbon price differs from the Pigouvian levy, as demonstrated in Section 3. Figure 2 illustrates both effects separately using model scenario (4a) as an example. In the first-best setting, the optimal carbon price τ_{Et}^* equals the Pigouvian levy (black lines with stars). In contrast, distortionary taxes not only lower the Pigouvian rate (blue dotted line with circles), but push the optimal carbon price below this value (solid blue line with circles).

The difference between the optimal and Pigouvian carbon price can be understood through Proposition 2 and Corollaries 1 and 2. First, the optimal carbon tax does not fully internalize utility damages, effectively discounting them by the MCF. Second, in the fiscal BAU scenarios (4a and 4b), the government may discount future production losses at a different rate than households due to intertemporal distortions. In addition, the government adjusts carbon taxes to account for interactions between climate policy and the relevant fiscal constraints, as shown in Corollaries 1 and 2. Table 5 decomposes these effects for carbon prices in 2025.

³⁴ Estimating the efficiency costs of capital income taxes in a global aggregate model with a single type of physical capital is, of course, a gross approximation. However, the estimated 0.82% welfare gain compares favorably with Lucas' (1990) estimates for the U.S. economy (0.75% to 1.25%).

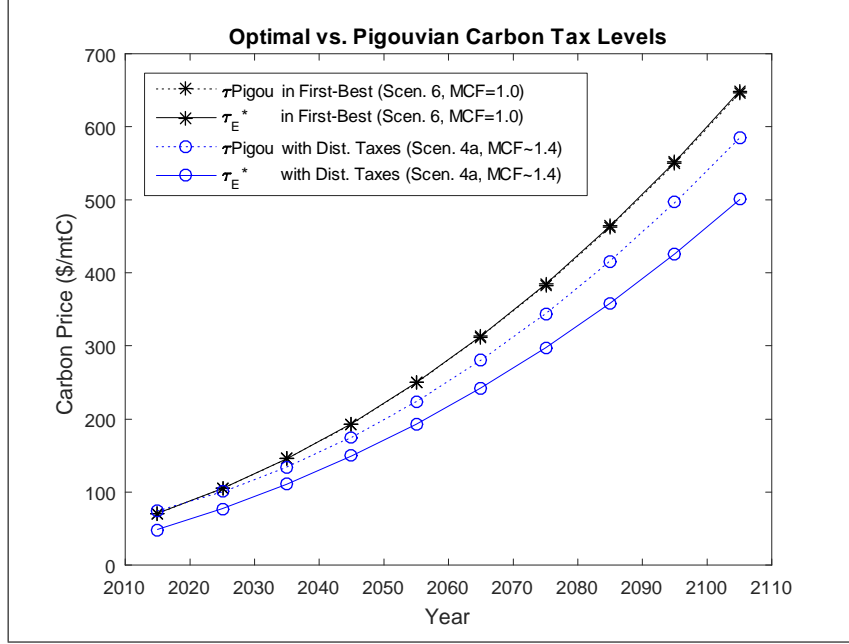


Figure 2

Scenario 4b [†] : Variable Labor Tax, Fixed Capital Income Tax $\bar{\tau}_k=34.57\%$ (MCF ~ 1.1)				
	Utility Damages	Production Damages	Fiscal Constraint Interactions	Total
τ_{Et}^{Pigou}	$\sum \beta^j \frac{U_{Tt+j}}{U_{ct}}$	$\sum \beta^j \frac{U_{ct+j}}{U_{ct}} F_{Tt+j}$		
	\$22	\$82		\$104
τ_{Et}^*	$\sum \beta^j \frac{U_{Tt+j}}{U_{ct}} \frac{1}{MCF_t}$	$\sum \beta^j \frac{\lambda_{1t+j}}{\lambda_{1t}} F_{Tt+j}$	$\sum \beta^j \frac{\Psi_{t-1+j}}{\lambda_{1t}} \frac{1}{\beta} \frac{\partial F_{1kt+j}}{\partial T_{t+j}} (1 - \bar{\tau}_k)$	
	\$18	\$69	\$5	\$92
Scenario 4a [†] : Fixed Labor Tax $\bar{\tau}_l=38.25\%$, Variable Capital Income Tax (MCF ~ 1.3)				
	Utility Damages	Production Damages	Fiscal Constraint Interactions	Total
τ_{Et}^{Pigou}	$\sum \beta^j \frac{U_{Tt+j}}{U_{ct}}$	$\sum \beta^j \frac{U_{ct+j}}{U_{ct}} F_{Tt+j}$		
	\$19	\$73		\$93
τ_{Et}^*	$\sum \beta^j \frac{U_{Tt+j}}{U_{ct}} \frac{1}{MCF_t}$	$\sum \beta^j \frac{\lambda_{1t+j}}{\lambda_{1t}} F_{Tt+j}$	$\sum \beta^j \frac{\lambda_{t+j}}{\lambda_{1t}} \frac{\partial F_{1lt+j}}{\partial T_{t+j}} (1 - \bar{\tau}_l)$	
	\$15	\$71	-\$6	\$80
[†] Differs from 4a,b in Table 4 in allowing variable tax rate to change over time (to match Corollaries 1 & 2 exactly).				

Table 5: Optimal vs. Pigouvian Carbon Tax Decomposition (2025)

The results in Table 5 show that all three factors alter the optimal carbon price relative to the Pigouvian levy. Importantly, however, these effects also change over time, as shown in Figure 3. Perhaps surprisingly, the optimal carbon price in the scenario with fixed capital income taxes (4b, pink line with hexagrams) rises slightly above the Pigouvian level by mid-century. Intuitively,

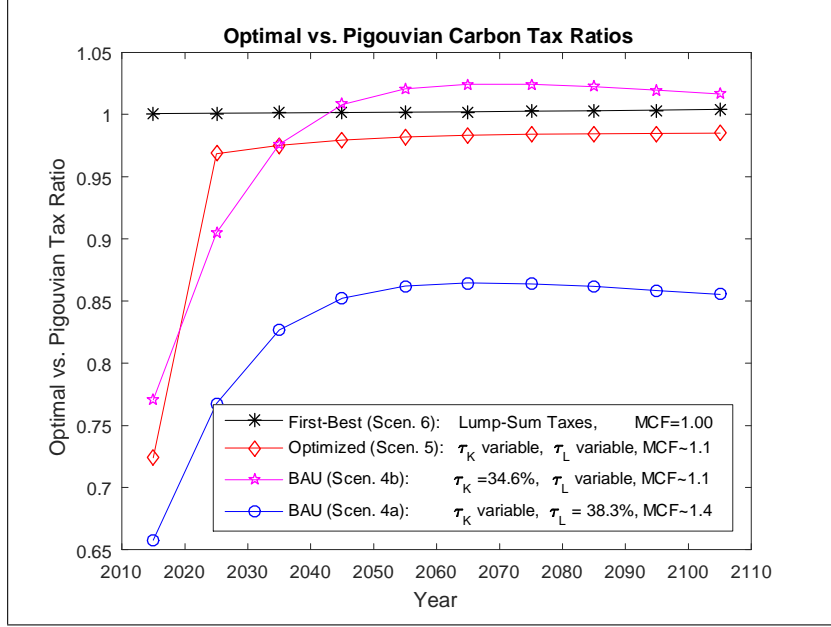


Figure 3

the capital income tax constraint gives the planner an additional reason to tax carbon (above and beyond direct utility and production damages) due to climate change impacts on the marginal returns to capital. While an analogous interaction occurs with the marginal product of labor in the scenario with a labor tax constraint (4a), the government values this interaction differently because the constraint is downwardly binding (i.e., $\Lambda_t < 0$). These results suggest that the optimal carbon tax is higher if the government is restricted to use its revenues to reduce labor income taxes (4b). While this result may be considered surprising in light of the literature, previous CGE studies have typically focused on welfare comparisons across revenue recycling scenarios for a given range of carbon prices. In this dimension, the results here agree that the efficiency gains from capital income tax reductions are highest. The difference thus arises for two reasons: First, the COMET solves an optimization problem for the (constrained)-optimal carbon price in each setting. Second, as the CGE literature has focused on utility damages, adjustments in the optimal carbon price would be limited to the first column in Table 5. That is, changes in marginal products and the output damage valuation over time would not arise in frameworks abstracting from production impacts.

