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

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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 article theoretically characterizes and then quantifies optimal carbon taxes in a dynamic general equilibrium climate–economy model with distortionary fiscal policy. First, this article 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 article shows how the standard logic against capital income taxes extends to distortions on environmental capital investments. Second, this article characterizes optimal climate policy in sub-optimal fiscal settings where income taxes are constrained to remain at their observed levels. Third, this article presents a detailed calibration that builds on the seminal DICE approach 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.

Key words: Carbon taxes, Climate–economy model, Social cost of carbon, Second best environmental policy, Double dividend, Revenue recycling, Capital income taxes, Ramsey taxation.

JEL Codes: E62, H21, H23, Q58.

1. INTRODUCTION

Raising revenues and addressing climate change are two fundamental challenges facing governments. This article 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 academic[1] and policy[2] studies of optimal carbon pricing focus on the climate externality

1. For example, Golosov *et al.* (2014, "GHKT"), Nordhaus (2008), Anthoff and Tol (2013), Acemoglu *et al.* (2012), Hope (2011), and Manne and Richels (2005), inter alia.

2. For example, U.S. Interagency Working Group (2010).

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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 labour 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 Wilcoxen, 1996; Babiker *et al.*, 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 article 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 economy[4] 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 U.S. government to value the impacts of carbon dioxide emissions. The main findings of this article 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 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 labour 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 *et al.*, 1999; Acemoglu *et al.*, 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

3. Specifically, the Pigouvian tax equals the social cost of carbon (SCC)—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.

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.

Taxation). The calibration uses International Monetary Fund (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 article 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 gains are at least as large as those from an idealized global Ramsey income tax reform that would optimally phases 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 article analytically characterizes jointly optimal pollution and capital income taxes in an infinite horizon Ramsey second-best economy endogenizing both labour 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 (Ligthart and van der Ploeg, 1994; Bovenberg and de Mooij, 1997; Hettich, 1998; Fullerton and Kim, 2008), but focus on long-run outcomes along a balanced growth path. This article 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 analysed by several studies focusing on carbon as a rent-generating resource, rather than the climate externality which is the focus of this article (*e.g.* Groth and Schou, 2007; Franks *et al.*, 2017, etc.).[9] Third, capital income taxes have been studied as a part of climate policy for reasons unrelated to fiscal needs, such as

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

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 *et al.* (1999), Schwartz and Repetto (2000), Cremer *et al.* (2001, 2010), Williams (2002), Bento and Jacobsen (2007), West and Williams (2007), Carbone and Smith (2008), Fullerton and Kim (2008), Kaplow (2012), Schmitt (2014), and d'Autume *et al.* (2016). See also Bovenberg and Goulder (2002).

8. Chiroleu-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 labour as exogenous, focusing on capital versus resource taxes.

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 distortions.[11] However, as these studies abstract from climate change impacts on production possibilities, this article'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 article 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 modelling literature, such as different forms of uncertainty (*e.g.* Lemoine and Traeger, 2014; Cai *et al.*, 2015). Instead, this article presents the first formal integration of distortionary taxes in a dynamic general equilibrium climate–economy model. This article thus analyses 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 *et al.* (2014).

The remainder of this article 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 *et al.* (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 and the climate as well. There are two production sectors. The aggregate final consumption-investment good is produced using capital, labour, and energy inputs. Climate change affects productivity in this sector. A

10. For example, 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), and Iverson (2014).

11. For example, Goulder (1995), Bovenberg and Goulder (1996), Jorgenson and Wilcoxen (1996), Babiker *et al.* (2003), Bernard and Vielle (2003), Carbone *et al.* (2013), Jorgenson *et al.* (2013), Rausch and Reilly (2015), and Williams *et al.* (2015).

12. For example, Manne and Richels (2005), Hope (2011), Acemoglu *et al.* (2012), Anthoff and Tol (2013), Lemoine and Traeger (2014), Cai *et al.* (2015), etc.

carbon-based energy input is produced from capital and labour. 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]

2.1. *Households*

An infinitely lived, representative household has well-behaved preferences over consumption C_t, labour 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:

$$U_0 \equiv \sum_{t=0}^{\infty} \beta^t U(C_t, L_t, T_t). \tag{2.1}$$

Environmental quality enters preferences additively separably from consumption and leisure:

$$U(C_t, L_t, T_t) = h(C_t, L_t) + v(T_t). \tag{2.2}$$

The literature on pollution tax interactions with distortionary taxes commonly assumes weak separability. The Supplementary Appendix shows that the main theoretical insights of this article are robust to relaxing assumption (2.2).[14] Each period, the representative household faces the following flow budget constraint:

$$C_t + \rho_t B_{t+1} + K_{t+1} \leq w_t(1-\tau_{lt})L_t + \{1+(r_t-\delta)(1-\tau_{kt})\}K_t + B_t + \Pi_t + G_t^T, \tag{2.3}$$

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 labour income, τ_{kt} linear taxes on capital income, r_t the return on capital, δ the depreciation 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 non-negative. Finally, initial asset holdings B_0 and K_0 are also given.

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

$$\frac{U_{ct}}{U_{ct+1}} = \beta\left\{1+(r_{t+1}-\delta)(1-\tau_{kt+1})\right\} \tag{2.4}$$

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).

$$\frac{-U_{lt}}{U_{ct}} = w_t(1-\tau_{lt}), \tag{2.5}$$

where U_{it} denotes the partial derivative of utility with respect to argument i at time t. In words, the Euler equation (2.4) states that households equate their marginal rate of substitution (MRS) between consumption in periods t and $t+1$ to the after-tax return on saving between periods t and $t+1$. Similarly, the implicit labour supply equation (2.5) states that agents equate their MRS between consumption and leisure to the after-tax return on working.

2.1.1. 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, labour 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}:

$$Y_t = (1-D(T_t))\cdot A_{1t}\widetilde{F}_1(L_{1t}, K_{1t}, E_t) \tag{2.6}$$

$$= F_1(A_{1t}, T_t, L_{1t}, K_{1t}, E_t). \tag{2.7}$$

The formulation of climate damages as fraction of output lost in (2.6) 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 (2.6). However, in a setting with distortionary taxes, distinguishing climate damages that affect production possibilities is necessary. Here, formulation (2.6) 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:

$$\begin{aligned} F_{1lt} &= w_t, \\ F_{1Et} &= p_{Et}, \\ F_{1kt} &= r_t, \end{aligned} \tag{2.8}$$

where F_{1it} denotes the partial derivative of (2.7) with respect to input i at time t.

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

$$E_t = A_{2t}F_2(K_{2t}, L_{2t}). \tag{2.9}$$

The constant returns to scale formulation (2.9) assume that carbon energy is in unlimited supply and therefore earns zero Hotelling profits. As argued by GHKT (2014), this is a reasonable

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 *et al.* (2012) for an assessment of *additive* damages).

