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

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Abstract

How should carbon be taxed as a part of fiscal policy? The literature on optimal carbon taxes often abstracts from other taxes. However, when governments raise revenues with distortionary taxes, carbon levies have fiscal impacts. While they raise revenues directly, they may shrink the bases of other taxes (e.g., by decreasing employment). This paper theoretically characterizes and then quantifies optimal carbon taxes in a dynamic general equilibrium climate-economy model with distortionary fiscal policy. First, this paper establishes a novel theoretical relationship between the optimal taxation of carbon and of capital income. This link arises because carbon emissions destroy natural capital: They accumulate in the atmosphere and decrease future output. Consequently, this paper shows how the standard logic against capital income taxes extends to environmental capital investments. Second, this study demonstrates that optimal carbon taxes must internalize climate change production impacts (e.g., on agriculture) and direct utility impacts (e.g., on biodiversity existence value) differently, and proposes a quantitative differentiation of these effects. Third, this paper compares the setting with distortionary taxes to the setting with lump-sum taxes considered in the literature. The central quantitative finding is that optimal carbon tax schedules are $6\% - 23\%$ lower when there are distortionary taxes.

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1 Introduction

Raising revenues and addressing climate change are two fundamental challenges facing governments. This paper considers these tasks jointly. Specifically, I study the optimal design of carbon taxes both as an instrument to control climate change and as a part of fiscal policy. Both academic[1] and policy[2] studies of optimal carbon pricing typically focus on the climate externality as the only distortion in the economy. In such a setting, the optimal carbon tax is *Pigouvian*: it internalizes the full environmental damage cost of carbon emissions.[3] However, theses studies do not consider potential interactions between carbon levies and other taxes.

Carbon pricing, if implemented, will interact with fiscal policy. On the one hand, carbon taxes raise revenues directly. On the other hand, they may decrease revenues indirectly by shrinking the bases of other taxes. For example, if climate policy decreases employment, this will reduce the revenue benefits and exacerbate the welfare costs of labor taxes. Several studies using detailed computable general equilibrium models have found that the welfare costs of these fiscal interactions likely exceed the (non-environmental) revenue benefits of carbon taxes (Goulder, 1995; Bovenberg and Goulder, 1996; Jorgenson and Wilcoxen, 1996; Babiker, Metcalf, and Reilley, 2003; etc.). Bovenberg and Goulder (1996) consequently advocate taxing carbon below Pigouvian rates. However, these papers abstract from the environmental benefits of climate policy. That is, they do not consider feedback effects between the climate and the economy.

This paper theoretically characterizes and then quantifies optimal carbon tax schedules in an integrated assessment climate-economy model (IAM) with distortionary fiscal policy. I combine a dynamic general equilibrium model of the world economy[4] that includes linear taxes 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 IAMs used by the United States government to value the impacts of carbon dioxide emissions. The three main findings of this paper are as follows.

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

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

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

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

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

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

Second, I find that carbon taxes must value climate damages that affect production possibilities differently from those that affect utility directly. Utility impacts reflect the value of the climate as a final consumption good (e.g., biodiversity existence value). Internalizing these damages yields no production gain and creates efficiency costs due to tax interactions. Consequently, I show that the optimal carbon tax does not fully internalize utility damages, pricing them below the Pigouvian rate.[5] Most studies on pollution control in the presence of distortionary taxes assume that environmental degradation affects only utility.[6] However, for climate change, I argue that production impacts account for around 75% of climate damages at $2.5°C$ warming. Consequently, I find that modeling all climate impacts as utility losses leads to an underestimate of the optimal carbon tax.

Third, I compare optimal climate policy in the setting with distortionary taxes to the setting with lump-sum taxes considered in the literature and policy realm. I find that the optimal carbon tax schedule is $6-23\%$ *lower* when there are distortionary taxes. Two effects explain this result. One, as factor taxes decrease the size of the economy, the value of climate damages is $3-7\%$ lower when fiscal policy is taken into account. Two, the optimal carbon tax does not fully internalize marginal damages due to tax interactions, accounting for a further $4-18\%$ reduction in the optimal carbon price. The welfare gains from carbon taxes in the twenty-first century are nonetheless estimated to be extremely large, ranging from \$21 $-$ 27 trillion (\$2005 lump-sum consumption equivalent). I also find that policy-makers can increase the welfare benefits of climate policy by considering the fiscal setting in setting carbon tax levels and revenue uses.

These results further relate to the literature in the following ways. On the theory side, the carbon-capital tax link is novel, to the best of my knowledge. While an extensive literature has explored pollution pricing alongside distortionary taxes,[7] this literature has predominantly

5 This result formally extends Bovenberg and Goulder's (1996) classic formulation to a dynamic setting.

6 Two important exceptions are Williams (2002) and Bovenberg and van der Ploeg (1994), who establish the need to differentiate output and production damages in a static setting. I provide conditions under which their result does and does not generalize to a dynamic setting.

7 Including, e.g.: Sandmo (1975); Bovenberg and de Mooij (1994, 1997, 1998); Bovenberg and van der Ploeg (1994); Ligthart and van der Ploeg (1994); Bovenberg and Goulder (1996); Parry, Williams, and Goulder (1999); Schwarz and Repetto (2000); Cremer, Gahvari, and Ladoux (2001; 2010); Williams (2002); Bento and

focused on static settings. As a result, few studies in this area have considered intertemporal distortions.[8] Similarly, while a substantial literature has explored environmental policy in dynamic general equilibrium growth models with capital accumulation,[9] these studies generally abstract from tax distortions.

On the quantitative side, the results similarly relate to two branches of the literature. On the one hand, several studies have employed detailed multi-sector dynamic computable general equilibrium (CGE) models to assess the welfare impacts of carbon levies in economies with tax distortions.[10] However, as these studies abstract from climate-economy interactions, this paper's results indicate that they may underestimate the optimal carbon tax. On the other hand, a rich and growing literature has developed integrated assessment models to quantify the effects of a variety of climate-economy interactions on optimal climate policy.[11] However, these models generally abstract from fiscal policy. The results of this paper indicate that they may thus overestimate the optimal carbon price, ceteris paribus.

There are, of course, many caveats to the present analysis. The model is based on a highly simplified representation of the global economy and fiscal policy. First, I thus also consider a multi-country version of the theoretical model, and derive conditions under which a uniform global carbon tax remains optimal despite cross-country heterogeneity. Second, while the benchmark theoretical results are based on a Ramsey framework with full commitment and zero optimal capital income taxes, it is well-known that various model modifications can change this policy prescription. I thus also provide both theoretical and quantitative results for a setting with exogenously given positive capital (and labor) taxes, calibrated based on empirical effective tax rate estimates from 107 countries.[12] 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

Jacobsen (2007); West and Williams (2007); Carbone and Smith (2008); Fullerton and Kim (2008); Kaplow (2012); Schmitt (2014); d'Autume, Schubert, and Withagen (2016). See also Bovenberg and Goulder (2002).

8 Chiroleu-Assouline and Fodhab (2006) consider general 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. Similarly, several studies model pollution levies in endogenous growth settings with distortionary taxes (Fullerton and Kim, 2008; Bovenberg and de Mooij, 1997; Hettich, 1998; Ligthart and van der Ploeg, 1994) but focus on long-run outcomes along a balanced growth path. This paper studies carbon taxes and fiscal policy in the near term and during the transition to balanced growth while taking long-run growth rates as given.