As a final quantitative assessment of the importance of differentiating climate change impacts on production and utility, Figure 4 depicts the ratio of the optimal carbon price relative to the Pigouvian levy (in 2025) across different shares of production damages.

In line with Proposition 2, the results suggest that, for a given fiscal scenario (MCF), the optimal carbon tax is increasing in the share of climate damages affecting production. Depending

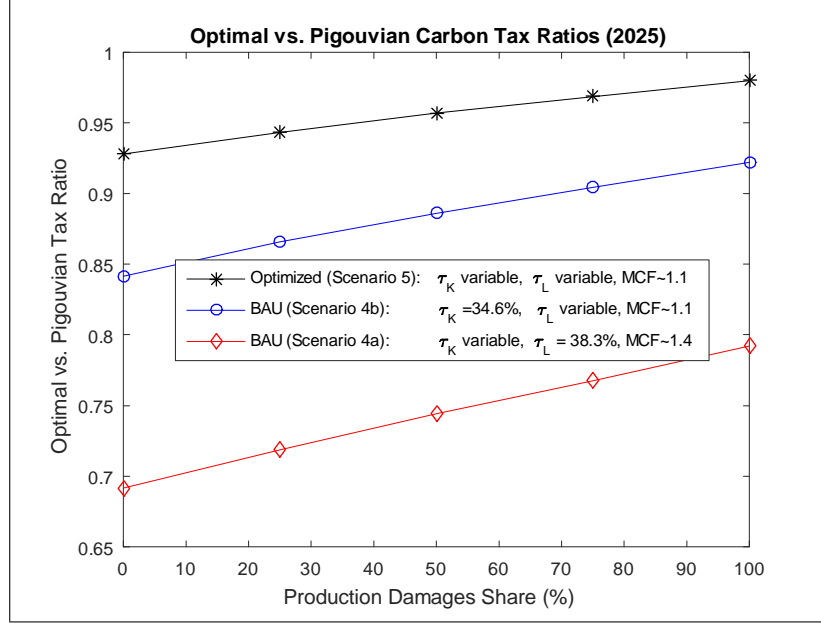


Figure 4

on the scenario, the optimal carbon price is between 7-30% below the Pigouvian levy if climate change affects only utility, but only 2-20% lower with full production damages. Compared to the estimated production damages share of 74%, abstracting from these impacts thus leads to an underestimate of the optimal carbon price.

6 Sensitivity and Extensions

6.1 Sensitivity Analysis

This section presents a sensitivity analysis for the model's key parameters. First, the Frisch elasticity of labor supply is changed from the benchmark 0.78 - a central estimate from the micro literature - to a value of 2, closer to standard estimates from the macro literature (Chetty et al., 2011). Next, the consumption elasticity is varied from its benchmark $\sigma = 1.5$ to both a higher (2) and lower (1.1) value. Finally, a permanent 10% increase and decrease in government spending are considered. The Online Appendix provides additional results for (i) variation in abatement costs, (ii) scenarios that prohibit intermediate goods taxation (i.e., $\bar{\tau}_I = 0$), and (iii) scenarios that allow the planner to vary capital and labor taxes *over time* in the fiscal BAU scenarios (as in Table 5), rather than holding them constant as in the benchmark.

In the exercises presented below, it should be noted that several model parameters adjust automatically to the modeled changes. For example, the leisure preference parameters are calibrated to rationalize base year labor supply at initial consumption, wages, and taxes, so that

a change in the consumption elasticity will also change these values. These dependencies are summarized in Table 3. In addition, I also adjust the ‘business as usual’ tax rates in order to meet the government revenue requirement at mutually consistent rates with the new parameters. Table 6 summarizes optimal policy, and Table 7 presents the welfare results.

To summarize, the sensitivity analysis continues to find that the optimal carbon tax should be decreased by 3-36% to account for a distortionary fiscal environment, in line with the main results. In the case with 10% higher government spending, adjusting carbon taxes to the fiscal setting can double the welfare gains associated with adding carbon levies to the tax code, from around \$11 trillion to \$20 trillion. By the same token, this importance and the magnitude of adjustments are diminished in the scenario with 10% lower government spending. While the overall magnitudes of climate policy adjustments and associated welfare gains thus clearly depend on the fiscal outlook, the potential importance of these interactions is robust to the variation in the parameters considered.

6.2 Heterogeneity Across Countries

The benchmark model considers a planner searching for a uniform optimal global carbon tax. In reality, countries have different tax codes, raising the question of whether a uniform carbon price provides a useful benchmark. This section derives two individually sufficient conditions for a uniform global carbon price to remain optimal in a multi-country setting: (i) If countries can make transfers to one another, or (ii) if welfare weights are set appropriately. d’Autume, Schubert and Withagen (2016) identify these same conditions in a static multi-country endowment economy with dirty and clean consumption goods and distortionary taxes to finance public goods. This section thus extends their result to a dynamic production economy with factor taxation. I then also characterize optimal country-specific carbon levies in a setting without transfers or trade and with arbitrary welfare weights. Overall, the climate policy implications of tax code heterogeneity are shown to be the same as those of cross-country heterogeneity in incomes. That is, the same assumptions that render uniform carbon taxes desirable in the standard setting (Nordhaus and Yang, 1996; Chichilnisky and Heal, 1994; Sandmo, 2007) will do so here as well.

6.2.1 Case 1: Transfers Across Countries Are Possible

The assumption that countries can make transfers to each other, but cannot impose lump-sum taxes on their citizens, may seem asymmetrical, but arguably matches reality. For example, in 2014, the United States disbursed \$41 billion (\$2014) in foreign aid to 190 countries, including through *direct cash transfers to foreign governments* (USAID, 2016). In contrast, historical

		τ_l^*	τ_k^*	MCF	Carbon Tax τ_{Et}^*			T_t max
					2015 \$/mtC	2025 \$/mtC	%Adjustment from FB (6.)	
Frisch elasticity = 2								
6.	First-Best	0	0	1	71	104	-	2.97
5.	Optimized Distortionary	43.7%	4.2%	1.13	53	85	-15%	3.04
4a	BAU Labor tax $\overline{\tau_l}$ =39%		40.9%	1.75	40	66	-36%	3.11
4b	BAU Capital tax $\overline{\tau_k}$ =40.9%	39.2%		1.19	50	82	-20%	3.06
Consumption elasticity: $\sigma = 2$								
6.	First-Best	0	0	1	49	71	-	3.16
5.	Optimized Distortionary	45.5%	3.9%	1.02	38	59	-14%	3.2
4a	BAU Labor tax $\overline{\tau_l}$ =40.75%		39.4%	1.4	30	47	-34%	3.20
4b	BAU Capital tax $\overline{\tau_k}$ =39.4%	40.9%		1.03	36	58	-18%	3.20
Consumption elasticity $\sigma = 1.1$								
6.	First-Best	0	0	1	104	151	-	2.69
5.	Optimized Distortionary	38.9%	2.0%	1.06	90	139	-5%	2.71
4a	BAU Labor tax $\overline{\tau_l}$ =35%		33.2%	1.45	73	113	-23%	2.75
4b	BAU Capital tax $\overline{\tau_k}$ =33.2%	35.2%		1.06	90	138	-6%	2.71
Government Spending -10%								
6.	First-Best	0	0	1	72	106	-	2.95
5.	Optimized Distortionary	35.9%	2.1%	1.04	64	99	-3%	2.96
4a	BAU Labor tax $\overline{\tau_l}$ =32%		29.6%	1.30	53	84	-19%	2.97
4b	BAU Capital tax $\overline{\tau_k}$ =29.6%	32.2%		1.03	63	99	-4%	2.97
Government Spending +10%								
6.	First-Best	0	0	1	70	103	-	3.00
5.	Optimized Distortionary	49%	3.8%	1.10	52	83	-16%	3.05
4a	BAU Labor tax $\overline{\tau_l}$ =45%		38%	1.64	41	66	-35%	3.13
4b	BAU Capital tax $\overline{\tau_k}$ =38%	45.2%		1.13	51	81	-19%	3.07
All figures represent average of 2015-2115 values unless noted otherwise.								