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

$$\begin{aligned} L_t &= L_{1t} + L_{2t} \\ K_t &= K_{1t} + K_{2t}. \end{aligned} \tag{2.10}$$

This assumption is in line with GHKT (2014). Due to the 10-year time step used in the empirical model, formulation (2.10) is also more realistic than in an annual formulation. An important implication of (2.10) is that factor prices will be equated across sectors in equilibrium. Competitive energy producers thus equate marginal factor products and prices:

$$\begin{aligned} [p_{Et} - \tau_{It} - \tau_{Et}]F_{2lt} &= w_t \\ [p_{Et} - \tau_{It} - \tau_{Et}]F_{2kt} &= r_t. \end{aligned} \tag{2.11}$$

Note that, at the optimum, the abatement term μ_t drops out of the firm's profit-maximizing conditions (2.11) 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}:

$$\tau_{Et} = \Theta_t'(\mu_t E_t) \tag{2.12}$$

2.1.3. Government. Following standard approaches in the literature (*e.g.* Jones *et al.*, 1993; Chari and Kehoe, 1999), the government needs to finance an exogenously given sequence of public consumption (G_t^C) and household transfers $\{G_t^C > 0, G_t^T\}_{t=0}^{\infty}$, 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 labour and capital income. In addition, the government can impose excise taxes τ_{It} on energy inputs and τ_{Et}

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; Fullerton and Kim, 2008; Franks *et al.*, 2017, for discussions of second-best taxation and untaxed rents).

on carbon emissions. The consumption good serves as the untaxed numeraire. The government's flow budget constraint is given by:

$$G_t^C + G_t^T + B_t^G = \tau_{lt} w_t L_t + \tau_{It} E_t + \tau_{Et} E_t^M + \tau_{kt}(r_t - \delta) K_t + \rho_t B_{t+1}^G. \tag{2.13}$$

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

$$B_{t+1}^G = B_{t+1}. \tag{2.14}$$

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.

2.1.4. 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 $\{\eta_s\}_{s=0}^t$ (*e.g.* land-based emissions):

$$T_t = F\left(\mathbf{S}_0, E_0^M, E_1^M, ..., E_t^M, \eta_0, ...\eta_t\right), \tag{2.15}$$

where:

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

2.1.5. 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 (2.1) subject to the constraints of (i) feasibility and (ii) the optimizing behaviour 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 $\{\eta_t\}$ in a competitive equilibrium satisfy:*

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

$$T_t \geq \digamma(\mathbf{S}_0, (1-\mu_0)E_0, (1-\mu_1)E_1, ..., (1-\mu_t)E_t, \eta_0, ...\eta_t) \tag{CCC}$$

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

$$L_{1t} + L_{2t} \leq L_t \tag{LC}$$

$$K_{1t} + K_{2t} \leq K_t \tag{KC}$$

$$\sum_{t=0}^{\infty} \beta^t \left[U_{ct} C_t + U_{lt} L_t - U_{ct} G_t^T \right] = U_{c0} [K_0 \{1 + (F_{1k0} - \delta)(1 - \overline{\tau_{k0}})\} + B_0] \tag{IMP}$$

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: Supplementary 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 (2.1) 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 MCF be defined as the ratio of the public marginal utility of consumption to the private marginal utility of consumption:*

$$\text{MCF}_t \equiv \frac{\lambda_{1t}}{U_{ct}}. \tag{2.16}$$

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_{Tt+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 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:*

$$\text{Production damages: } \tau_{Et}^{Pigou,Y} \equiv (-1) \sum_{j=0}^{\infty} \beta^j \frac{U_{ct+j}}{U_{ct}} \left[\frac{\partial Y_{t+j}}{\partial T_{t+j}} \frac{\partial T_{t+j}}{\partial E_t^M} \right] \tag{2.17}$$

$$\text{Utility damages: } \tau_{Et}^{Pigou,U} = (-1) \sum_{j=0}^{\infty} \beta^j \frac{U_{Tt+j}}{U_{ct}} \left[\frac{\partial T_{t+j}}{\partial E_t^M} \right]. \tag{2.18}$$

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

$$\tau_{Et}^{Pigou,T} \equiv \tau_{Et}^{Pigou,U} + \tau_{Et}^{Pigou,Y}. \tag{2.19}$$

Finally, the level of the Pigouvian tax in each fiscal scenario is given by (2.19) 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, Golosov *et al.* (2014) show that (2.17) 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 labour 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 (2.11), it is straightforward to show (see Appendix A) the following: provided that capital and labour income taxes are set appropriately, the optimal intermediate goods tax on energy inputs is zero ($\tau_{It}^* = 0 \; \forall \; t > 0$), whereas the optimal carbon tax for $t > 0$ is implicitly defined as follows:

$$\tau_{Et}^* = \underbrace{\sum_{j=0}^{\infty} \beta^j \left[\frac{-U_{Tt+j}}{U_{ct}} \frac{1}{MCF_t} \right] \left[\frac{\partial T_{t+j}}{\partial E_t^M} \right]}_{\text{Utility damages}} + \underbrace{\sum_{j=0}^{\infty} \beta^j \left[\frac{-\partial Y_{t+j}}{\partial T_{t+j}} \frac{\lambda_{1t+j}}{\lambda_{1t}} \right] \left[\frac{\partial T_{t+j}}{\partial E_t^M} \right]}_{\text{Production damages}}. \tag{3.1}$$

Expression (3.1) shows that the optimal carbon price consists of two components: one to internalize 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 ($\text{MCF}_t > 1$), 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 constant elasticity of substitution (CES) forms leads to the following result:

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

$$U(C_t, L_t, T_t) = \frac{C_t^{1-\sigma}}{1-\sigma} + \vartheta(L_t) + v(T_t) \tag{3.2}$$

$$U(C_t, L_t, T_t) = \frac{(C_t L_t^{-\gamma})^{1-\sigma}}{1-\sigma} + v(T_t) \tag{3.3}$$

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:

$$\tau^*_{Et} = \frac{\tau_{Et}^{Pigou,U}}{MCF_t} + \tau_{Et}^{Pigou,Y} \tag{3.4}$$

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:

$$\tau^*_{Et} = \tau_{Et}^{Pigou,T} \left[1 + \theta_t^u \frac{(1 - MCF_t)}{MCF_t} \right] \tag{3.5}$$

Proof: See Appendix A. In words, Proposition 2 shows that, for preferences (3.2)–(3.3) 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 (3.4) in a static setting. Proposition 2 thus provides conditions under which their result generalizes to a dynamic economy. More generally, it is clear from (3.1) that (3.4) 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 (3.1) may not reduce to (3.4) depending on intertemporal distortions in the economy. In order to elucidate and contextualize this result, the remainder of this section analyses output and utility damages separately.

3.1.1. 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 (3.1) reduces to:

$$\tau^*_{Et} = \sum_{j=0}^{\infty} \beta^j \left[\frac{-U_{Tt+j}}{U_{ct}} \frac{1}{\mathrm{MCF}_t} \right] \left[\frac{\partial T_{t+j}}{\partial E_t^M} \right] = \frac{\tau_{Et}^{Pigou,U}}{\mathrm{MCF}_t}, \tag{3.6}$$

where the second equation follows from the definition of $\tau_{Et}^{Pigou,U}$ (2.18). Expression (3.6) extends to a dynamic setting the classic result from static models that $(\tau^*_E = \tau_E^{Pigou} /$

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).

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 (3.6) implies that the optimal allocation leaves a wedge between the household's 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 labour, 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 labour 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).