9 E.g., van der Ploeg and Withagen (1991, 2014); Bovenberg and Smulders (1996); Leach (2009); Hassler and Krusell (2012); GHKT (2014); Rezai and van der Ploeg (2014); Iverson (2014); Gerlagh and Liski (2016).

10 E.g.: Goulder (1995); Bovenberg and Goulder (1996); Jorgenson and Wilcoxen (1996); Babiker, Metcalf, and Reilley (2003); Bernard and Vielle (2003); Carbone, Morgenstern, and Williams (2012); Jorgenson et al. (2013); Rausch and Reilly (2015).

11 E.g., Manne and Richels (2005); Nordhaus (2008); Hope (2011); Acemoglu, Aghion, Bursztyn, and Hemous (2012); Anthoff and Tol (2013); Lemoine and Traeger (2014); GHKT (2014), Desmet and Rossi-Hansberg (2015); Cai, Judd, and Lontzek (2015), etc.

12 Section 4 also discusses the implications of limited commitment based on recent work by Schmitt (2014).

climate-economy modeling literature, such as different forms of uncertainty (e.g., Lemoine and Treager, 2014; Cai, Judd, Lontzek, 2015). Instead, this paper presents the first formal integration of distortionary taxes in a dynamic general equilibrium climate-economy model. This paper thus analyzes the ceteris paribus implications of tax distortions for optimal climate policy in a transparent setting, building on the seminal DICE model (Nordhaus, 2008, 2010) and the benchmark GHKT (2014) framework.

The remainder of this paper proceeds as follows. Section 2 describes the theoretical model. Section 3 provides the benchmark theory results. Section 4 discusses robustness to the multi-country setting and discusses limited commitment. Section 5 presents the calibration and additional features of the quantitative model. Section 6 presents the quantitative results, and Section 7 concludes.

2 Model

This section describes the theoretical model, which is kept as simple as possible to maximize analytic transparency. To summarize, the model combines a climate-economy structure based on Golosov, Hassler, Krusell, and Tsyvinski (GHKT) (2014) with an optimal dynamic taxation framework in the Ramsey tradition (see, e.g., Chari and Kehoe, 1999). Following GHKT, I focus on an infinitely-lived, globally representative household. An important difference to GHKT is that agents have preferences not only over consumption, but over leisure and the climate as well. There are two production sectors. The aggregate final consumption-investment good is produced using capital, labor, and energy inputs. Climate change affects productivity in this sector. A carbon-based energy input is produced from capital and labor. Energy use generates greenhouse gas emissions, which accumulate and change the climate. The central innovation over GHKT is that the government faces the dual task of addressing this environmental 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 taxes are not available, following the standard Ramsey approach.[13]

Households

An infinitely-lived, representative household has well-behaved preferences over consumption C_t, labor supply L_t, and a climate change variable T_t. Integrated assessment models vary in the climate indicators they consider. I follow the common approach of using *mean global surface*

[13] The revenues raised from Pigouvian carbon taxes are thus assumed to be insufficient to meet government revenue needs.

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 :

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

I generally assume that environmental quality enters preferences additively separably from consumption and leisure:

$$U(C_t, L_t, T_t) = h(C_t, L_t) + v(T_t) \tag{2}$$

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

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

where B_{t+1} denotes one-period government bond purchases, ρ_t the price of one-period bonds, K_{t+1} the household's capital holdings in period $t+1$, w_t the gross wage, τ_{lt} linear taxes on labor income, τ_{kt} linear taxes on capital income, r_t the return on capital, δ the depreciation rate, and Π_t profits from energy production. I place several restrictions on these variables. 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. Finally, initial asset holdings B_0 are given.

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

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

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

where U_{it} denotes the partial derivative of utility with respect to argument i at time t. In words, the Euler equation (4) states that households equate their marginal rate of substitution between

[14] Specifically, the optimal internalization of production versus utility damages alongside distortionary taxes is unchanged. However, non-separability adds terms to the optimal *total* carbon tax, which could increase or decrease depending on whether temperature change is a relative complement or substitute to leisure (in line with, e.g., Schwartz and Repetto, 2000). See Online Appendix for further details.

consumption in periods t and $t+1$ to the after-tax return on saving between periods t and $t+1$. Similarly, the implicit labor supply equation (5) states that agents equate their marginal rate of substitution between consumption and leisure to the after-tax return on working.

Final Goods Production

There are two production sectors: a final consumption-investment good (indexed by "1") and energy (indexed by "2"). The consumption-investment good is produced by a technology $\widetilde{F_1}$ which features constant returns to scale in energy E_t, labor L_{1t}, and capital K_{1t} inputs, and satisfies the standard Inada conditions. Output Y_t further depends on temperature change T_t and an exogenous technology parameter A_{1t} :

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

The formulation of climate damages as fraction of output lost in (6) was pioneered by Nordhaus (1991) and is extensively used in the literature.[15,16] A common approach is to monetize all types of damages, including ones that do not affect the production of consumption goods (e.g., biodiversity existence value), and to subtract those costs from output as in (6). However, in a setting with distortionary taxes, distinguishing climate damages that affect production possibilities is necessary. Here, formulation (6) thus represents only actual production effects of climate change (e.g., in agriculture, fisheries, skiing services, etc.). Final goods producers choose factor inputs in competitive markets so as to equate their marginal products with their prices:

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

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

[15] Climate impacts can, of course, be positive as well (see, e.g., Tol, 2002). The calibration incorporates positive impact estimates where applicable (see Section 5). The theoretical implications of heterogeneity are addressed in Section 4.

[16] Rezai, van der Ploeg, and Withagen (2012) study the implications of *additive* production damages.

Energy Production

Carbon-based energy can be produced from capital K_{2t} and labor L_{2t} inputs through a constant returns to scale technology:

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

Profits from energy production are then given by:

$$\Pi_t = (p_{Et} - \tau_{Et})E_t - w_t L_{2t} - r_t K_{2t} \tag{10}$$

where τ_{Et} denotes the excise tax on carbon energy. The constant returns to scale formulation (9) assumes that carbon energy is in unlimited supply and therefore earns zero Hotelling profits. As argued by GHKT (2014), this is a reasonable assumption for coal. In addition, the key theoretical results are robust to consideration of non-renewable resource dynamics.[17] The quantitative version of the model also incorporates the possibility of clean energy production. However, as these technologies do not influence the theoretical results, I abstract from them here.

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

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

This assumption is in line with GHKT (2014). Due to the 10 year time step used in the empirical model, formulation (11) is also more realistic than in an annual formulation. An important implication of (11) is that factor prices will be equated across sectors in equilibrium. Competitive energy producers thus equate marginal factor products and prices:

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

Government

As is standard in the Ramsey approach to optimal taxation, I assume that the government needs to finance an exogenously given sequence of positive revenue requirements $\{G_t > 0\}_{t=0}^{\infty}$, and

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

to pay off inherited debt B_0^G. The government can issue new, one-period bonds B_{t+1}^G and levy linear taxes on labor and capital income. In addition, the government can impose excise taxes τ_{Et} on carbon emissions E_t.[18] The consumption good serves as the untaxed numeraire. The government's flow budget constraint each period is given by:

$$G_t + B_t^G = \tau_{lt} w_t L_t + \tau_{Et} E_t + \tau_{kt}(r_t - \delta)K_t + \rho_t B_{t+1}^G \tag{13}$$

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

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

The analysis assumes that the government can commit to a tax policy sequence at time zero. Though common, this assumption is not innocuous. I discuss its implications in Section 4.