Table 6: Sensitivity Analysis - Policy

	Tax Scenario			Δ Welfare	
	Labor	Capital	Carbon & Energy	ΔC_{2015} (\$tril.)	$\% \Delta C_t \forall t$
Frisch elasticity = 2					
1a.	39.6%	$\bar{\tau}_k=40.9\%$	None (until 2115)	-	-
3b.	39.3%	$\bar{\tau}_k=40.9\%$	'Wrong' (First-Best)	\$19.3	0.72%
4b.	39.2%	$\bar{\tau}_k=40.9\%$	Optimized	\$22.4	0.83%
3a.	$\bar{\tau}_l=39\%$	42.4%	'Wrong' (First-Best)	\$15.1	0.57%
4a.	$\bar{\tau}_l=39\%$	40.9%	Optimized	\$21.4	0.79%
5.	Optimized			\$72.6	2.54%
Consumption elasticity: $\sigma = 2$					
1a.	41.2%	$\bar{\tau}_k=39.4\%$	None (until 2115)	-	-
3b.	40.9%	$\bar{\tau}_k=39.4\%$	'Wrong' (First-Best)	\$9.0	0.43%
4b.	40.9%	$\bar{\tau}_k=39.4\%$	Optimized	\$10.1	0.48%
3a.	$\bar{\tau}_l=40.75\%$	40.2%	'Wrong' (First-Best)	\$7.6	0.36%
4a.	$\bar{\tau}_l=40.75\%$	39.4%	Optimized	\$9.5	0.45%
5.	Optimized			\$37.4	1.71%
Consumption elasticity: $\sigma = 1.1$					
1a.	35.7%	$\bar{\tau}_k=33.2\%$	None (until 2115)	-	-
3b.	35.2%	$\bar{\tau}_k=33.2\%$	'Wrong' (First-Best)	\$44.6	1.17%
4b.	35.2%	$\bar{\tau}_k=33.2\%$	Optimized	\$45.5	1.19%
3a.	$\bar{\tau}_l=35\%$	34.6%	'Wrong' (First-Best)	\$39.5	1.04%
4a.	$\bar{\tau}_l=35\%$	33.2	Optimized	\$44.2	1.16%
5.	Optimized			\$73.9	1.89%
Government Spending -10%					
1a.	32.5%	$\bar{\tau}_k=29.6\%$	None (until 2115)	-	-
3b.	32.1%	$\bar{\tau}_k=29.6\%$	'Wrong' (First-Best)	\$23.1	0.79%
4b.	32.2%	$\bar{\tau}_k=29.6\%$	Optimized	\$23.2	0.79%
3a.	$\bar{\tau}_l=32\%$	29.6%	'Wrong' (First-Best)	\$22.1	0.76%
4a.	$\bar{\tau}_l=32\%$	29.6%	Optimized	\$22.7	0.77%
5.	Optimized			\$38.5	1.29%
Government Spending +10%					
1a.	45.6%	$\bar{\tau}_k=38\%$	None (until 2115)	-	-
3b.	45.6%	$\bar{\tau}_k=38\%$	'Wrong' (First-Best)	\$11.2	0.45%
4b.	45.2%	$\bar{\tau}_k=38\%$	Optimized	\$20.8	0.83%
3a.	$\bar{\tau}_l=45\%$	40.2%	'Wrong' (First-Best)	\$11.2	0.45%
4a.	$\bar{\tau}_l=45\%$	38.2%	Optimized	\$19.6	0.79%
5.	Optimized			\$56.3	2.16%

Table 7: Sensitivity Analysis - Welfare

attempts at domestic lump-sum taxation have failed due to political resistance.³⁵ In the environmental realm, climate negotiators have created multilateral financial institutions (e.g., Green Climate Fund) to couple emissions reduction agreements with resource transfers across countries.

Assume there are N countries with the economic structure as outlined in Section 2. The representative consumer in country i has preferences over his consumption C_{it} , labor supply, L_{it} , and global temperature change T_t (separably). Letting γ_t^i denote the weight that the global planner attaches to country i 's utility at time t , he seeks to maximize:

$$\max \sum_{i=1}^N \sum_{t=0}^{\infty} \beta^t \gamma_t^i U(C_{it}, L_{it}, T_t)$$

subject to feasibility and the optimizing behavior of agents and firms. If the planner can transfer resources between countries, he effectively faces a single global resource constraint for the final consumption-investment good:

$$\sum_{i=1}^N \left\{ (1 - D^i(T_t)) A_{1it} \tilde{F}_{1i}(L_{1it}, K_{1it}, E_{it}) + (1 - \delta) K_{it} - C_{it} - G_{it}^C - K_{it+1} - \Theta_{it}(\mu_{it} E_{it}) \right\} \geq 0 \quad (45)$$

Note that (45) allows for heterogeneity in climate damages $D^i(T_t)$, production structures $A_{1it} \tilde{F}_{1i}(\cdot)$, abatement technologies Θ_{it} , and government consumption requirements $\{G_{it}^C\}_{t=0}^{\infty}$ across countries. Also note that (45) remains valid regardless of whether countries can trade the energy good, as net exports across countries sum to zero in the aggregate (see Online Appendix). Letting λ_{1t} denote the Lagrange multiplier on (45), we have the following result:

Corollary 3 *If resources can be transferred across countries, the optimal global carbon tax for $t > 0$ is uniform across countries and implicitly defined by:*

$$\tau_{Eit}^* = \tau_{Et}^* = \sum_{j=0}^{\infty} \sum_{n=1}^N \beta^j \left(\gamma_t^n \frac{(-U_{Tnt+j}/U_{cnt})}{MCF_t^n} + \frac{\lambda_{1t+j}}{\lambda_{1t}} \left(\frac{-\partial Y_{t+j}^n}{\partial T_{t+j}} \right) \right) \frac{\partial T_{t+j}}{\partial E_t^M} \quad (46)$$

Proof: See Online Appendix. Intuitively, the optimal carbon tax is uniform because marginal *aggregate* damages of emissions are uniform. That is, the planner seeks to internalize the weighted sum of marginal climate impacts across countries. From a global planner's perspective, heterogeneity in climate damages is thus irrelevant for setting country-specific carbon taxes. In contrast, the critical role of transfers here is that the planner's marginal value of resources is equated across countries. Consequently, a uniform carbon price will equate the social marginal

³⁵ For example, Margaret Thatcher's proposed poll tax was met with widespread riots. Similarly, an estimated 50% of Irish homeowners refused to pay a \$133 flat-rate property tax imposed in 2012 (Dalby, 2012).

costs of emissions reductions across countries, as desired. Comparing (46) with the benchmark optimal tax expression (20) further shows that the theoretical results on the internalization of production versus utility damages are robust to the multi-country setting.

6.2.2 Case 2: Transfers Across Countries Are Not Possible

Without cross-country transfers, it may still be possible for the marginal utility of resources to be equated across countries depending on, e.g., trade policy (Keen and Wildasin, 2004). In order to consider the strongest case against uniform carbon taxes, assume no trade and no cross-country transfers. In this setting, the planner faces N distinct national resource constraints with associated Lagrange multipliers λ_{1nt} , $n \in \{1, \dots, N\}$. Let ϕ_i denote the Lagrange multiplier on country i 's implementability constraint, and define $H_t^i \equiv U_{cit}C_{it} + U_{lit}L_{it} - U_{cit}G_{it}^T$, so that H_{ct}^i captures the effect of additional consumption on household i 's offer curves and thus the ability of the planner to decentralize an allocation in a competitive equilibrium with distortionary taxes. Further let upper bars denote averages across countries.