3.1.2. 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 (3.1) reduces to:

$$\tau_{Et}^{*}=\sum_{j=0}^{\infty}\beta^{j}\left[\frac{-\partial Y_{t+j}}{\partial T_{t+j}}\frac{\lambda_{1t+j}}{\lambda_{1t}}\right]\left[\frac{\partial T_{t+j}}{\partial E_{t}^{M}}\right]. \tag{3.7}$$

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 (Golosov *et al.*, 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 (2.16)). Whether (3.7) matches the Pigouvian tax (2.17) 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 $t+j$th term in the sum of (3.7) 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 $\left(\frac{\lambda_{1t+j}}{\lambda_{1t+j-1}}\frac{\lambda_{1t+j-1}}{\lambda_{1t+j-2}}\dots\frac{\lambda_{1t+1}}{\lambda_{1t}}\right)$. 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:

$$\frac{\lambda_{1t}}{\lambda_{1t+1}}=\beta\left[F_{1kt+1}+(1-\delta)\right]. \tag{3.8}$$

Third, combining households' (2.4) and firms' (2.8) optimality conditions shows that, in equilibrium,

$$\frac{U_{ct}}{U_{ct+1}}=\beta\left\{1+(F_{1kt+1}-\delta)(1-\tau_{kt+1})\right\}. \tag{3.9}$$

Comparing (3.8) and (3.9) immediately shows that, if the government optimally chooses to set capital income taxes in period $t+1$ to zero, then:

$$\frac{\lambda_{1t}}{\lambda_{1t+1}} = \frac{U_{ct}}{U_{ct+1}}. \tag{3.10}$$

If the government optimally sets capital income taxes to zero from period $t+1$ *onwards,* this implies that condition (3.10) 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 (3.7) yields the desired result:

$$\tau^*_{Et} = \sum_{j=0}^{\infty} \beta^j \left[\frac{U_{ct+j}}{U_{ct}} \frac{-\partial Y_{t+j}}{\partial T_{t+j}} \right] \left[\frac{\partial T_{t+j}}{\partial E^M_t} \right] = \tau^{Pigou,Y}_{Et} \qquad \blacksquare. \tag{3.11}$$

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 (3.4) even if labour 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 *et al.*, 1999; Acemoglu *et al.*, 2011). A number of studies have explored the implications of this result for human capital taxation (Judd, 1999; Jones *et al.*, 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 *et al.*, 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).

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

In contrast, with an exogenous constraint that capital income levies be fixed at some positive level $\overline{\tau_k} \in (0,1)$ (due to *e.g.* unmodelled 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" (BAU) scenario that maintains capital or labour income taxes at current rates, Corollaries 1 and 2 provide an analytic characterization of optimal climate policy in two of the settings analysed 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 $\overline{\tau_k}$ $\forall t > 0$:*

$$\frac{U_{ct}}{\beta U_{ct+1}} = 1 + (1 - \overline{\tau_k})(F_{1kt+1} - \delta) \tag{3.12}$$

then, letting Ψ_t denote the planner's Lagrange multiplier on (3.12) in period t, the optimal carbon tax for $t > 0$ is implicitly defined by:

$$\tau_{Et}^{*} = (-1)\left[\sum_{j=0}^{\infty} \beta^j \underbrace{\frac{U_{Tt+j}}{U_{ct}} \frac{1}{MCF_t} + \frac{\lambda_{1t+j}}{\lambda_{1t}} \frac{\partial Y_{t+j}}{\partial T_{t+j}}}_{\textit{Utility + Production impacts}} + \underbrace{\frac{\Psi_{t-1+j}}{\lambda_{1t}} \frac{1}{\beta} \frac{\partial F_{1kt+j}}{\partial T_{t+j}} (1 - \overline{\tau_k})}_{\textit{Fiscal constraint interaction}}\right] \left[\frac{\partial T_{t+j}}{\partial E_t^M}\right], \tag{3.13}$$

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

$$\frac{\beta \lambda_{1t+1}}{\lambda_{1t}} = [F_{1kt+1} + (1-\delta) + \frac{\Psi_t}{\lambda_{1t+1}} \frac{1}{\beta} \frac{\partial F_{1kt+1}}{\partial K_{1t+1}} (1 - \overline{\tau_k})]^{-1}. \tag{3.14}$$

Corollary 2 *If the government is constrained to maintain labour income taxes at $\overline{\tau_l}$ $\forall t > 0$:*

$$\frac{-U_{lt}}{U_{ct}} = (1 - \overline{\tau_l}) F_{1lt} \tag{3.15}$$

then, letting Λ_t denote the planner's Lagrange multiplier on (3.15) in period t, the optimal carbon tax for $t > 0$ is implicitly defined by:

$$\tau_{Et}^{*} = (-1)\left[\sum_{j=0}^{\infty} \beta^j \underbrace{\frac{U_{Tt+j}}{U_{ct}} \frac{1}{MCF_t} + \frac{\lambda_{1t+j}}{\lambda_{1t}} \frac{\partial Y_{t+j}}{\partial T_{t+j}}}_{\textit{Utility + Production impacts}} + \underbrace{\frac{\Lambda_{t+j}}{\lambda_{1t}} \frac{\partial F_{1lt+j}}{\partial T_{t+j}} (1 - \overline{\tau_l})}_{\textit{Fiscal constraint interaction}}\right] \left[\frac{\partial T_{t+j}}{\partial E_t^M}\right], \tag{3.16}$$

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

$$\frac{\beta \lambda_{1t+1}}{\lambda_{1t}} = [F_{1kt+1} + (1-\delta) + \frac{\Lambda_{t+1}}{\lambda_{1t+1}} \frac{\partial F_{1lt+1}}{\partial K_{1t+1}} (1 - \overline{\tau_l})]^{-1} \tag{3.17}$$

Proofs: See Supplementary Appendix. In a third-best setting with limited potential for tax reform, the optimal carbon tax thus differs from (3.1) 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 (3.14) and (3.17). 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 (3.14) 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 (3.12). 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 (3.12) and (3.15) 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 labour, and therefore interacts with the fiscal constraints. The Supplementary 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 *et al*, 2003; Klein and Ríos-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 separate representations of production and utility damages. The calibration matches data on world gross domestic product (GDP), energy consumption, labour 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.

19. For example, Cremer *et al.* (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.

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 Supplementary Appendix Table A1.

4.1. *Carbon cycle and climate model*

The relationship between carbon emissions and temperature change (2.15) is adopted from DICE (Nordhaus, 2010). The calibration keeps track of two exogenous climate shifters η_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 (2.15) 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}):

$$\begin{pmatrix} S_t^{At} \\ S_t^{Up} \\ S_t^{Lo} \end{pmatrix} = \begin{pmatrix} \phi_{11} & \phi_{21} & 0 \\ \phi_{12} & \phi_{22} & \phi_{32} \\ 0 & \phi_{23} & \phi_{33} \end{pmatrix} \begin{pmatrix} S_{t-1}^{At} \\ S_{t-1}^{Up} \\ S_{t-1}^{Lo} \end{pmatrix} + \begin{pmatrix} E_t^M + E_t^{Land} \\ 0 \\ 0 \end{pmatrix} \tag{4.1}$$

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

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

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:

$$\begin{pmatrix} T_t \\ T_t^{Lo} \end{pmatrix} = \begin{pmatrix} (1-\zeta_1\zeta_2-\zeta_1\zeta_3) & \zeta_1\zeta_3 \\ (1-\zeta_4) & \zeta_4 \end{pmatrix} \begin{pmatrix} T_{t-1} \\ T_{t-1}^{Lo} \end{pmatrix} + \begin{pmatrix} \zeta_1 \chi_t \\ 0 \end{pmatrix} \tag{4.2}$$

Given a set of initial conditions $\mathbf{S}_0 = \{S_0^{At}, S_0^{Up}, S_0^{Lo}, T_0, T_0^{Lo}\}$, shifters $\{\eta_0\}_{s=0}^t$, and emissions $\{E_s^M\}_{s=0}^t$, iteratively combining (4.1)–(4.2) thus defines the emissions-temperature relationship (2.15). 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 Supplementary Appendix.