Carbon Cycle

The only assumption placed on the carbon cycle at this stage is that temperature change T_t at time t is a function of initial carbon concentrations S_0 and all past carbon emissions:

$$T_t = F_t\left(S_0, E_0, E_1, ..., E_t\right) \tag{15}$$

where:

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

Competitive Equilibrium

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

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

(i) the allocations solve the consumer's and the firm's 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

(iii) markets clear.

The Ramsey framework assumes that the government seeks to maximize the household's lifetime utility (1) subject to the constraints of (i) feasibility and (ii) the optimizing behavior of households and firms, for a given set of initial conditions. I characterize the optimal allocations

[18] Energy is denoted in units of carbon content. One unit of energy thus emits one ton of carbon.

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

$$Y_t + (1-\delta)K_t \geq C_t + G_t + K_{t+1} \tag{RC}$$

$$T_t \geq \digamma_t(S_0, E_0, E_1, ...E_t) \tag{CCC}$$

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

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

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

and

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

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: Online Appendix. This proposition and its proof differ from the setup in Chari and Kehoe (1999) mainly through the addition of the energy production sector and the carbon cycle constraint. In words, Proposition 1 ensures that any allocation satisfying conditions (RC)-(IMP) can be decentralized as a competitive equilibrium. I assume that the solution to the Ramsey problem is interior and that the planner's first order conditions are both necessary and sufficient.

Formally, the government's problem is thus to maximize household lifetime utility (1) subject to (RC)-(IMP) (see Appendix A). Let λ_{1t} denote the Lagrange multiplier on the aggregate resource constraint (RC) in period t.

Before describing the results, define the following two concepts. First, the *marginal cost of public funds* (MCF) measures the welfare cost of raising an additional dollar of government revenue. As lump-sum taxes are pure transfers, their MCF is one. In contrast, raising \$1 from distortionary taxes costs households \$1 *plus* the excess burden (or the marginal deadweight loss) of the associated tax increase. Estimates from the literature (summarized in the Online Appendix) yield a GDP-weighted global average MCF of 1.48, implying that \$0.48 of welfare are lost for every \$1 of revenue raised on average. I follow the standard approach of defining the MCF as follows:

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

$$MCF \equiv \frac{\lambda_{1t}}{U_{ct}} \tag{16}$$

The MCF thus measures the welfare cost of transferring a unit of the consumption good from households to the government.[19] Second, define "Pigouvian" carbon taxes as follows:

Definition: *Let the Pigouvian carbon tax be defined as the present value of marginal damages evaluated at the optimal allocation, and valued at the agent's marginal utility of consumption. Pigouvian taxes to internalize climate impacts on production and utility, respectively, are:*

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

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

and the total Pigouvian carbon tax is defined as fully internalizing both types of damages:

$$\tau_{Et}^{Pigou,T} \equiv \tau_{Et}^{Pigou,U} + \tau_{Et}^{Pigou,Y} \tag{19}$$

Here, $\frac{\partial Y_{t+j}}{\partial T_{t+j}}$ is the marginal output change from temperature at time $t+j$, U_{Tt+j} denotes the marginal disutility of temperature change at time $t+j$, and $\frac{\partial T_{t+j}}{\partial E_t}$ is the change in temperature at time $t+j$ caused by a marginal increase in today's carbon emissions. These definitions are standard. Focusing on production impacts, GHKT (2014) show that (17) defines the optimal carbon price in the first-best setting. The next section characterizes optimal carbon tax design alongside other, distortionary taxes.

3 Theory Results

This section first presents the optimal carbon tax formulation in the general case, and then develops intuition for and implications of the results for two special cases where climate change affects only utility or production possibilities. Combining the planner's first order conditions from (A.1), comparing them with the energy producer's profit-maximizing conditions (12), it is straightforward to show (see Appendix A) the following: The carbon tax in period $t > 0$ that decentralizes the optimal allocation - provided that all other prices and policies are set

[19] The MCF cannot be expressed in closed-form in this setting. Even on a balanced growth path, long-run tax rates are endogenous to the history of taxes and government revenues collected. See Barrage (2014).

appropriately - is implicitly defined as follows:

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

Expression (20) shows that the optimal carbon price consists of two components: one to internalize the discounted sum of future utility damages $\left(\frac{-U_{Tt+j}}{U_{ct}}\right)$ associated with an increase in time t carbon emissions $\left(\frac{\partial T_{t+j}}{\partial E_t}\right)$, and one to internalize the sum of future production impacts $\left(\frac{-\partial Y_{t+j}}{\partial T_{t+j}}\right)$. 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 the tax code is distortionary ($MCF_t > 1$), then the optimal policy does not fully internalize utility damages from carbon emissions. In contrast, the planner's valuation of production damages depends on the evolution of the public marginal utility of income λ_{1t+j} over time. While it is difficult to derive concrete insights on this term in the fully general case, restricting preferences to two commonly used CES forms leads to the following result:

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

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

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

then the optimal carbon tax for period $t > 0$ is implicitly defined by:

$$\tau^*_{Et} = \frac{\tau^{Pigou,U}_{Et}}{MCF_t} + \tau^{Pigou,Y}_{Et} \tag{23}$$

Alternatively, letting $\theta^u_t \equiv (\tau^{Pigou,U}_{Et}/\tau^{Pigou,T}_{Et})$ denote the share utility impacts in the present value of marginal damages from period t emissions, the optimal carbon tax is implicitly defined by:

$$\tau^*_{Et} = \tau^{Pigou,T}_{Et}\left[1 + \theta^u_t \frac{(1 - MCF_t)}{MCF_t}\right] \tag{24}$$

Proof: See Appendix A. In words, Proposition 2 shows that, for commonly used CES preferences (21)-(22), the optimal policy fully internalizes output damages from carbon missions, but does not fully internalize utility impacts if the tax code is distortionary ($MCF > 1$).[20] The extent

[20] Both Bovenberg and van der Ploeg (1994) and Williams (2002) derive analogous expressions to (23) in a

to which the second-best pollution tax differs from the Pigouvian rate thus depends critically on (i) the extent to which damages affect utility versus production θ_t^u, and (ii) the severity of tax distortions (MCF_t).[21] In order to elucidate and contextualize these results, the remainder of this section analyzes output and utility damages separately.

Special Case 1: Climate Change Affects Only Utility

Previous studies on environmental policy alongside other taxes typically assume that pollution affects only utility. In this case, we have the following result:

Remark 1 *The optimal carbon tax in period $t > 0$ is implicitly defined by:*

$$\tau_{Et}^{*} = \frac{\tau_{Et}^{Pigou,U}}{MCF_t} \tag{25}$$

where MCF_t is the contemporaneous marginal cost of public funds as defined in (16).

Proof: Without output damages, the optimal carbon tax expression (20) reduces to the present value of utility damages divided by the MCF_t :

$$\tau_{Et}^{*} = \sum_{j=0}^{\infty} \beta^j \left[\frac{-U_{Tt+j}}{U_{ct}} \frac{1}{MCF_t} \right] \frac{\partial T_{t+j}}{\partial E_t} \tag{26}$$

Combining (26) with the definition of $\tau_{Et}^{Pigou,U}$ (18) yields the result (25). Note that Remark 1 holds regardless of whether preferences match (21)-(22).