Corollary 4 *If resources cannot be transferred across countries, but if the global planner weights country i 's utility at time t according to:*

$$\gamma_t^i = \frac{\overline{U_{ct}} + \overline{\phi H_{ct}} - \phi_i H_{ct}^i}{U_{cit}} \quad (47)$$

then the optimal carbon tax for $t > 0$ remains uniform across countries and is defined by:

$$\tau_{Eit}^* = \tau_{Et}^* = \sum_{j=0}^{\infty} \sum_{n=1}^N \beta^j \left(\gamma_t^n \frac{(-U_{Tnt+j}/U_{cnt})}{MCF_t^n} + \frac{\lambda_{1nt+j}}{\lambda_{1nt}} \left(\frac{-\partial Y_{t+j}^n}{\partial T_{t+j}} \right) \right) \frac{\partial T_{t+j}}{\partial E_{it}^M} \quad (48)$$

Proof: See Online Appendix. Note that, in the first-best setting with domestic lump-sum taxation, the implementability constraint is non-binding ($\phi = 0$), and (47) reduces to the standard time-varying Negishi weights employed by, e.g., Nordhaus and Yang (1996). Intuitively, with equal welfare weights, a global planner would seek to make massive resource transfers to equalize the marginal utility of consumption across countries. Welfare weights (47) help ensure that the planner takes the initial global distribution of resources - and, in this case, tax distortions - as given (i.e., desirable), and focuses the planner's problem on optimal climate policy design.

Finally, the optimal *country-specific* carbon tax in a setting without transfers or trade and for arbitrary welfare weights γ_t^i is defined by:

$$\tau_{Eit} = \sum_{j=0}^{\infty} \sum_{n=0}^N \beta^j \left(\frac{MCF_t^n U_{cnt}}{MCF_t^i U_{cit}} \right) \left\{ \gamma_t^n \frac{(-U_{Tnt+j}/U_{cnt})}{MCF_t^n} + \frac{\lambda_{1nt+j}}{\lambda_{1nt}} \left(\frac{-\partial Y_{t+j}^n}{\partial T_{t+j}} \right) \right\} \frac{\partial T_{t+j}}{\partial E_{it}^M} \quad (49)$$

Formulation (49) reveals that each country pays a weighted share of the present discounted sum of global damages from carbon emissions. In particular, country i 's weight in accounting for damages in country n are inversely proportional to both its marginal utility of consumption U_{cit} and its marginal cost of public funds MCF_t^i : Countries that are poorer and/or have a more distortionary tax code should pay lower carbon taxes, *ceteris paribus*. While this potential climate policy implication of differing marginal utilities is well-known (see, e.g., Chichilnisky and Heal, 1994; Hassler and Krusell, 2012) expression (49) formally extends this general insight to a dynamic setting with distortionary taxes and variation in the MCF across countries.³⁶

Overall, this section has shown that the optimal carbon tax is uniform across countries with heterogeneous tax codes under assumptions that are plausible and/or in line with the literature solving for global carbon taxes as a benchmark (GHKT, 2014; Nordhaus, 2008, etc.).

6.3 Limited Commitment

The analysis assumes that the government can commit to a sequence of tax rates at time zero. While this assumption is common in the Ramsey taxation literature and has been motivated on grounds such as reputational mechanisms, it is not innocuous. Both optimal tax policy and public expenditures have been shown to be highly sensitive to the planner's assumed commitment horizon (e.g., Klein and Rios-Rull, 2003). Schmitt (2014) thus analyzes the no-commitment case for jointly optimal carbon and income taxation.³⁷ The direct interactions of climate policy with pre-distorted factor markets (for labor and savings) remain at the core of second-best carbon tax design with limited commitment. Qualitatively, Schmitt (2014) finds that this setting changes the structure of some of these effects. For example, consider an increase in the carbon tax at time t that reduces contemporaneous labor supply but increases labor supply in the preceding periods ($t-1$, $t-2$, etc.). A Ramsey planner who can set taxes at time zero will take this benefit into account, whereas a government without a commitment technology will not.³⁸ The net effect of these changes is theoretically ambiguous. Quantitatively, however, Schmitt (2014) finds that relaxing the commitment assumption has very small overall effects. For baseline optimal carbon taxes in the year 2010, he finds a first-best tax of \$89/mtC, a second-best tax of \$77/mtC with commitment, and a second-best tax of \$78/mtC without commitment in Markov-perfect equilibrium. By the end of the twenty-first century, this difference is larger but remains modest:

³⁶ A quantification of (49) in a multi-country integrated assessment model would be interesting but is beyond the scope of this study. Babiker, Metcalf, and Reilly (2003) and Bernard and Vielle (2003) provide positive quantitative analyses of the non-environmental welfare impacts of carbon taxes across countries with heterogeneous tax codes. Anthoff (2011) uses the FUND model to assess region-specific optimal carbon taxes with utilitarian welfare weights in a first-best setting.

³⁷ As noted by Schmitt (2014), his work is subsequent to this paper.

³⁸ This insight is analogous to results pertaining to optimal taxation and public expenditures by Klein, Krusell, and Rios-Rull (2008), as noted by Schmitt (2014).

Second-best carbon taxes are 36% below first-best rates without commitment, compared to 44% below first-best rates with commitment.

It is important to note that this paper’s quantitative analysis considers several scenarios with positive capital income taxes calibrated to match real world rates. While the reasons for these positive capital income taxes are not endogenized as being due to, e.g., limited commitment, Schmitt’s (2014) results indicate that the direct effect of the distortion dominates in driving the difference to first-best carbon taxes. Consequently, I focus on the (i) full commitment and (ii) exogenous observed tax rate cases as benchmark results, and leave extensions to more detailed fiscally and politically constrained environments as an interesting area for future research.

7 Conclusion

This paper studies climate policy design alongside revenue-raising distortionary taxes. It theoretically characterizes and quantifies optimal carbon levies in a dynamic general equilibrium integrated assessment model with distortionary taxes in the Ramsey tradition.

On the one hand, this paper demonstrates that governments seeking to reduce intertemporal distortions should be concerned not only with capital income tax reform, but also with climate policy. Formally, I show that if the government optimally sets capital income taxes to zero, then carbon taxes to internalize production losses from climate change should be set at Pigouvian rates, even if labor markets are distorted. Intuitively, this is because setting carbon taxes below Pigouvian levels distorts incentives to invest in the environmental capital stock, relative to the social optimum. This is analogous to capital income taxes, which distort incentives to invest in physical capital. Quantitatively, the estimated global welfare costs from *failure* to tax carbon appropriately in the twenty-first century (\$21-26 trillion, \$2005 lump-sum consumption equivalent) are estimated to be at least as large as the efficiency costs associated with capital income tax distortions (\$22 trillion, or 0.82% permanent consumption equivalent).

On the other hand, this paper showcases the importance of fiscal considerations for climate policy design. Compared to the first-best setting commonly considered in the integrated assessment literature and the policy realm, optimal carbon taxes are 8-24% lower when levied alongside distortionary taxes. Importantly, however, the results also suggest that this second-best carbon tax may not be as low as suggested by some prior studies that have focused on climate policy interactions with pre-existing taxes. Specifically, while a number of studies have used highly detailed computable general equilibrium models to study these interactions, they have also typically assumed that climate change impacts affect only utility. In contrast, this paper argues that, at the global level, the majority of climate change impacts fall on production possibilities, and estimates that abstracting from the resulting climate-economy feedback effects leads to an

underestimate of the optimal carbon tax.