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; Golosov *et al.*, 2014), pure utility losses (*e.g.* Acemoglu *et al.*, 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 versus 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 and Boyer, 2000; Nordhaus, 2007). 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.

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

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 U.S., 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.

TABLE 1
Climate damage categorization

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

While the classification of some impacts is straightforward (*e.g.* agriculture), three categories warrant further explanation. First, seal-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 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 labour 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 labour market impacts of climate change, I use projected years of life lost to separately estimate (i) the global labour time endowment reduction and corresponding output loss and (ii) the disutility from lost leisure time. In addition, as labour productivity impacts have not generally been included in climate–economy models (Tol, 2011), I use available evidence in the literature to compute labour 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 modelled 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 *et al.*, 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

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.

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 labour productivity losses from malaria due to Bleakley (2003), with World Bank malaria prevalence data and impact estimates from Tol (2008). See Barrage (2014).

frontiers is to formalize the effects of such factors (*e.g.* Desmet and Rossi-Hansberg, 2015). However, as this article 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 to the 2010-DICE model's aggregate impacts yields the following moments:[28]

$$\begin{aligned} \text{Share of output damages} &: 74\% \\ \text{Total damages from } 2.5^{\circ}\text{C warming} &: 1.74\% \text{ of output} \\ \text{Total } \textit{production damages} &: 1.29\% \text{ of output} \\ \text{Total } \textit{direct utility damages} &: 0.46\% \text{ of output} \end{aligned} \tag{4.3}$$

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

$$(1-D_t(T_t)) = \frac{1}{1+\theta_1 T_t^2}. \tag{4.4}$$

Solving (4.4) for (4.3) 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 labour 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 Supplementary Appendix). The utility discount factor is set to 1.5% per year, or $\beta = (0.985)^{10}$ 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 labour supply from the literature ($= 0.78$ based on Chetty *et al.*, 2011) and base year labour supply ($l_{2005} = 0.227$ from from Organisation for Economic Co-operation and Development (OECD) data) at base year effective labour 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 (3.2)–(3.3) do not satisfy all of these criteria. For example, specification (3.2) is only consistent with balanced growth for logarithmic utility ($\sigma = 1$) (King *et al.*, 2002). Consequently, I adopt a modified version of (3.3) building on other

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.

quantitative dynamic Ramsey taxation models (*e.g.* Jones *et al.*, 1993):[29,30]

$$U(c_t, l_t, T_t) = \frac{\left[c_t \cdot (1-\varsigma l_t)^{\gamma}\right]^{1-\sigma}}{1-\sigma} + \frac{\left(1+\alpha_0 T_t^2\right)^{-(1-\sigma)}}{1-\sigma}. \tag{4.5}$$

The formulation of preferences over climate change in (4.5) 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°C equals 0.46% of output as per (4.3). 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 modelled as:

$$\widetilde{F}_1(K_{1t}, L_{1t}, E_t) = K_{1t}^{\alpha} L_{1t}^{1-\alpha-\nu} E_t^{\nu} \tag{4.6}$$

with expenditure shares $\alpha = 0.3$ and $\nu = 0.03$, following Golosov *et al.* (2014).[31] Projections of productivity growth are taken from DICE (2010) and listed in the Supplementary 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:

$$E_t = A_{2t}(K_{2t}^{1-\alpha_E} L_{2t}^{\alpha_E}). \tag{4.7}$$

Paired with the assumption of perfect competition, formulation (4.7) permits inferring the output elasticity α_E from observed expenditure shares. Using U.S. Bureau of Economic Analysis data, I estimate a labour share in the energy sector of $\alpha_E = 0.403$ (see Supplementary 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:

$$\Theta_t(\mu_t E_t) = \frac{\overline{a} P_t^{\text{backstop}}}{1 + a_t \exp(b_{0t} - b_{1t}(\mu_t E_t))^{b_2}} \cdot (\mu_t E_t). \tag{4.8}$$

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 (4.8) versus DICE (see Supplementary Appendix for details).

29. Specification (4.5) adds ς as an additional degree of freedom to calibrate to the desired moments. It is easy to show that (4.5) is consistent with balanced growth at the desired parameters (see Barrage, 2014).

30. While (4.5) does not deliver the same unambiguous theoretical prediction of zero capital income taxes for all periods $t \geq 1$ as (3.2)–(3.3), quantitatively, the optimal policy path is almost identical (see Supplementary Appendix "Calibration Details"). Theoretically, it is moreover easy to show that labour supply convergence to a steady level is a sufficient condition for (4.5) to yield the same theoretical results as (3.2)–(3.3) 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 *et al.*, 2012).

TABLE 2
Government expenditure shares (2005)

	% 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.

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 (Lucas, 1990; Jones *et al.*, 1993, 1997). 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 purchasing power parity (PPP) adjusted GDP-weighted expenditure breakdown shown in Table 2. The *level* of total public spending is thus set to 31.07% of base decade GDP, and assumed to grow at the rates of labour productivity and population growth, in line with prior studies (Jones *et al.*, 1993; Goulder, 1995). 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 Supplementary Appendix), yielding the following base year GDP-weighted average rates:

Effective capital tax (τ_k)	33.40%
Effective labour tax	28.10%
Effective consumption tax	11.11%
$\Rightarrow$ Labour-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 BAU 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).

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 labour 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 labour supply and thus output would be 16% higher, leading to a correspondingly higher first-best carbon tax (see Supplementary Appendix "Additional Sensitivity"). Re-calibration thus mitigates the effect of distortionary taxes on carbon prices.