Intuitively, utility damages reflect the value of the climate as a final consumption good (e.g., amenity value, cultural treasures, etc.). Expression (25) implies that the optimal allocation leaves a wedge between the household's marginal rate of substitution (MRS) and the marginal rate of transformation (MRT) between the climate and the final consumption good. The provision of the climate good is thus distorted, as damages are not fully internalized.

Intuitively, if climate change affects only utility, imposing a carbon tax provides no productivity benefits. To the contrary, carbon taxes will decrease the real returns to labor, as higher energy prices increase the cost of the consumption-investment good relative to leisure. By decreasing employment, carbon pricing can thus exacerbate the welfare costs of labor income taxes, which alter labor supply decisions by lowering the after-tax return to labor.[22] In order to account for the welfare cost of these tax interactions, the optimal carbon tax thus discounts utility

static setting. Here, I provide conditions under which (23) does and does not generalize to a dynamic setting.

[21] Of course, the level of the Pigouvian tax itself changes due to tax distortions. Section 6 addresses this issue.

[22] This is the tax interaction effect that has been extensively studied in the literature (see review by Bovenberg and Goulder, 2002).

damages by the MCF_t.This is the core "tax interaction effect" that has been extensively studied in the literature (see, e.g., Bovenberg and Goulder, 2002). Indeed, the static version of (25), ($\tau_E^* = \tau_E^{Pigou}/MCF$), is a classic formulation (Bovenberg and van der Ploeg, 1994; Bovenberg and Goulder, 1996, etc.). Remark 1 thus provides a generalization of this result to carbon taxation in a dynamic setting.

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 (26) reduces to:

$$\tau_{Et}^* = \sum_{j=0}^{\infty} \beta^j \left[\frac{-\partial Y_{t+j}}{\partial T_{t+j}} \frac{\lambda_{1t+j}}{\lambda_{1t}} \right] \frac{\partial T_{t+j}}{\partial E_t} \tag{27}$$

As previously noted, this term represents the discounted sum of marginal output changes $\left(\frac{-\partial Y_{t+j}}{\partial T_{t+j}}\right)$, as in the standard setting (GHKT, 2014). However, with distortionary taxes, the public value of output λ_{1t} differs from the household's ($\lambda_{1t+j} \neq U_{ct+j}$, see (16)). Whether (27) matches the Pigouvian tax (17) thus depends critically on how the planner's *relative* valuation of output in periods $t+j$ and t ($\frac{\lambda_{1t+j}}{\lambda_{1t}}$) 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 (27) by:

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

Each term $\frac{\lambda_{1t+j}}{\lambda_{1t}}$ can then be rearranged to equal $\left(\frac{\lambda_{1t+j}}{\lambda_{1t+j-1}} \frac{\lambda_{1t+j-1}}{\lambda_{1t-2}} ... \frac{\lambda_{1t+1}}{\lambda_{1t}} \right)$.

Second, combine the planner's FOCs 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:

$$\frac{\lambda_{1t}}{\lambda_{1t+1}} = \beta \left[F_{kt+1} + (1 - \delta) \right] \tag{28}$$

Third, from the capital optimality conditions of households (4) and firms (8), note that, in equilibrium,

$$\frac{U_{ct}}{U_{ct+1}} = \beta \left\{ 1 + (F_{kt+1} - \delta)(1 - \tau_{kt+1}) \right\} \tag{29}$$

Comparing (28) and (29) immediately shows that, if the government optimally chooses to set capital income taxes in period $t+1$ to zero, then:

$$\frac{\lambda_{1t}}{\lambda_{1t+1}} = \frac{U_{ct}}{U_{ct+1}} \tag{30}$$

If the government optimally sets capital income taxes to zero from period $t+1$ *onwards,* this implies that condition (30) 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 (27) yields the desired result: ■

$$\tau^*_{Et} = \sum_{j=0}^{\infty} \beta^j \left[\frac{U_{ct+j}}{U_{ct}} \frac{-\partial Y_{t+j}}{\partial T_{t+j}} \right] \frac{\partial T_{t+j}}{\partial E_t} = \tau^{Pigou,Y}_{Et} \tag{31}$$

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. 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.

To make these points more concrete, briefly consider a simplified two-period version of the model. The marginal rate of transformation between consumption in the two periods based on investment in physical capital is given by:

$$MRT^K_{0,1} = \frac{\text{Give up 1 unit of } C_0 \text{ to invest in capital}}{\text{Get } (F_{k1} + (1-\delta)) \text{ units of } C_1 \text{ tomorrow:}} = \frac{-1}{F_{k1} + 1 - \delta}$$

An *undistorted intertemporal margin* requires that this $MRT^K_{0,1}$ be equated with the household's marginal rate of substitution between consumption in the two periods:

$$\frac{\beta U_{c1}}{U_{c0}} = \frac{1}{F_{k1} + 1 - \delta} \tag{32}$$

Implementing the allocation (32) requires a zero effective capital income tax. However, the key issue in this economy is that there is an additional technology for converting C_0 into C_1: investments in climate capital. Specifically, assume initial period carbon emissions E_0 are reduced by one unit. In terms of the initial period consumption good, this will create a loss of F_{E0}, the marginal product of energy. However, it will also save marginal energy production costs MC. The net loss of C_0 associated with the emissions reduction is thus $F_{E0} - MC$. Society's aggregate return on this investment is avoided output losses from climate change in the next period $(\partial Y_1/\partial T_1)(\partial T_1/\partial E_0)$. In sum, the social MRT based on investments in climate capital is given by:

$$MRT_{0,1}^{\text{Climate}} = \frac{\text{Reduce } E_0 \text{ by 1 unit} \rightarrow \text{Give up } F_{E0} - MC \text{ units of } C_0}{\text{Get } (\partial Y_1/\partial T_1)(\partial T_1/\partial E_0) \text{ units of } C_1} = \frac{F_{E0} - MC}{(\partial Y_1/\partial T_1)(\partial T_1/\partial E_0)}$$

Equating the household's MRS with this MRT yields:

$$\frac{\beta U_{c1}}{U_{c0}} = \frac{F_{E0} - MC}{(\partial Y_1/\partial T_1)(\partial T_1/\partial E_0)} \tag{33}$$

What carbon tax decentralizes (33)? Multiplying both sides by $(\partial Y_1/\partial T_1)(\partial T_1/\partial E_0)$ immediately demonstrates that *an undistorted intertemporal margin for climate capital investments requires precisely a Pigouvian tax on carbon:*[23]

$$\frac{\beta U_{c1}}{U_{c0}} \left(\frac{\partial Y_1}{\partial T_1} \frac{\partial T_1}{\partial E_0} \right) = F_{E0} - MC = \tau_{E0}^{Pigou}$$

The literature on optimal dynamic Ramsey taxation has found that capital income taxes are undesirable in a range of models and settings (see, e.g., Judd, 1985; Chamley, 1986;[24] Atkeson, Chari, and Kehoe, 1999; Acemoglu, Golosov, and Tsyvinski, 2011). A number of studies have explored the implications of this result for human capital taxation (Judd, 1999; Jones, Manuelli, and Rossi, 1993, 1997). Proposition 3 demonstrates that the logic against capital income taxes further extends to distortions on investments in environmental capital:

Remark 2 *If preferences are of either commonly used constant elasticity form* (21)*-*(22)*, then:*

(i) the optimal capital income tax in period $t > 0$ is zero, and:

(ii) the optimal carbon tax to internalize production damages in period $t > 0$ is Pigouvian:

$$\tau_{Et}^{*} = \tau_{Et}^{Pigou,Y}$$

Both results follow from the fact that, with preferences (21) or (22), the planner's FOCs with respect to consumption and capital simplify to imply that $\frac{\lambda_{1t+1}}{\lambda_t} = \frac{U_{ct+1}}{U_{ct}}$ for all $t > 0$. As discussed in the proof of Proposition 3, this condition implies both the desirability of an effective capital

23 Here, the second equality follows because (i) competitive factor pricing implies that $F_{E0} = p_{E0}$ in equilibrium (see (8)), and (ii) the energy sector produces carbon up until the point where $(p_{Et} - \tau_{Et}) = MC$ (see (12)).