As this paper presents a relatively simple representation of fiscal and climate policy, it invites several potential extensions. First, I find that optimal climate policy adjustments to the fiscal setting depend not only on the levels but also on the reasons for pre-existing tax distortions. This paper focuses on a Ramsey setting with linear taxes, an infinitely lived representative agent, and full commitment. Climate policy design under alternative fiscal frameworks giving rise to different optimal tax structures is thus an interesting area for future research. Second, this paper focuses on a deterministic setting as a natural benchmark. Climate-economy models are increasingly incorporating different kinds of uncertainty. For example, Lemoine and Traeger (2014) find that consideration of uncertainty over tipping points in the climate system increases near-term optimal carbon taxes by 25-40% (see also Lontzek et al., 2015). Some recent studies consider climate and economic uncertainty jointly, with Cai, Judd, and Lontzek (2015) showing that both factors can significantly increase optimal carbon prices. Other work has focused on climate policy and business cycles (Heutel, 2012; Fischer and Springborn, 2011). It is an open question how accounting for tax distortions would interact with these different types of uncertainty. A stochastic version of the COMET could moreover consider uncertainty in yet another dimension: fiscal fluctuations. Chari and Kehoe (1999) find that optimal labor, capital, and asset taxes vary differentially in response to fiscal shocks. It would be interesting to study the optimal response of carbon taxes to fiscal shocks, particularly in light of this paper's finding that optimal capital and carbon taxes are linked.

For many countries around the world, the fiscal outlook is gloomy. This study has argued that carbon taxes have to be designed with care to account for their potentially adverse effects on other tax bases, such as employment. At the same time, global climate change continues to accelerate, posing a fundamental threat to economic activity and human welfare. This study concludes that the imposition of appropriately designed carbon taxes could yield extremely large benefits, both in terms of raising revenues and by significantly improving intertemporal production efficiency.

A Appendix A

A.1 Proof of Proposition 2

Step 1: Derive General Optimal Tax Expressions (20)

The planner's problem is defined by Proposition 1. In particular, splitting the implementability constraint into its time zero and lifetime summation components, including the latter in the maximand, and defining the resulting function $W_t = W(C_t, L_t, T_t, \phi) \equiv U(C_t, L_t, T_t) + \phi [U_{ct}C_t + U_{lt}L_t - U_{ct}G_t^T]$, the planner's problem is given by:

$$\begin{aligned}
& \max \sum_{t=0}^{\infty} \beta^t \underbrace{[U(C_t, L_t, T_t) + \phi [U_{ct}C_t + U_{lt}L_t - U_{ct}G_t^T]]}_{\equiv W_t} & (A.1) \\
& - \phi \{U_{c0} [K_0 \{1 + (F_{k0} - \delta)(1 - \tau_{k0})\} + B_0]\} \\
& + \sum_{t=0}^{\infty} \beta^t \lambda_{1t} \left[\left\{ (1 - D(T_t)) A_{1t} \widetilde{F}_1(L_{1t}, K_{1t}, E_t) \right\} + (1 - \delta)K_t - C_t - G_t^C - K_{t+1} - \Theta_t(\mu_t E_t) \right] \\
& + \sum_{t=0}^{\infty} \beta^t \xi_t [T_t - F(\mathbf{S}_0, (1 - \mu_0)E_0, (1 - \mu_1)E_1, \dots, E_t, \boldsymbol{\eta}_0, \dots, \boldsymbol{\eta}_t)] \\
& + \sum_{t=0}^{\infty} \beta^t \lambda_{lt} [L_t - L_{1t} - L_{2t}] \\
& + \sum_{t=0}^{\infty} \beta^t \lambda_{kt} [K_t - K_{1t} - K_{2t}] \\
& + \sum_{t=0}^{\infty} \beta^t \lambda_{2t} [A_{2t} F_2(K_{2t}, L_{2t}) - E_t]
\end{aligned}$$

First, combining the planner's first-order conditions (FOCs) for energy E_t , abatement μ_t , sectoral labor supplies L_{1t} and L_{2t} , and temperature change T_t at $t > 0$ yields the following optimality conditions for energy and climate policy:

$$\begin{aligned}
F_{1Et} - \frac{F_{1lt}}{F_{2lt}} &= \Theta'_t = \frac{1}{\lambda_{1t}} \sum_{j=0}^{\infty} \beta^j \xi_{t+j} \frac{\partial T_{t+j}}{\partial E_t^M} & (A.2) \\
&= \frac{1}{\lambda_{1t}} \sum_{j=0}^{\infty} \beta^j \left[U_{T_{t+j}} + \lambda_{1t+j} \frac{\partial Y_{t+j}}{\partial T_{t+j}} \right] \frac{\partial T_{t+j}}{\partial E_t^M}
\end{aligned}$$

Intuitively, (A.2) shows that both the wedge between the marginal product of energy (F_{1Et}) and its private production cost $\left(\frac{F_{1lt}}{F_{2lt}}\right)$ and the marginal abatement cost (Θ'_t) are equated to the present value of the externality costs of carbon emissions at the optimal allocation. Energy and carbon taxes that can decentralize (A.2) follow straightforwardly from the energy producer's profit-maximizing conditions (11):

$$\begin{aligned} [p_{Et} - \tau_{It} - \tau_{Et}]F_{2lt} &= w_t \\ \tau_{Et} &= \Theta'_t \end{aligned} \quad (\text{A.3})$$

Invoking competitive equilibrium prices based on (8) and (11) and comparing the decentralized behavior of firms (A.3) with the planner's optimality condition (A.2) shows that the optimal allocation for $t > 0$ can be decentralized by policies:

$$\begin{aligned} \tau_{Et}^* &= \frac{1}{\lambda_{1t}} \sum_{j=0}^{\infty} \beta^j \left[U_{Tt+j} + \lambda_{1t+j} \frac{\partial Y_{t+j}}{\partial T_{t+j}} \right] \frac{\partial T_{t+j}}{\partial E_t^M} \\ \tau_{It}^* &= 0 \end{aligned}$$

Separating production and utility damages, multiplying the latter by U_{ct}/U_{ct} and invoking the definition of the MCF_t (16), yields the general optimal carbon tax expression (20):

$$\tau_{Et}^* = \underbrace{\sum_{j=0}^{\infty} \beta^j \left[\frac{-U_{Tt+j}}{U_{ct}} \frac{1}{MCF_t} \right] \frac{\partial T_{t+j}}{\partial E_t}}_{\text{Utility Damages}} + \underbrace{\sum_{j=0}^{\infty} \beta^j \left[\frac{-\partial Y_{t+j}}{\partial T_{t+j}} \frac{\lambda_{1t+j}}{\lambda_{1t}} \right] \frac{\partial T_{t+j}}{\partial E_t^M}}_{\text{Production Damages}} \quad (\text{A.4})$$

Next, note that the utility damages term in (A.4) already equals $\frac{\tau_{Et}^{Pigou,U}}{MCF_t}$ as per the definition of $\tau_{Et}^{Pigou,U}$ in (18). Next, the planner's optimality condition for consumption C_t for $t > 0$ yields:

$$\lambda_{1t} = W_{ct} = U_{ct} + \phi[U_{ct} + U_{cct}C_t + U_{lct}L_t - U_{cct}G_t^T]$$

For the assumed CES preferences (21), one can easily show that:

$$W_{ct} = U_{ct} \left[1 + \phi \left(1 - \sigma + \sigma \frac{G_t^T}{C_t} \right) \right]$$

Similarly, for preferences (22),

$$W_{ct} = U_{ct} \left[1 + \phi \left[1 - \sigma - \gamma(1 - \sigma) - \frac{G_t^T}{C_t} \right] \right]$$

Consequently, if government spending is fully wasteful (i.e., $G_t^T = 0$ as all government spending is consumption G_t^C), or if transfers to households constitute a constant fraction of consumption so that $\frac{G_t^T}{C_t} = \frac{G_{t+1}^T}{C_{t+1}} \forall t > 0$, for either type of preferences it is the case that:

$$\frac{\lambda_{1t}}{\lambda_{1t+1}} = \frac{W_{ct}}{W_{ct+1}} = \frac{U_{ct}}{U_{ct+1}} \quad (\text{A.5})$$

First, for the optimal carbon tax, (A.5) implies that the production damages term in (A.4) reduces to $\tau_{Et}^{Pigou,Y}$ as per the proof of Proposition 3. Finally, for the optimal capital income tax,

note that the planner's FOCs with respect to K_{t+1} and K_{1t} imply (for $t > 0$):

$$\frac{\lambda_{1t}}{\beta\lambda_{1t+1}} = F_{1kt+1} + (1 - \delta) \quad (\text{A.6})$$

Combining (A.6) with (A.5) and comparing to the household's intertemporal optimality conditions (4) then demonstrates that the optimal allocation is decentralized by a capital income tax set to zero for $t > 1$ (i.e., $\tau_{kt+1}^* = 0$ for $t > 0$).