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

TABLE 3
Summary of key calibration parameters

Parameter	Value	Sources and notes
Preferences: $U(c_t,l_t,T_t)=\frac{[c_t\cdot(1-\varsigma l_t)^\gamma]^{1-\sigma}}{1-\sigma}+\frac{\left(1+\alpha_0 T_t^2\right)^{-(1-\sigma)}}{1-\sigma}$		
σ	1.5	Nordhaus (2010)
β	$(0.985)^{10}$	Nordhaus (2010)
ς	$\begin{cases} 2.2381 & \text{if distortionary} \\ 2.0785 & \text{if first-best} \end{cases}$	Jointly match Frisch elasticity (0.78) and rationalize base labour supply ($l_{2005}=0.2272$)
γ	$\begin{cases} 0.7178 & \text{if distortionary} \\ 1.2985 & \text{if first-best} \end{cases}$	at base year marginal product of labour w_{2005} with $\tau_{l,2005}$=0.3609 or $\tau_{l,2005}=0$, respectively
α_0	$\begin{cases} 0.00023808 & \text{if distortionary} \\ 0.00027942 & \text{if first-best} \end{cases}$	Match disutility from 2.5°C warming equiv. to 0.46% output loss given the relevant ς,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°C warming
Final goods production: $F_1(A_{1t},T_t,L_{1t},K_{1t},E_t)=(1-D_t(T_t))A_{1t}(K_{1t}^{\alpha}L_{1t}^{1-\alpha-\nu}E_t^{\nu})$		
α	0.3	GHKT (2014)
ν	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: $\Theta_t(\mu_t E_t)=\frac{\bar{a}P_t^{\text{backstop}}}{1+a_t\exp(b_{0t}-b_{1t}(\mu_t E_t))^{b_2}}\cdot(\mu_t E_t)$ for $t\leq 2250$, $=0$ afterwards		
$\bar{a}$	0.9245	
a_t	$=49.9096+1.0995\log(t)$	Minimize sum of squared errors in
b_{0t}	$=15.5724+3.4648\log(t)$	difference to DICE abatement costs
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	$=(0.331)(0.57)(\text{GDP}_{2005}^{\text{World}}\cdot 10)$ (\$2005)
G_{2005}^T	73.713 \$trillion	$=(0.331)(0.43)(\text{GDP}_{2005}^{\text{World}}\cdot 10)$ (\$2005)
B_0	34.659 \$trillion	$=(0.6263)(\text{GDP}_{2005}^{\text{World}})$ (\$2005), World Bank WDI

Notes: See Supplementary Appendix for full parameter listing and further details.

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:

TABLE 4
Main results

	Fiscal scenario			τ_l^*	τ_k^*	MCF	Carbon tax τ_{Et}^*			T_t	Δ Welfare[b]	
	Labour	Capital	Carbon and energy		Avg. 2025–2255		2015 $/mtC	2025 $/mtC	%Adjust.[a] from FB (6)	Max	ΔC_{2015} ($tril.)	$\%\Delta C_t\ \forall t$
1a.	Variable	$\overline{\tau_k}$ = 34.6%	None (until 2115)[c]	38.3%		1.06	0	0		4.31	–	–
1b.	$\overline{\tau_l}$ = 38.3%	Variable	None (until 2115)		34.3%	1.43	0	0		4.30	$0.05	0.00
2.	Optimized		None (until 2115)	42.1%	2.8%[d]	1.06	0	0		4.31	$22.42	0.82
3a.	$\overline{\tau_l}$ = 38.3%	Variable	"Wrong" (First-best)		31.9%	1.37	71	105		2.78	$24.88	0.90
4a.	$\overline{\tau_l}$ = 38.3%	Variable	Optimized[e]		31.1%	1.35	49	77	−24%	3.03	$26.21	0.95
3b.	Variable	$\overline{\tau_k}$ = 34.6%	"Wrong" (First-best)	37.9%		1.05	71	105		2.82	$21.27	0.78
4b.	Variable	$\overline{\tau_k}$ = 34.6%	Optimized[f]	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[g]	3.25

[a]Average adjustment of optimal vs. first-best carbon tax during twenty-first century. [b]Relative to BAU scenario (1a). Equivalent variation change in aggregate initial consumption ΔC_{2015} or permanent change in consumption $\%\Delta C_t\ \forall t$. [c]Carbon taxes are allowed after 2115 so as to keep the analysis in an appropriate range for the (smooth) damage function. [d]Consists of high initial tax followed by ∼0% tax (see Supplementary Appendix for graph of τ_{kt}^* over time). [e]Includes non-zero intermediate input tax on clean and dirty energy (τ_I^* = \$35/mtC-eq in 2025). See Supplementary Appendix for derivation and alt. results with $\overline{\tau_I}$=0. [f]Includes non-zero intermediate input tax on clean and dirty energy (τ_I^* = −\$3/mtC-eq in 2025). See Supplementary Appendix for derivation and alt. results with $\overline{\tau_I}$=0. [g]Calculation 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 τ_{l0} = 36.09% in the second-best.

1. A BAU scenario with no carbon tax throughout the twenty-first century.[33] Variant (1a) holds labour income taxes fixed at $\overline{\tau_l}=38.25\%$ (as in (3.12)) and adjusts the capital income tax to meet the government budget constraint. Variant (1b) holds capital income taxes fixed at $\overline{\tau_k}=34.57\%$ (as in (3.15)) and adjusts the labour tax. Income taxes are moreover restricted to remain constant over time.
2. An *income tax reform* scenario where capital and labour 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 labour taxes at $\overline{\tau_l}=38.25\%$ and thus uses carbon tax revenues to reduce the capital income tax. Variant (3b) holds capital income taxes at $\overline{\tau_k}=34.57\%$ and recycles revenues to reduce the labour income tax. These scenarios measure the welfare gains from environmental tax reform with the "wrong" carbon tax.
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 labour taxes at $\overline{\tau_l}=38.25\%$, whereas variant (4b) holds capital income taxes at $\overline{\tau_k}=34.57\%$.
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 8–24% lower when levied alongside distortionary taxes, depending on the scenario. The reasons for these change are analysed 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 labour income tax rates ($22 trillion or 0.80%). Intuitively, this is because capital income taxes have a much higher marginal cost of funds than labour 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 labour 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 phases out all capital income taxes ($22 trillion

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°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.

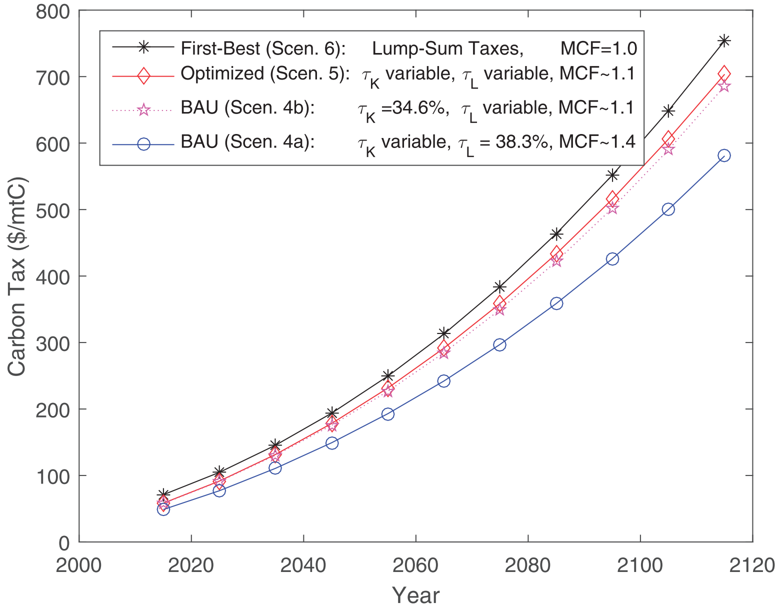

FIGURE 1

Optimal carbon tax paths across fiscal scenarios.

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 SCC—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 (4*a*) as an example.