24 While Straub and Werning (2014) raise questions about these early studies, these apply to a different setting with an upper bound on capital income taxes. I discuss this case further below.

income tax of zero, and of a Pigouvian tax on carbon from period $t > 0$ onwards - even if labor markets are distorted.

Positive Capital Income Taxes In reality, most countries tax capital income in various forms (see Online Appendix for a review of effective tax rate estimates across countries). 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 taxes are positive.

For example, if an upper bound on capital income taxes is added to the current setup, the government optimally sets capital income taxes at this upper bound for a finite number of periods and eventually decreases them to zero.[25] In this setting, one can show that carbon taxes to internalize output damages are lower than Pigouvian rates for as long as capital income taxes remain positive (see Barrage, 2014).

In contrast, with an exogenous constraint that capital income tax rates be fixed at some positive level $\overline{\tau_k} \in (0, 1)$, carbon taxes to internalize output damages may be adjusted upwards or downwards relative to Pigouvian rates. From the consumer and final goods producer's first order conditions for capital, such a constraint can be formalized as:

$$\frac{U_{ct}}{\beta U_{ct+1}} = 1 + (1 - \overline{\tau_k})(F_{kt+1} - \delta) \tag{34}$$

for all $t > 0$. In this setting, the impacts of changes in energy use, factor allocation to energy production, and temperature change on the tightness with which (34) binds all figure into the optimal carbon tax formulation (see Appendix A for the derivation and details.)

Importantly, *production damages* from climate change now enter the optimal carbon tax formulation in two ways. On the one hand, they decrease welfare directly by reducing available resources in future periods as shown in the benchmark expression (27). These future output losses are now discounted at a higher rate than households' intertemporal marginal rate of substitution due to the intertemporal wedge in (34). If this were the only difference to the benchmark model with production damages, the optimal carbon tax would thus be less-than-Pigouvian.

However, output losses also interact with the constraint (34). Consider the case where the optimal capital tax is below $\overline{\tau_k}$. The net-of-tax marginal rate of transformation faced by agents when making their savings decisions is thus lower than the planner would want it to be. Climate change production losses decrease the marginal product of capital in future periods. Consequently, climate change exacerbates the capital income tax constraint in (34). This interaction provides the planner with an additional incentive to avoid climate change. Ceteris paribus, this

[25] This implication of upper capital income tax bounds is well-known (Atkeson, Chari, and Kehoe, 1999).

effect thus *increases* the optimal carbon tax to internalize output damages. In sum, the exogenous capital income tax can increase or decrease the optimal levy on production damages from climate change relative to the Pigouvian rate.

There are additional variables related to climate policy that interact with constraint (34) and alter the optimal total carbon tax formulation. For example, decreased energy use may decrease the marginal product of capital as well, depending on the complementarity between capital and energy in production. In that case, the carbon tax would need to be adjusted downward, ceteris paribus. The optimal *total* energy tax is thus also ex-ante ambiguously affected by a capital income tax constraint (34).

Of course there are many 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., Pikkety and Saez, 2013; Golosov, Kocherlakota, and Tsyvinski, 2003; Klein and Rios-Rull, 2003; etc.). Integrating climate capital into these models and exploring optimal carbon taxes in those frameworks is beyond the scope of this study but an interesting area for future research.[26,27]

4 Robustness

4.1 Heterogeneity Across Countries

The benchmark model considers a planner searching for a uniform optimal global carbon tax. In reality, countries have different tax codes, raising the question of whether a uniform carbon price provides a useful benchmark. This section derives two individually sufficient conditions for a uniform global carbon price to remain optimal in a multi-country setting: (i) If countries can make transfers to one another, or (ii) if welfare weights are set appropriately.[28] 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 (see, e.g., Nordhaus and Yang, 1996; also Chichilnisky and Heal, 1994; Sandmo, 2007) will do so here as well.

[26] For example, Cremer, Gahvari, and Ladoux (2001) study pollution taxes in a static Mirrleesian model, where distortions arise due to informational frictions. It would thus be interesting to extend their work to the dynamic setting.

[27] As discussed below, Schmitt (2014) studies optimal carbon taxes in a model of time-consistent fiscal policy building on Klein, Krusell, and Rios-Rull (2008). While he assumes a common labor-capital income tax, capital is thus taxed in his setting.

[28] d'Autume, Schubert and Withagen (2016) derive this result in a static multi-country endowment economy with dirty and clean consumption goods and distortionary taxes to finance public goods. This section extends their result to a dynamic production economy with factor taxation.

4.1.1 Case 1: Transfers Across Countries Are Possible

The assumption that countries can make transfers to each other, but cannot impose lump-sum taxes on their citizens, may seem asymmetrical, but arguably matches reality. For example, in 2014, the United States disbursed \$41 billion (\$2014) in foreign aid to 190 counties, including through *direct cash transfers to foreign governments* (USAID, 2016). In contrast, historical attempts at domestic lump-sum taxation have failed due to political resistance.[29] In the environmental realm, climate negotiators have created multilateral financial institutions (e.g., Green Climate Fund) to couple emissions reduction agreements with resource transfers across countries.

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

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

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

$$\sum_{i=1}^{n} \left\{ (1 - D^i(T_t)) A_{1it} \widetilde{F}_{1i}(L_{1it}, K_{1it}, E_{it}) + (1 - \delta) K_{it} - C_{it} - G_{it} - K_{it+1} \right\} \geq 0 \qquad (35)$$

Note that (35) allows for heterogeneity in climate damages $D^i(T_t)$, production structures $A_{1it}\widetilde{F}_{1i}(.)$, and government revenue requirements $\{G_{it}\}_{t=0}^{\infty}$ across countries. Also note that (35) remains valid regardless of whether countries can trade the energy good, as net exports across countries sum to zero in the aggregate (see Online Appendix). Letting λ_{1t} denote the Lagrange multiplier on (35), we have the following result:

Corollary 1 *If resources can be transferred across countries, the optimal global carbon tax for* $t > 0$ *is uniform across countries and implicitly defined by:*

$$\tau_{Eit}^* = \tau_{Et}^* = \sum_{j=0}^{\infty} \sum_{m=1}^{n} \beta^j \left(\gamma_t^m \frac{(-U_{Tmt+j}/U_{Cmt})}{MCF_{mt}} + \frac{\lambda_{1t+j}}{\lambda_{1t}} \left(\frac{-\partial Y_{t+j}^m}{\partial T_{t+j}} \right) \right) \frac{\partial T_{t+j}}{\partial E_t} \qquad (36)$$

Proof: Online Appendix.