B Appendix B

B.1 Calibration of Preferences for Climate Change

The goal of the calibration is to find a parameter α_0 such that the disutility of $2.5C^\circ$ climate change - a standard calibration point in the literature (e.g., Nordhaus, 2010) - is equivalent to the utility loss resulting from 0.46% output damages. Given the chosen preference specification (41), the total utility change from $2.5C^\circ$ warming utility damages is given by:

$$\begin{aligned} \Delta U^U &= U(T_t) - U(0^\circ) \\ &= \left[\frac{(1 + \alpha_0(2.5)^2)^{-(1-\sigma)}}{1 - \sigma} - \frac{1}{1 - \sigma} \right] \end{aligned} \quad (\text{B.1})$$

Analogously, the total utility change from a consumption loss of $D(2.5^\circ)$ can be approximated:³⁹

$$\begin{aligned} \Delta U^Y &\approx U(2.5^\circ) - U(0^\circ) \\ &= \frac{(1 - \zeta l_t)^{\gamma(1-\sigma)}}{1 - \sigma} \left[C_t^{*(1-\sigma)} (1 - D(2.5^\circ))^{1-\sigma} - C_t^{*1-\sigma} \right] \end{aligned} \quad (\text{B.2})$$

where C_t^* denotes counterfactual (of climate change) consumption. Equating (B.1) and (B.2) allows one to solve for the parameter α_0 that creates utility losses from temperature change equivalent to the desired target value $D(2.5^\circ)$. Consumption levels $C_{2.5^\circ C}$ are taken from a modified business-as-usual (BAU) run of the 2010 DICE model.⁴⁰ Labor supply $l_{2.5^\circ C}$ is set at the baseline COMET value, since the BAU scenario represents the idea of no tax reform. The benchmark COMET has $\alpha_0 = .00023808$ with distortionary taxes, and $\alpha_0 = .00027942$ without distortionary taxes. Finally, note that one can easily show that the temperature risk aversion

³⁹ Specification (B.2) is only an approximation because it ignores general equilibrium effects on labor supply and employment. However, this is intentional as utility damages are assumed to be separable and so the general equilibrium effects from a consumption change should not be included in the equivalent utility loss.

⁴⁰ Specifically, I use slightly older output damage function parameters which includes sea level rise, and modify the carbon cycle in the first period so as to reflect changes in base year emissions. Finally, consumption is adjusted downward by the base year share of government consumption in the COMET.

coefficient (Weitzman, 2010) implied by utility function (41) is given by:

$$\frac{TU_{TT}}{U_T} = \frac{1}{1 + \alpha_0 T_t^2}$$

for utility damages. Similarly, for consumption losses in (B.2) with $(1 - D(2.5^\circ)) = \frac{1}{1 + \theta_1 T_t^2}$ as assumed for production damages in (40), we one can easily derive that:

$$\frac{TU_{TT}}{U_T} = \frac{1}{1 + \theta_1 T_t^2}$$

Consequently, for a given amount of damages, the temperature risk aversion coefficient of utility damages matches that of an equivalent consumption loss (ignoring general equilibrium effects).

B.2 Computation

In order to numerically solve the planner's infinite horizon problem, I follow a similar though slightly different approach as Jones, Manuelli, and Rossi (1993), also employed in Barrage (2014b). First, I optimize over all allocations for T periods as well as over the continuation gross savings rate for period T . In the calibration, $T = 25$, representing 250 years. In contrast to studies such as Jones, Manuelli, and Rossi (1993), however, one cannot impose a balanced growth path after some terminal period T in the current setting. The reason is that full effects of carbon emissions in late periods would not be accounted for due to lags in the climate system between emissions and warming. In addition, a balanced growth path requires that the climate be in steady state, that is, that carbon concentrations have stabilized. Given the assumption that clean energy backstop technologies will become fully cost competitive by the year 2255 (Nordhaus, 2010), industrial carbon emissions will stop at the latest thereafter, allowing the climate to gradually reach a new steady state.

After the last direct optimization period $T > 2255$, I thus use the continuation gross savings rate as well as the period T labor supply and period T factor distribution across sectors (i.e., the share of capital allocated to energy and final goods production) to simulate the economy and climate for another 100 years. Finally, after this additional 100 years (in the year 2365), I assume that the economy has reached a balanced growth path and calculate the consumption continuation value based on the theoretically calculated balanced growth path savings rate, and thus compute the present value of all future utility. The optimization is performed in Matlab.

References

- [1] Acemoglu, Daron, Philippe Aghion, Leonardo Bursztyn, and David Hemous (2012) "The Environment and Directed Technical Change," *American Economic Review*, 102(1): 131-66.

- [2] Acemoglu, Daron, Mikhail Golosov, and Aleh Tsyvinski (2011) "Political economy of Ramsey taxation" *Journal of Public Economics* 95(7): 467-475.
- [3] Anthoff, David (2011) "Optimal Global Dynamic Carbon Abatement," Working paper.
- [4] Anthoff, David, and Richard S.J. Tol (2013) "The uncertainty about the social cost of carbon: A decomposition analysis using fund" *Climatic Change*, 117:515–530.
- [5] Atkeson, Andrew, V.V. Chari, and Patrick J. Kehoe (1999) "Taxing Capital Income: A Bad Idea" *Federal Reserve Bank of Minneapolis Quarterly Review*, 23(3): 3-17.
- [6] Atkin, David (2013) "Trade, tastes, and nutrition in India" *American Economic Review*, 103(5): 1629-1663.
- [7] Babiker, Mustafa H., Gilbert E. Metcalf, and John Reilly (2003) "Tax distortions and global climate policy" *Journal of Environmental Economics and Management*, 46(2): 269-287.
- [8] Barrage, Lint (2014) "Optimal Dynamic Carbon Taxes in a Climate-Economy Model with Distortionary Fiscal Policy" *Working paper*.
- [9] Barrage, Lint (2014b) "Sensitivity Analysis for Golosov, Hassler, Krusell, and Tsyvinski (2014): 'Optimal Taxes on Fossil Fuel in General Equilibrium'" Supplementary Material, *Econometrica*, 82(1): 41-88.
- [10] Bento, Antonio M., and Mark Jacobsen (2007) "Ricardian rents, environmental policy and the 'double-dividend' hypothesis" *Journal of Environmental Economics and Management*, 53(1): 17-31.
- [11] Bernard, Alain L., and Marc Vielle (2003) "Measuring the welfare cost of climate change policies: A comparative assessment based on the computable general equilibrium model GEMINI-E3" *Environmental Modeling and Assessment*, 8: 199–217.
- [12] Bleakley, Hoyt (2003) "Disease and Development: Evidence From The American South" *Journal of the European Economic Association*, 1(2/3), Papers and Proceedings of the Seventeenth Annual Congress of the European Economic Association: 376-386.
- [13] Bovenberg, Lans A., and Ruud A. de Mooij (1997) "Environmental Tax Reform and Endogenous Growth" *Journal of Public Economics*, 63: 207-237.
- [14] Bovenberg, Lans A., and Ruud A. de Mooij (1994) "Environmental Levies and Distortionary Taxation" *American Economic Review*, 94(4): 1085-1089.
- [15] Bovenberg, Lans A., and Lawrence H. Goulder (1996) "Optimal environmental taxation in the presence of other taxes: general-equilibrium analyses" *American Economic Review*, 86(4): 985-1000.
- [16] Bovenberg, Lans A., and Lawrence H. Goulder (2002) "Environmental Taxation and Regulation" Chapter 23 in: Alan J. Auerbach and Martin Feldstein (eds.) *Handbook of Public Economics*, Elsevier, Volume 3, Pages 1471-1545.