In the first-best setting, the optimal carbon price τ_{Et}^* equals the Pigouvian levy (lines with stars). In contrast, distortionary taxes not only lower the Pigouvian rate (dotted line with circles), but push the optimal carbon price below this value (solid 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.

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.

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 favourably with Lucas' (1990) estimates for the U.S. economy (0.75–1.25%).

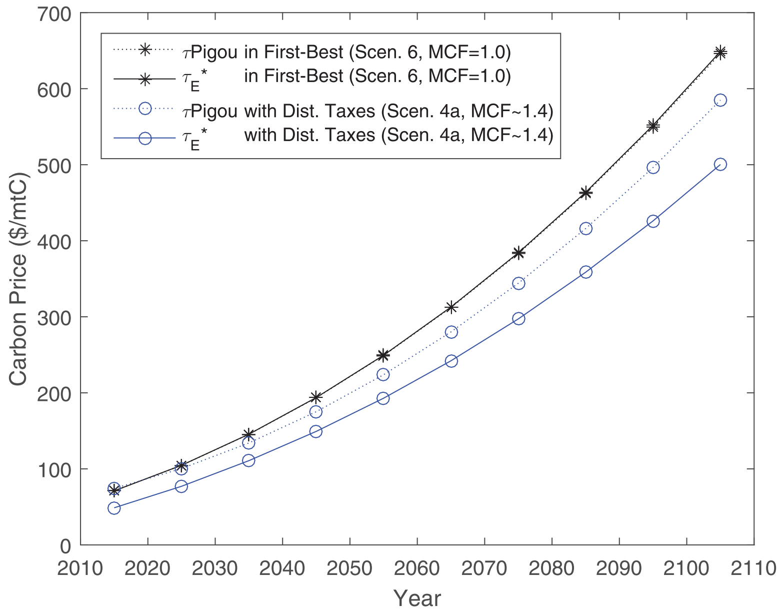

FIGURE 2

Optimal vs. pigouvian carbon tax levels.

Perhaps surprisingly, the optimal carbon price in the scenario with fixed capital income taxes (4b, line with hexagrams) rises slightly above the Pigouvian level by mid-century. Intuitively, 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 labour in the scenario with a labour 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 labour 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 on the scenario, the optimal carbon price is between 7% and 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.

TABLE 5

Optimal versus Pigouvian carbon tax decomposition (2025)

Scenario 4b[a]: Variable labour tax, fixed capital income tax $\overline{\tau_k}$=34.57% (MCF ∼ 1.1)				
	Utility damages	Production damages	Fiscal constraint interactions	Total
τ_{Et}^{Pigou}	$\Sigma\beta^j \frac{U_{Tt+j}}{U_{ct}}$	$\Sigma\beta^j \frac{U_{ct+j}}{U_{ct}} F_{Tt+j}$		
	\$22	\$82		\$104
τ_{Et}^{*}	$\Sigma\beta^j \frac{U_{Tt+j}}{U_{ct}} \frac{1}{MCF_t}$	$\Sigma\beta^j \frac{\lambda_{1t+j}}{\lambda_{1t}} F_{Tt+j}$	$\Sigma\beta^j \frac{\Psi_{t-1+j}}{\lambda_{1t}} \frac{1}{\beta} \frac{\partial F_{1kt+j}}{\partial T_{t+j}} (1-\overline{\tau_k})$	
	\$18	\$69	\$5	\$92
Scenario 4a[a] : Fixed labour tax $\overline{\tau_l}$=38.25%, variable capital income tax (MCF ∼ 1.3)				
	Utility damages	Production damages	Fiscal constraint interactions	Total
τ_{Et}^{Pigou}	$\Sigma\beta^j \frac{U_{Tt+j}}{U_{ct}}$	$\Sigma\beta^j \frac{U_{ct+j}}{U_{ct}} F_{Tt+j}$		
	\$19	\$73		\$93
τ_{Et}^{*}	$\Sigma\beta^j \frac{U_{Tt+j}}{U_{ct}} \frac{1}{MCF_t}$	$\Sigma\beta^j \frac{\lambda_{1t+j}}{\lambda_{1t}} F_{Tt+j}$	$\Sigma\beta^j \frac{\Lambda_{t+j}}{\lambda_{1t}} \frac{\partial F_{1lt+j}}{\partial T_{t+j}} (1-\overline{\tau_l})$	
	\$15	\$71	-\$6	\$80

[a]Differs from 4a,b in Table 4 in allowing variable tax rate to change over time (to match Corollaries 1 and 2 exactly).

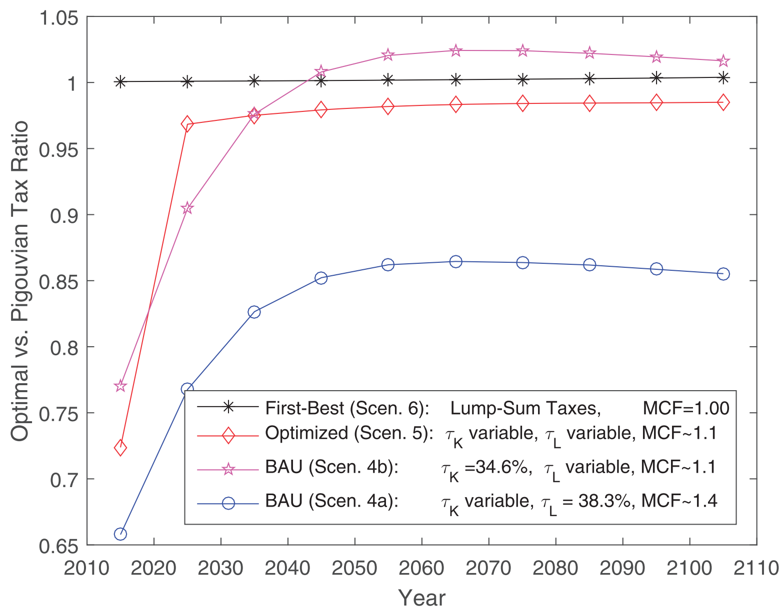

FIGURE 3

Optimal vs. pigouvian carbon tax ratios.

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 labour 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)

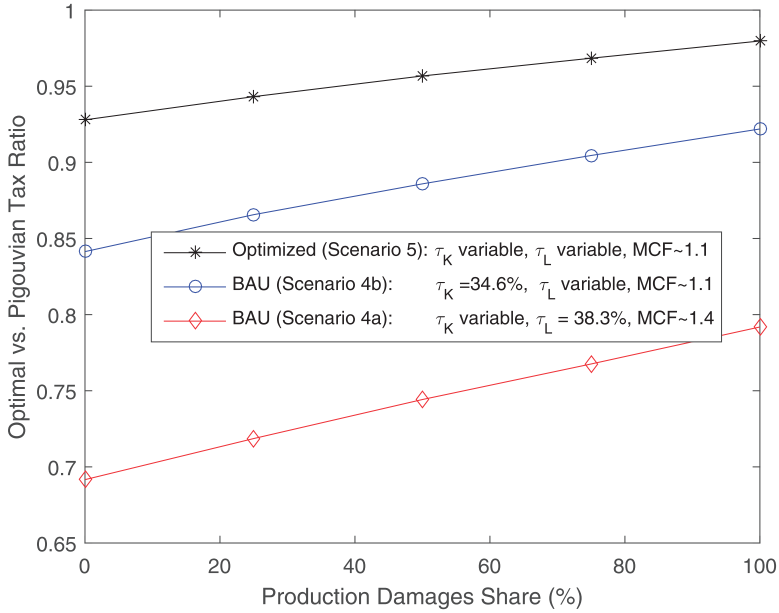

FIGURE 4

Optimal vs. pigouvian carbon tax ratios (2025).