29 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).

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 (36) with the benchmark optimal tax expression (20) further shows that the key theoretical results on the internalization of production versus utility damages are robust to the multi-country setting.

4.1.2 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_{1t}^m, $m \in \{1, ...n\}$. Let ϕ_i denote the Lagrange multiplier on country $i's$ implementability constraint, and define $H_t^i \equiv U_{cit}C_{it} + U_{lit}L_{it}$, 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. The Online Appendix shows the following:

Corollary 2 *If resources cannot be transferred across countries, but if the global planner weights country $i's$ utility at time t according to:*

$$\gamma_t^i = \frac{\overline{U_{ct}} + \overline{\phi H}_{ct} - \phi_i H_{ct}^i}{U_{ct}^i} \tag{37}$$

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

$$\tau_{Eit}^* = \tau_{Et}^* = \sum_{j=0}^{\infty} \sum_{m=1}^{n} \beta^j \left(\gamma_t^m \frac{(-U_{Tmt+j}/U_{Cmt})}{MCF_{mt}} + \frac{\lambda_{1mt+j}}{\lambda_{1mt}} \left(\frac{-\partial Y_{t+j}^m}{\partial T_{t+j}} \right) \right) \frac{\partial T_{t+j}}{\partial E_t} \tag{38}$$

Proof: Online Appendix.

Note that, in the first-best setting with domestic lump-sum taxation, the implementability constraint is non-binding ($\phi = 0$), and (37) 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 (37) 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:

$$\tau_{Eit} = \sum_{j=0}^{\infty}\sum_{m=0}^{n}\beta^j \left(\frac{MCF_t^m}{MCF_t^i}\frac{U_{ct}^m}{U_{ct}^i}\right)\left\{\gamma_t^m \frac{(-U_{Tmt+j}/U_{cmt})}{MCF_{mt}} + \frac{\lambda_{1mt+j}}{\lambda_{1mt}}\left(\frac{-\partial Y_{t+j}^m}{\partial T_{t+j}}\right)\right\}\frac{\partial T_{t+j}}{\partial E_{it}} \tag{39}$$

Formulation (39) 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 m are inversely proportional to both its marginal utility of consumption U_{ct}^i 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 (39) formally extends this general insight to a setting with distortionary taxes and variation in the MCF across countries.[30]

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

4.2 Limited Commitment

The analysis assumes that the government can commit to a sequence of tax rates at time zero. While this assumption is common in the Ramsey taxation literature and has been motivated on grounds such as reputational mechanisms, it is not innocuous. Both optimal tax policy and public expenditures have been shown to be highly sensitive to the planner's assumed commitment horizon (e.g., Klein and Rios-Rull, 2003). Schmitt (2014) thus analyzes the no-commitment case for jointly optimal carbon and income taxation.[31] The direct interactions of climate policy with pre-distorted factor markets (for labor and savings) remain at the core of second-best carbon tax design with limited commitment. Qualitatively, Schmitt (2014) finds that this setting changes

[30] A quantification of (39) in a multi-country IAM would be interesting but is beyond the scope of this study. Babiker, Metcalf, and Reilley (2003) and Bernard and Veille (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. An optimizing multi-country IAM with heterogeneous tax codes but no transfers thus remains an open challenge for future work.

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

the structure of some of these effects. For example, consider an increase in the carbon tax at time t that reduces contemporaneous labor supply but increases labor supply in the preceding periods ($t-1$, $t-2$, etc.). A Ramsey planner who can set taxes at time zero will take this benefit into account, whereas a government without a commitment technology will not.[32] 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 21st 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 paper's quantitative analysis considers several scenarios with positive capital income taxes calibrated to match real world rates. While the reasons for these positive capital income taxes are not endogenized as being due to, e.g.,, limited commitment, Schmitt's (2014) results indicate that the direct effect of the distortion dominates in driving the difference to first-best carbon taxes. Consequently, I focus on the (i) full commitment and (ii) exogenous realistic tax rate cases as benchmark results, and leave extensions to more detailed fiscally and politically constrained environments as an interesting area for future research.

5 Calibration of the COMET Model

This section describes the calibration of the Climate Optimization Model of the Economy and Taxation (COMET) outlined above. I build on the seminal DICE climate-economy model by Nordhaus (e.g., 2008), which serves as benchmark in the literature and policy applications. Broadly speaking, the COMET expands upon DICE by introducing tax policy and government expenditures, preferences for leisure and climate change, separate representations of production and utility damages, and an explicit energy production sector. The computational procedure is described in Appendix B, and the details of the calibration are as follows:

5.1 Carbon Cycle and Climate Model

The carbon cycle is taken directly from DICE (Nordhaus, 2010). There are three carbon reservoirs: the atmosphere, the upper ocean and biosphere, and the deep ocean. Endogenous industrial emissions E_t and exogenous land-based emissions first enter the atmosphere, and subse-

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

quently begin to be absorbed by the upper oceans and biosphere. Increases in atmospheric carbon change the earth's radiative energy balance, which, in turn, increases atmospheric temperatures T_t. DICE tracks both atmospheric and lower ocean temperature change, and accounts for delays in the warming of the climate system. The parameters match an equilibrium temperature change associated with a doubling of carbon dioxide concentrations (i.e., a climate sensitivity) of $3.2°C$.

5.2 Damages

The theoretical results demonstrate that it is necessary to account separately for production and utility damages in an environment with distortionary taxes. The literature commonly aggregates climate damages into pure production losses (e.g., Nordhaus, 2008; Golosov, Hassler, Krusell, and Tsyvinski, 2014), pure utility losses (e.g., Acemoglu, Aghion, Bursztyn, and Hemous, 2012), or distinguishes market vs. non-market impacts (*PAGE*, Hope, 2006, 2011; MERGE, Manne and Richels, 2005; *FUND*,[33] Tol, 1995, 1997). However, the differentiation of production vs. utility damages requires a different approach, as discussed below.

In order to maintain comparability with DICE, I use the regional-sectoral damage estimates underlying the DICE/RICE models (Nordhaus, 2007; Nordhaus and Boyer, 2000). These models present estimates of eight types of climate change impacts in each of twelve regions.[34] I first split and then re-aggregate these impacts according to the classification scheme presented in Table 1.

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

Table 1: Climate Damage Categorization

While the classification of some impacts is straightforward (e.g., agriculture), three categories

[33] 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).