- [17] Bovenberg, Lans A., and Sjak A. Smulders (1996) "Transitional Impacts of Environmental Policy in an Endogenous Growth Model" *International Economic Review*, 37(4): 861-893.
- [18] Bovenberg, Lans A., and Frederick van der Ploeg (1994) "Environmental policy, public finance, and the labor market in a second-best world" *Journal of Public Economics*, 55: 349-390. Reprinted in Lawrence H. Goulder (ed.) (2002) *Environmental Policy Making in Economies with Prior Tax Distortions*, Edward Elgar Publishing.
- [19] Cai, Yongyang, Kenneth L. Judd, and Thomas S. Lontzek (2015) "The Social Cost of Carbon with Economic and Climate Risks" Working paper.
- [20] Carbone, Jared C., Richard D. Morgenstern, and Roberton C. Williams III (2013) "Carbon Taxes and Deficit Reduction," *RFF Report*.
- [21] Carbone, Jared C., and V. Kerry Smith (2008) "Evaluating policy interventions with general equilibrium externalities" *Journal of Public Economics*, 92: 1254-1274.
- [22] Chamley, Christophe (1986) "Optimal taxation of capital income in general equilibrium with infinite lives" *Econometrica*, 54: 607-22.
- [23] Chari, V.V., and Patrick J. Kehoe (1999) "Optimal Fiscal and Monetary Policy" *Handbook of Macroeconomics*, 1: 1671-1745.
- [24] Chetty, Raj, Adam Guren, Day Manoli, and Andrea Weber (2011) "Micro and Macro Labor Supply Elasticities Consistent? A Review of Evidence on the Intensive and Extensive Margins" *American Economic Review Papers and Proceedings*, 101(3): 471-475.
- [25] Chichilnisky, Graciela, and Geoffrey Heal (1994) "Who should abate carbon emissions?: An international viewpoint" *Economics Letters* 44(4): 443-449.
- [26] Chiroleu-Assouline, Mireillen and Mouez Fodha (2006) "Double dividend hypothesis, golden rule and welfare distribution" *Journal of Environmental Economics and Management*, 51(3): 323-335.
- [27] Cremer, Helmuth, Firouz Gahvari, and Norbert Ladoux (2010) "Environmental Tax Design with Endogenous Earning Abilities (with applications to France)" *Journal of Environmental Economics and Management*, 59: 82-93.
- [28] Cremer, Helmuth, Firouz Gahvari, and Norbert Ladoux (2001) "Second-Best Pollution Taxes and the Structure of Preferences" *Southern Economic Journal*, 68(2): 258-280.
- [29] Dalby, Douglas (2012) "Half of Irish Homeowners Join Boycott of New Property Tax" *New York Times*, April 2, 2012.
- [30] Dao, Nguyen Thang, and Ottmar Edenhofer (2018) "On the fiscal strategies of escaping poverty-environment traps towards sustainable growth" *Journal of Macroeconomics*, 55: 253-273.
- [31] d'Autume, Antoine, Katheline Schubert, and Cees Withagen (2016) "Should the carbon price be the same in all countries?" *Journal of Public Economic Theory*, pp. 1-17.

- [32] Desmet, Klaus, and Esteban Rossi-Hansberg (2015) "On the spatial economic impact of global warming" *Journal of Urban Economics*, 88: 16-37.
- [33] Fischer, Carolyn, and Michael Springborn (2011) "Emissions Targets and the Real Business Cycle: Intensity Targets versus Caps or Taxes" *Journal of Environmental Economics and Management*, 62: 352-366.
- [34] Franks, Max, Ottmar Edenhofer, and Kai Lessmann (2017) "Why finance ministers favor carbon taxes, even if they do not take climate change into account." *Environmental and Resource Economics* 68, no. 3 (2017): 445-472.
- [35] Fullerton, Don, and Seung-Rae Kim (2008) "Environmental investment and policy with distortionary taxes, and endogenous growth" *Journal of Environmental Economics and Management*, 56: 141-154.
- [36] Gerlagh, Reyer, and Matti Liski (2017) "Consistent climate policies." *Journal of the European Economic Association*: jvx010.
- [37] Golosov, Mikhail, John Hassler, Per Krusell, and Aleh Tsyvinski (2014) "Optimal taxes on fossil fuel in general equilibrium" *Econometrica*, 82:1: 41-88.
- [38] Golosov, Mikhail, Aleh Tsyvinski, and Ivan Werning (2006) "New dynamic public finance: a user's guide" *NBER Macroeconomics Annual 2006*, Volume 21. MIT Press, Cambridge, MA.
- [39] Goulder, Lawrence H. (1995) "Effects of Carbon Taxes in an Economy with Prior Tax Distortions: An Intertemporal General Equilibrium Analysis" *Journal of Environmental Economics and Management*, 29: 271-297.
- [40] Groth, Christian, and Poul Schou (2007) "Growth and non-renewable resources: The different roles of capital and resource taxes." *Journal of Environmental Economics and Management* 53, no. 1: 80-98.
- [41] Hassler, John, and Per Krusell (2012) "Economics and Climate Change: Integrated Assessment in a Multi-Region World" *Journal of the European Economic Association*, 10(5): 974-1000.
- [42] Hassler, John, Per Krusell, and Conny Olovsson (2012) "Energy-Saving Technical Change" NBER Working Paper No. 18456.
- [43] Hettich, Frank (1998) "Growth Effects of a Revenue-neutral Environmental Tax Reform" *Journal of Economics*, 67(3): 287-316.
- [44] Heutel, Garth (2012) "How should environmental policy respond to business cycles? Optimal policy under persistent productivity shocks" *Review of Economic Dynamics*, 15: 244-264.
- [45] Hope, Chris (2011) "The Social Cost of CO_2 from the PAGE09 Model" *Economics E-Journal Discussion Paper No. 2011-39*.

- [46] Hope, Chris (2006) "The Marginal Impact of CO_2 from PAGE2002: An Integrated Assessment Model Incorporating the IPCC's Five Reasons for Concern" *The Integrated Assessment Journal*, 6(1): 19-56.
- [47] IMF (2001) "Government Finance Statistics Manual 2001" International Monetary Fund. Available at: <http://www.imf.org/external/pubs/ft/gfs/manual/pdf/all.pdf> (accessed June 2012).
- [48] Interagency Working Group on Social Cost of Carbon (2010) "Social Cost of Carbon for Regulatory Impact Analysis under Executive Order 12866" United States Government. Available at: <http://www.whitehouse.gov/sites/default/files/omb/inforeg/for-agencies/Social-Cost-of-Carbon-for-RIA.pdf>
- [49] Iverson, Terrence (2014) "Optimal carbon taxes with non-constant time preference." *Working paper*.
- [50] Jones, Larry E., Rodolfo E. Manuelli, and Peter E. Rossi (1997) "On the Optimal Taxation of Capital Income" *Journal of Economic Theory*, 73: 93-117.
- [51] Jones, Larry E., Rodolfo E. Manuelli, and Peter E. Rossi (1993) "Optimal Taxation in Models of Endogenous Growth" *Journal of Political Economy*, 101(3): 485-517.
- [52] Jorgenson, Dale W., Richard J. Goettle, Brian H. Hurd, and Joel B. Smith (2004) "U.S. Market Consequences of Global Climate Change" Pew Center on Global Climate Change.
- [53] Jorgenson, Dale W., Richard J. Goettle, Mun S. Ho, and Peter J. Wilcoxon (2013) *Double Dividend*, MIT Press, Cambridge, MA.
- [54] Jorgenson, Dale W. and Peter J. Wilcoxon (1996) "Results from the Jorgenson-Wilcoxon Model Reducing US Carbon Emissions: An Econometric General Equilibrium Assessment" in Goulder, Lawrence H. (ed.) (2002) *Environmental Policy Making in Economies with Prior Tax Distortions*, Edward Elgar Publishing.
- [55] Judd, Kenneth L. (1999) "Optimal taxation and spending in general competitive growth models" *Journal of Public Economics*, 71: 1-26.
- [56] Judd, Kenneth L. (1985) "Redistributive taxation in a simple perfect foresight model" *Journal of Public Economics*, 28:59-83.
- [57] Kaplow, Louis (2012) "Optimal Control of Externalities in the Presence of Income Taxation" *International Economic Review*, 53(2): 487-509.
- [58] Keen, Michael, and David Wildasin (2004) "Pareto-efficient international taxation" *American Economic Review*, 94(1): 259-275.
- [59] King, Robert G., Charles I. Plosser, and Sergio T. Rebelo (2001) "Production, Growth, and Business Cycles: Technical Appendix."
- [60] Klein, Paul, Per Krusell, and Jose-Victor Rios-Rull (2008) "Time-consistent public policy" *Review of Economic Studies*, 75(3): 789-808.