and lower (1.1) value. Finally, a permanent 10% increase and decrease in government spending are considered. The Supplementary Appendix provides additional results for (i) variation in abatement costs, (ii) scenarios that prohibit intermediate goods taxation (*i.e.* $\overline{\tau_I}=0$), and (iii) scenarios that allow the planner to vary capital and labour 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 modelled changes. For example, the leisure preference parameters are calibrated to rationalize base year labour 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 "BAU" 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

TABLE 6
Sensitivity analysis—policy

		τ_l^*	τ_k^*	MCF	Carbon tax τ_{Et}^* 2015 \$/mtC	2025 \$/mtC	%Adjustment from FB (6.)	T_t max
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 labour 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 labour 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 labour 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 labour 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 labour 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

Notes: All figures represent average of 2015–115 values unless noted otherwise.

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 *et al.* (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 (Chichilnisky and Heal, 1994; Nordhaus and Yang, 1996; 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 U.S. disbursed \$41 billion (\$2014) in foreign aid to 190 counties, including through *direct cash transfers to foreign governments* (USAID, 2016). In contrast, historical attempts at domestic lump-sum taxation

TABLE 7
Sensitivity analysis—welfare

	Tax scenario			Δ Welfare	
	Labour	Capital	Carbon and energy	ΔC_{2015} ($tril.)	$\%\Delta C_t\ \forall t$
Frisch elasticity = 2					
1a.	39.6%	$\overline{\tau_k}$ = 40.9%	None (until 2115)	–	–
3b.	39.3%	$\overline{\tau_k}$ = 40.9%	"Wrong" (First-Best)	$19.3	0.72%
4b.	39.2%	$\overline{\tau_k}$ = 40.9%	Optimized	$22.4	0.83%
3a.	$\overline{\tau_l}$ = 39%	42.4%	"Wrong" (First-Best)	$15.1	0.57%
4a.	$\overline{\tau_l}$ = 39%	40.9%	Optimized	$21.4	0.79%
5.		Optimized		$72.6	2.54%
Consumption elasticity: $\sigma = 2$					
1a.	41.2%	$\overline{\tau_k}$ = 39.4%	None (until 2115)	–	–
3b.	40.9%	$\overline{\tau_k}$ = 39.4%	"Wrong" (First-Best)	$9.0	0.43%
4b.	40.9%	$\overline{\tau_k}$ = 39.4%	Optimized	$10.1	0.48%
3a.	$\overline{\tau_l}$ = 40.75%	40.2%	"Wrong" (First-Best)	$7.6	0.36%
4a.	$\overline{\tau_l}$ = 40.75%	39.4%	Optimized	$9.5	0.45%
5.		Optimized		$37.4	1.71%
Consumption elasticity: $\sigma = 1.1$					
1a.	35.7%	$\overline{\tau_k}$ = 33.2%	None (until 2115)	–	–
3b.	35.2%	$\overline{\tau_k}$ = 33.2%	"Wrong" (First-Best)	$44.6	1.17%
4b.	35.2%	$\overline{\tau_k}$ = 33.2%	Optimized	$45.5	1.19%
3a.	$\overline{\tau_l}$ = 35%	34.6%	"Wrong" (First-Best)	$39.5	1.04%
4a.	$\overline{\tau_l}$ = 35%	33.2	Optimized	$44.2	1.16%
5.		Optimized		$73.9	1.89%
Government spending −10%					
1a.	32.5%	$\overline{\tau_k}$ = 29.6%	None (until 2115)	–	–
3b.	32.1%	$\overline{\tau_k}$ = 29.6%	"Wrong" (First-Best)	$23.1	0.79%
4b.	32.2%	$\overline{\tau_k}$ =29.6%	Optimized	$23.2	0.79%
3a.	$\overline{\tau_l}$ = 32%	29.6%	"Wrong" (First-Best)	$22.1	0.76%
4a.	$\overline{\tau_l}$ = 32%	29.6%	Optimized	$22.7	0.77%
5.		Optimized		$38.5	1.29%
Government spending +10%					
1a.	45.6%	$\overline{\tau_k}$ = 38%	None (until 2115)	–	–
3b.	45.6%	$\overline{\tau_k}$ = 38%	"Wrong" (First-Best)	$11.2	0.45%
4b.	45.2%	$\overline{\tau_k}$ = 38%	Optimized	$20.8	0.83%
3a.	$\overline{\tau_l}$ = 45%	40.2%	"Wrong" (First-Best)	$11.2	0.45%
4a.	$\overline{\tau_l}$ = 45%	38.2%	Optimized	$19.6	0.79%
5.		Optimized		$56.3	2.16%

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}, labour 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:

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

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).

subject to feasibility and the optimizing behaviour 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:

$$\sum_{i=1}^{N}\left\{(1-D^i(T_t))A_{1it}\widetilde{F}_{1i}(L_{1it},K_{1it},E_{it})+(1-\delta)K_{it}-C_{it}-G_{it}^C-K_{it+1}-\Theta_{it}(\mu_{it}E_{it})\right\}\geq 0 \quad (6.1)$$

Note that (6.1) allows for heterogeneity in climate damages $D^i(T_t)$, production structures $A_{1it}\widetilde{F}_{1i}(.)$, abatement technologies Θ_{it}, and government consumption requirements $\{G_{it}^C\}_{t=0}^{\infty}$ across countries. Also note that (6.1) remains valid regardless of whether countries can trade the energy good, as net exports across countries sum to zero in the aggregate (see Supplementary Appendix). Letting λ_{1t} denote the Lagrange multiplier on (6.1), 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:*

$$\tau_{Eit}^{*}=\tau_{Et}^{*}=\sum_{j=0}^{\infty}\sum_{n=1}^{N}\beta^j\left(\gamma_t^n\frac{(-U_{Tnt+j}/U_{cnt})}{MCF_t^n}+\frac{\lambda_{1t+j}}{\lambda_{1t}}\left(\frac{-\partial Y_{t+j}^n}{\partial T_{t+j}}\right)\right)\frac{\partial T_{t+j}}{\partial E_t^M} \quad (6.2)$$

Proof: See Supplementary 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 costs of emissions reductions across countries, as desired. Comparing (6.2) with the benchmark optimal tax expression (3.1) 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}, $n\in\{1,\ldots,N\}$. 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:*

$$\gamma_t^i=\frac{\overline{U_{ct}}+\overline{\phi H}_{ct}-\phi_i H_{ct}^i}{U_{cit}} \quad (6.3)$$

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

$$\tau^*_{Eit}=\tau^*_{Et}=\sum_{j=0}^{\infty}\sum_{n=1}^{N}\beta^j\left(\gamma_t^n\frac{(-U_{Tnt+j}/U_{cnt})}{MCF_t^n}+\frac{\lambda_{1nt+j}}{\lambda_{1nt}}\left(\frac{-\partial Y^n_{t+j}}{\partial T_{t+j}}\right)\right)\frac{\partial T_{t+j}}{\partial E_t^M} \tag{6.4}$$