[34] The distinct regions represented are: the United States, Western Europe, Russia, Eastern Europe/former Soviet Union, Japan, China, India, Middle East, Sub-Saharan Africa, Latin America, other Asian countries, and other high income countries.

warrant further explanation. First, seal-level rise coastal impacts represent damages to capital. Extending the benchmark model to incorporate climate-dependent capital depreciation ($\delta(T_t)$), one can easily show that the optimal carbon tax internalizes these losses identically to production damages.[35] Second, the catastrophic impact costs in DICE are based on expected damages from events equivalent to a permanent income loss of 30% of global GDP. However, this loss represents both literal 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.[36,37]

Third, while human health impacts are typically classified as "non-market" effects, they can alter production possibilities, such as by decreasing time endowments and labor productivity. In the literature, a common approach is to value projected years of life lost (YLL) from climate-sensitive diseases based on the value of statistical life literature (e.g., DICE, Nordhaus, 2008; FUND 3.7, Anthoff and Tol, 2013). In contrast, in order to capture labor market impacts of climate change, I use projected YLLs to separately estimate (i) the global labor time endowment reduction and corresponding output loss and (ii) the disutility from lost leisure time.[38] In addition, as labor productivity impacts have not generally been included in climate-economy models (Tol, 2011), I use available evidence in the literature to compute labor productivity losses associated with malaria - one of the most climate-sensitive diseases (WHO, 2009).[39]

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, different types of impacts are modeled with income elasticities to reflect, e.g., decreased disease vulnerability or higher amenity values as income levels grow (see Nordhaus and Boyer, 2000). Similarly, they use agricultural impact estimates from Ricardian models that incorporate adaptation (see Mendelsohn, Nordhaus, and Shaw, 1994). They also assume some amount of necessary migration due to sea-level rise, and compute an associated disutility of re-settlement. However, considerable uncertainty remains over factors such as trade, migration, and future changes in technology or even preferences (see, e.g., Atkin, 2013). One of the frontiers in the literature is to formalize the effects of such

[35] 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.

[36] In contrast, some prior studies focusing on a market/non-market delineation of climate damages have categorized catastrophic impacts as 'non-market' because they are difficult to monetize (e.g., Manne and Richels, 2006, on a potential shutdown of the North Atlantic thermohaline circulation).

[37] Note that (i) damage shares are measured relative to the *absolute value* of total non-catastrophic damages 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.

[38] Williams (2002) analyzes second-best environmental policy with health effects.

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

factors (e.g., Desmet and Rossi-Hansberg, 2015). However, as the research focus of this paper is to isolate the effects of distortionary taxes, I adopt the standard DICE damage estimates to maintain comparability to the literature.

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:[40]

$$\begin{array}{rcl} \text{Share of output damages} & : & 74\% \\ \text{Total damages from } 2.5° \text{ warming} & = & 1.74\% \text{ of output} \\ \text{Total } \textbf{production damages} & : & 1.29\% \text{ of output} \\ \text{Total } \textbf{direct utility damages} & : & 0.46\% \text{ of output} \end{array} \tag{40}$$

The COMET also adopts the functional form of the output damage function from DICE. However, the damage coefficient θ_1 is calibrated based on (40), yielding:

$$\begin{aligned} (1 - D_t(T_t)) &= \frac{1}{1 + \theta_1 T_t^2} \\ \theta_1 &= 0.0021 \end{aligned} \tag{41}$$

5.3 Preferences

Household preferences over per-capita consumption $c_t \equiv C_t/N_t$ (where N_t is the population at time t), labor l_t and climate change T_t are given by :

$$U(c_t, l_t, T_t) = \frac{\left[c_t \cdot (1 - \phi l_t)^\gamma\right]^{1-\sigma}}{1-\sigma} + \frac{\left(1 + \alpha_0 T_t^2\right)^{-(1-\sigma)}}{1-\sigma} \tag{42}$$

Specification (42) builds on King, Plosser, and Rebelo (2001) preferences with two modifications. First, I add parameter ϕ so as to jointly match base year labor supply ($l_{2005} = 0.227$ from OECD data), the inverse intertemporal elasticity of substitution (IES) from DICE ($\sigma = 1.5$), and a Frisch elasticity of labor supply of $\eta^F = 0.78$ (see survey by Chetty, Guren, Manoli, and Weber, 2011). The parameters either rationalize observed l_{2005} at $\tau_{l2005} = 36.09\%$ for the distortionary tax scenarios, or at $\tau_{l2005} = 0$ for the lump-sum taxation scenarios. The Online Appendix demonstrates that (42) retains consistency with a balanced growth path for the relevant parameter range, and provides further details.

[40] 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.

Second, (42) includes preferences over climate change. The specification 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 the split in (40). The Appendix provides further details. Finally, I adopt the DICE model's pure rate of social time preference of 1.5% per year ($\beta = 0.985$).

5.4 Production

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

$$\widetilde{F_1}(K_{1t}, L_{1t}, E_t) = K_{1t}^{\alpha} L_{1t}^{1-\alpha-v} E_t^{v} \tag{43}$$

with expenditure shares $\alpha = 0.3$ and $v = 0.03$, following GHKT (2014).[41] Projections of both productivity and population growth are taken from DICE (2010).

The energy sector produces two types of inputs: fossil fuel-based and clean (zero-emissions). 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:

$$E_t = A_{Et} \cdot (K_{Et}^{1-\alpha_E} L_{Et}^{\alpha_E}) \tag{44}$$

Paired with the assumption of perfect competition, formulation (44) permits extracting the output elasticity α_E from observed expenditure shares. Using U.S. Bureau of Economic Analysis data, I estimate a labor share in the energy sector of $\alpha_E = 0.403$ (see Online Appendix). Next, the calibration of the clean energy production premium $\Theta_t(E_t^{clean})$ converts the DICE model's abatement cost estimates into a per-ton cost measure through a logistic approximation:

$$\Theta_t(E_t^{clean}) = \frac{\overline{a} P_t^{backstop}}{1 + a_t \exp(b_{0t} - b_{1t}(E_t^{clean}))^{b_2}} \cdot E_t^{clean} \tag{45}$$

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 (45) versus DICE (see Online Appendix for details).

[41] While the Cobb-Douglas specification has been shown to be a poor representation of energy input use in the short-run, in the long run, a unit elasticity appears plausible (Hassler, Krusell, and Olovsson, 2012). Given the 10-year time step of the model, I follow GHKT (2014), Leach (2009), and others in working with (43).

5.5 Government

The COMET disaggregates government spending G_t into consumption G_t^C and social transfers G_t^T (e.g., disability insurance).[42] This distinction is in line with other calibrated Ramsey tax models (Jones, Manuelli, and Rossi, 1997, 1993; Lucas, 1990). Government spending is calibrated based on IMF Government Finance Statistics for all available countries in the model base year (2005).[43] The data yield the following PPP-adjusted GDP-weighted expenditure breakdown:

	% of GDP	% of Government Spending
Government Consumption	17.75	57
Social Benefits	13.32	43
Total	33.75	

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

Table 2: Government Expenditure Shares (2005)

The *level* of total public spending is thus set to 33.75% of base year GDP, and assumed to grow at the rates of labor productivity and population growth.[44] The spending shares allocated to government consumption and transfers remain at 57% and 43%, respectively.

Lastly, the model requires estimates of baseline tax rates. From the literature estimating effective tax rates on capital, labor, and/or consumption, I obtain one or more tax wedge estimates for a sample of 107 countries (see Online Appendix). The base year GDP-weighted averages of rates are as follows:

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

While I adopt these values to calibrate initial tax rates (i.e., $\tau_{k0} = 0.3340$), 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 $\overline{\tau_l} = 37.51\%$ and $\overline{\tau_k} = 34.87\%$ (see Table 3).

[42] The Online Appendix derives the budget and implementability constraints with transfers.

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

[44] Goulder (1995) similarly models government expenditure as growing from an initial level at the technology growth rate of the model, as do Jones, Manuelli, and Rossi (1993).