- [61] Klein, Paul, and José-Víctor Ríos-Rull (2003) "Time-consistent optimal fiscal policy" *International Economic Review*, 44(4): 1217-1245.
- [62] Iverson, Terrence (2014) "Optimal carbon taxes with non-constant time preference" *Working paper*.
- [63] Leach, Andrew J. (2009) "The Welfare Implications of Climate Change Policy" *Journal of Environmental Economics and Management*, 57: 151-165.
- [64] Lemoine, Derek M., and Christian Traeger (2014) "Watch your step: Optimal policy in a tipping climate" *American Economic Journal: Economic Policy*, 6(1): 137-166.
- [65] Lucas, Robert E. Jr. (1990) "Supply-Side Economics: An Analytical Review" *Oxford Economic Papers* 42(2): 293-316.
- [66] Ligthart, Jenny E. and Rick van der Ploeg (1994) "Pollution, the Cost of Funds and Endogenous Growth" *Economics Letters*, 46: 339-349.
- [67] Lontzek, Thomas S., Yongyang Cai, Kenneth L. Judd, and Timothy M. Lenton (2015) "Stochastic integrated assessment of climate tipping points indicates the need for strict climate policy" *Nature Climate Change* 5(5): 441-444.
- [68] Manne, Alan S., and Richard G. Richels (2005) "MERGE: An Integrated Assessment Model for Global Climate Change" *Energy and Environment*, 175-189.
- [69] Mendelsohn, Robert, William D. Nordhaus, and Daigee Shaw (1994) "The impact of global warming on agriculture: a Ricardian analysis" *American Economic Review*: 753-771.
- [70] Nordhaus, William D. (2010) "Economic aspects of global warming in a post-Copenhagen environment" *Proceedings of the National Academy of Sciences*, 107(26): 11721-11726.
- [71] Nordhaus, William D. (2010) *DICE-2010 model*, available at <http://nordhaus.econ.yale.edu/RICEmodels.htm>
- [72] Nordhaus, William D. (2008) *A Question of Balance*, Yale University Press, New Haven, CT.
- [73] Nordhaus, William D. (2007) "Accompanying Notes and Documentation on Development of DICE-2007 Model" Available at: http://www.nordhaus.econ.yale.edu/Accom_Notes_100507.pdf
- [74] Nordhaus, William D. (1991) "To Slow or Not to Slow: The Economics of the Greenhouse Effect" *The Economic Journal*, 101(407): 920-937.
- [75] Nordhaus, William D., and Joseph Boyer (2000) *Warming the world: economic models of global warming*, MIT Press, Cambridge, MA.
- [76] Nordhaus, William D., and Zili Yang (1996) "A regional dynamic general-equilibrium model of alternative climate-change strategies" *American Economic Review*, pp: 741-765.

- [77] Parry, Ian W. H., Robertson Williams III, and Lawrence H. Goulder (1999) "When Can Carbon Abatement Policies Increase Welfare? The Fundamental Role of Distorted Factor Markets" *Journal of Environmental Economics and Management*, 37(1): 52-84.
- [78] Piketty, Thomas, and Emmanuel Saez (2012) "A Theory of Optimal Capital Taxation" NBER Working Paper 17989.
- [79] Rausch, Sebastian, and John Reilly (2015) "Carbon taxes, deficits, and energy policy interactions" *National Tax Journal*, 68(1): 157-178.
- [80] Rezai, Armon H., and Rick Van der Ploeg (2014) "Abandoning fossil fuel: how fast and how much?" *CEPR Discussion Paper No. DP9921*.
- [81] Rezai, Armon, Frederick van der Ploeg, and Cees Withagen (2012) "The Optimal Carbon Tax and Economic Growth: Additive versus multiplicative damages" OxCarre Research Paper 93.
- [82] Sandmo, Agnar (1975) "Optimal Taxation in the Presence of Externalities" *Swedish Journal of Economics*, 77(1): 86-98.
- [83] Sandmo, Agnar (2007) "Global Public Economics: Public Goods and Externalities" *Économie publique/Public economics*.
- [84] Schmitt, Alex (2014) "Optimal Carbon and Income Taxation" in: *Beyond Pigou: Climate Change Mitigation, Policy Making and Distortions*, Doctoral Dissertation, Stockholm University.
- [85] Schwartz, Jesse, and Robert Repetto (2000) "Nonseparable Utility and the Double Dividend Debate: Reconsidering the Tax Interaction Effect" *Environmental and Resource Economics*, 15: 149-157.
- [86] Sinn, Hans-Werner (2008) "Public policies against global warming: a supply side approach." *International Tax and Public Finance*, 15(4): 360-394.
- [87] Sørensen, Peter Birch (2007) "Can Capital Income Taxes Survive? And Should They?" *CESifo Economic Studies*, Vol. 53, 2/2007, 172-228.
- [88] Straub, Ludwig, and Iván Werning (2014) "Positive Long Run Capital Taxation: Chamley-Judd Revisited" NBER WP 20441.
- [89] Tol, Richard S.J. (2011) "The Social Cost of Carbon" *Annual Review of Resource Economics*, 3:419-43.
- [90] Tol, Richard S.J. (2008) "Climate, development and malaria: an application of FUND" *Climate Change*, 88:21-34.
- [91] Tol, Richard S.J. (2002) "Estimates of the Damage Costs of Climate Change - Part 1: Benchmark Estimates" *Environmental and Resource Economics*, 21: 47-73.

- [92] Tol, Richard S.J. (1997). "On the Optimal Control of Carbon Dioxide Emissions – An Application of FUND" *Environmental Modelling and Assessment* 2: 151-163.
- [93] Tol, Richard S.J. (1995) "The Damage Costs of Climate Change Toward More Comprehensive Calculations" *Environmental and Resource Economics*, 5: 353-374.
- [94] USAID (2016) Foreign Aid Explorer, Available at URL: <https://explorer.usaid.gov/>
- [95] van der Ploeg, Frederick, and Cees Withagen (2014) "Growth, Renewables and the Optimal Carbon Tax" *International Economic Review*, 55(1): 283-311.
- [96] van der Ploeg, Frederick, and Cees Withagen (1991) "Pollution Control and the Ramsey Problem" *Environmental and Resource Economics*, 1(2): 215-236.
- [97] Weitzman, Martin L. (2010) "What Is The" Damages Function" For Global Warming— And What Difference Might It Make?" *Climate Change Economics*, 1(1): 57-69.
- [98] West, Sarah E., and Roberton C. Williams (2007) "Optimal taxation and cross-price effects on labor supply: estimates of the optimal gas tax" *Journal of Public Economics*, 91(3): 593-617.
- [99] Williams III, Roberton C. (2002) "Environmental Tax Interactions When Pollution Affects Health Or Productivity," *Journal of Environmental Economics and Management*, 44: 261-270.
- [100] Williams III, Roberton C. (2001) "Tax normalizations, the marginal cost of funds, and optimal environmental taxes" *Economics Letters*, 71: 137-142.
- [101] World Health Organization (2009) "Protecting Health from Climate Change: Connecting Science, Policy, and People."