Proof: See Supplementary Appendix. Note that, in the first-best setting with domestic lump-sum taxation, the implementability constraint is non-binding ($\phi=0$), and (6.3) 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 (6.3) 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:

$$\tau_{Eit}=\sum_{j=0}^{\infty}\sum_{n=0}^{N}\beta^j\left(\frac{\mathrm{MCF}_t^n}{\mathrm{MCF}_t^i}\frac{U_{cnt}}{U_{cit}}\right)\left\{\gamma_t^n\frac{(-U_{Tnt+j}/U_{cnt})}{\mathrm{MCF}_t^n}+\frac{\lambda_{1nt+j}}{\lambda_{1nt}}\left(\frac{-\partial Y^n_{t+j}}{\partial T_{t+j}}\right)\right\}\frac{\partial T_{t+j}}{\partial E_{it}^M}. \tag{6.5}$$

Formulation (6.5) 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 (6.5) 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 (Nordhaus, 2008; Golosov *et al.*, 2014, 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 Ríos-Rull, 2003). Schmitt (2014) thus analyses the no-commitment case for jointly optimal carbon and income taxation.[37] The direct interactions of climate policy with pre-distorted factor markets (for labour 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

36. A quantification of (6.5) in a multi-country integrated assessment model would be interesting but is beyond the scope of this study. Babiker *et al.* (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 article.

reduces contemporaneous labour supply but increases labour 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: 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 article'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 article 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 article 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 labour 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 article 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 article 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.

38. This insight is analogous to results pertaining to optimal taxation and public expenditures by Klein *et al.* (2008), as noted by Schmitt (2014).

As this article 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 article 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 article 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 *et al.* (2015) showing that both factors can significantly increase optimal carbon prices. Other work has focused on climate policy and business cycles (Fischer and Springborn, 2011; Heutel, 2012). 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 labour, 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 article'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.

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Supplementary Data

Supplementary data are available at *Review of Economic Studies* online.

A. APPENDIX A

A.1. *Proof of Proposition 2*

Step 1: Derive general optimal tax expressions (3.1)

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 $W_t = W(C_t, L_t, T_t, \phi) \equiv U(C_t, L_t, T_t) + \phi\left[U_{ct}C_t + U_{lt}L_t - U_{ct}G_t^T\right]$, the planner's problem is given by:

$$\max \sum_{t=0}^{\infty} \beta^t \underbrace{[U(C_t, L_t, T_t) + \phi\left[U_{ct}C_t + U_{lt}L_t - U_{ct}G_t^T\right]]}_{\equiv W_t} \tag{A.1}$$
$$-\phi\left\{U_{c0}\left[K_0\left\{1+(F_{k0}-\delta)(1-\tau_{k_0})\right\}+B_0\right]\right\}$$

$$+\sum_{t=0}^{\infty}\beta^t\lambda_{1t}\left[\left\{(1-D(T_t))A_{1t}\widetilde{F}_1(L_{1t},K_{1t},E_t)\right\}+(1-\delta)K_t-C_t-G_t^C-K_{t+1}-\Theta_t(\mu_tE_t)\right]$$

$$+\sum_{t=0}^{\infty}\beta^t\xi_t[T_t-F(\mathbf{S}_0,(1-\mu_0)E_0,(1-\mu_1)E_1,...,(1-\mu_t)E_t,\eta_0,....\eta_t)]$$

$$+\sum_{t=0}^{\infty}\beta^t\lambda_{lt}[L_t-L_{1t}-L_{2t}]$$

$$+\sum_{t=0}^{\infty}\beta^t\lambda_{kt}[K_t-K_{1t}-K_{2t}]$$

$$+\sum_{t=0}^{\infty}\beta^t\lambda_{2t}[A_{2t}F_2(K_{2t},L_{2t})-E_t]$$

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

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

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 (2.11):

$$\begin{aligned} [p_{Et}-\tau_{It}-\tau_{Et}]F_{2lt} &= w_t \\ \tau_{Et} &= \Theta_t'. \end{aligned} \tag{A.3}$$

Invoking competitive equilibrium prices based on (2.8) and (2.11) and comparing the decentralized behaviour 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:

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

Separating production and utility damages, multiplying the latter by U_{ct}/U_{ct} and invoking the definition of the MCF_t (2.16), yields the general optimal carbon tax expression (3.1):

$$\tau_{Et}^*=\underbrace{\sum_{j=0}^{\infty}\beta^j\left[\frac{-U_{Tt+j}}{U_{ct}}\frac{1}{\text{MCF}_t}\right]\frac{\partial T_{t+j}}{\partial E^{M_t}}}_{\text{Utility damages}}+\underbrace{\sum_{j=0}^{\infty}\beta^j\left[\frac{-\partial Y_{t+j}}{\partial T_{t+j}}\frac{\lambda_{1t+j}}{\lambda_{1t}}\right]\frac{\partial T_{t+j}}{\partial E^{M_t}}}_{\text{Production damages}} \tag{A.4}$$

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 (2.18). 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 (3.2), one can easily show that:

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

Similarly, for preferences (3.3),

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

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:

$$\frac{\lambda_{1t}}{\lambda_{1t+1}} = \frac{W_{ct}}{W_{ct+1}} = \frac{U_{ct}}{U_{ct+1}}. \tag{A.5}$$

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 $t > 0$):

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

Combining (A.6) with (A.5) and comparing to the household's intertemporal optimality conditions (2.4) 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 2.5°C 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 (4.5), the total utility change from 2.5°C warming utility damages is given by:

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

Analogously, the total utility change from a consumption loss of $D(2.5°)$ can be approximated:[39]

$$\begin{aligned}\Delta U^Y &\approx U(2.5°) - U(0°) \\ &= \frac{(1-\varsigma l_t)^{\gamma(1-\sigma)}}{1-\sigma}\left[C_t^{\star(1-\sigma)}(1-D(2.5°))^{1-\sigma} - C_t^{\star 1-\sigma}\right],\end{aligned} \tag{B.2}$$

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 $D(2.5°)$. Consumption levels $C_{2.5°\mathrm{C}}$ are taken from a modified business-as-usual (BAU) run of the 2010 DICE model.[40] Labour supply $l_{2.5°\mathrm{C}}$ is set at the baseline COMET value, since the BAU scenario represents the idea of no tax reform. The benchmark COMET has $\alpha_0 = 0.00023808$ with distortionary taxes, and $\alpha_0 = 0.00027942$ without distortionary taxes. Finally, note that one can easily show that the temperature risk aversion coefficient (Weitzman, 2010) implied by utility function (4.5) 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 $(1-D(2.5°)) = \frac{1}{1+\theta_1 T_t^2}$ as assumed for production damages in (4.4), 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).

39. Specification (B.2) is only an approximation because it ignores general equilibrium effects on labour 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.

B.2. *Computation*

In order to numerically solve the planner's infinite horizon problem, I follow a similar though slightly different approach as Jones *et al.* (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 *et al.* (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 labour 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.

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