6 Quantitative Results

This section presents the quantitative results in two parts. The first focuses on the more policy-relevant comparison of optimal carbon prices with and without distortionary taxes. I compute optimal policy and welfare across fiscal scenarios and compare them to a "First-Best" model run that abstracts from distortionary taxes, matching the standard implicit assumption in integrated assessment models and their policy applications (e.g., U.S. Interagency Working Group, 2010). The first set of quantitative results thus relates to these studies by extending the benchmark DICE framework to incorporate a transparent representation of fiscal policy and its effects on the optimal carbon price.

The second part focuses on the more theoretically-relevant comparison of optimal carbon prices versus the SCC *within a given fiscal scenario.* I use the model to illustrate the quantitative importance of the theoretical results pertaining to the effects of (i) the share of utility damages and (ii) the MCF.[45]

6.1 Quantitative Results: Summary

Table 3 summarizes the key quantitative results for the following COMET runs:

1. An "All Taxes BAU" scenario where there are no carbon taxes throughout the twenty-first century.[46] Variant (1a) holds labor income taxes fixed at 37.51% and varies capital income taxes to meet the government budget constraint. Variant (1b) holds capital income taxes fixed at 34.87% and varies labor taxes.

2. An "Income Tax Reform" scenario where income taxes are optimized but there are no carbon taxes in the twenty-first century. This scenario measures the welfare gains from conventional tax reform as considered by the literature on optimal capital income taxes (e.g., Lucas, 1990).

3. A "Green Tax Reform, Optimal Carbon Taxes" scenario where carbon taxes are set optimally. Variant (3a) holds labor income taxes fixed at 37.51% and thus uses carbon and energy tax revenues to reduce capital income taxes ('revenue recycling'). Variant (3b) holds capital income taxes fixed at 34.87% and recycles revenues to reduce labor income

[45] Of course, these results may also be policy-relevant to the extent that they inform a bridge between prior studies on optimal carbon pricing that have abstracted from production impacts (e.g., Bovenberg and Goulder, 1996) or from distortionary taxes (e.g., GHKT, 2014).

[46] 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.

taxes. These scenarios measure the welfare gains from environmental tax reform. Note that taxation (but not subsidization) of clean energy/abatement is permitted.

4. A "Green Tax Reform, 'Wrong' Carbon Taxes" scenario which is identical to (3) except that carbon taxes are set at first-best levels that would be optimal if there were no distortionary taxes. The differences in welfare between (4) and (3) reflect the additional value of adjusting carbon taxes to the fiscal setting.

5. A "Fully Optimized" scenario that optimizes over both income taxes and carbon taxes.

6. A "First-Best" scenario with lump-sum taxation and optimized carbon pricing. This scenario represents the standard implicit assumption in integrated assessment models.

Table 3 summarizes the central quantitative results:

	Fiscal Scenario		Capital Tax	Labor Tax	Carbon Tax			MCF	T_t	ΔWelfare[1]	
			Avg.	Avg.	$\$/mtC$			Avg.	C°	\$2005 bil.	$\%\Delta C_t$
	Income Taxes:	Carbon Tax:	2025-2255	2025-2255	2015	2025	2035	2025-2255	Max	ΔC_{2015}	$\forall t$
(1a)	BAU (τ_k fixed)	None (until 2115)[8]	34.87	37.51	0	0	0	1.05[6]	4.29	-	-
(1b)	BAU (τ_l fixed)	None (until 2115)	34.22	37.51	0	0	0	1.46[5]	4.28	(\$743)	(0.03)
(2)	Optimized	None (until 2115)	2.47[3]	41.30	0	0	0	1.06	4.29	\$22,139	0.82%
(3a)	BAU+ RR(τ_k)[2]	Optimized	30.89	37.51	49[4]	76	109	1.38	3.01	\$26,904	0.98%
(4a)	BAU+ RR(τ_k)[2]	'Wrong' (first-best)	31.71	37.51	71	103	142	1.39[5]	2.76	\$25,648	0.93%
(3b)	BAU+ RR(τ_l)[2]	Optimized	34.87	37.12	55	89	127	1.05[6]	3.00	\$21,529	0.79%
(4b)	BAU+ RR(τ_l)[2]	'Wrong' (first-best)	34.87	37.15	71	103	142	1.04[6]	2.82	\$20,883	0.76%
(5)	Optimized	Optimized	2.42[3]	41.19	59	90	129	1.06	2.99	\$44,992	1.60%
(6)	First-Best	Optimized	0	0	70	102	141	1.0	2.96	[\$79,167][7]	[2.72%]

[1] Relative to All Tax BAU scenario (1a). EV change in aggregate initial consumption ΔC_{2015} or permanent change in consumption $\%\Delta C_t$.

[2] Carbon tax revenue recycled to reduce only capital income tax rates RR(τ_k) or labor income tax rates RR(τ_l).

[3] Consists of high initial tax followed by ~0% tax (except for the last direct optimization period $T = 2265$; see Appendix B.)

[4] Carbon tax here is defined as the difference between total taxes on carbon energy (\$77/t in 2015, \$114 in 2025, etc.) and on clean energy (\$28/t in 2015,\$38 in 2025, etc.). Here, all types of energy are taxed because they tighten the labor income tax constraint of 37.51%.

[5] Measures the MCF of raising revenues from capital income taxes.

[6] Measures the MCF of raising revenues from labor income taxes.

[7] 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 $\tau_{l0} = 37\%$ in the second-best.

[8] Carbon taxes are allowed after 2115 so as to keep the analysis in an appropriate range for the (smooth) damage function.

Table 3: Main Results

Several findings emerge from the results in Table 3. First, optimal carbon levies are consistently lower when there are distortionary taxes. Figure 1 displays optimal carbon tax schedules for the twenty-first century:

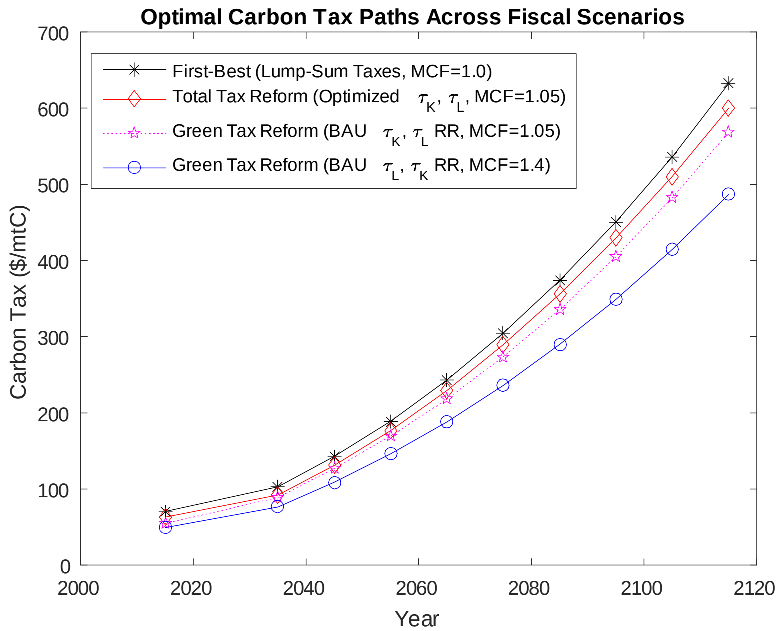

Figure 1

Throughout the century, optimal carbon taxes are 6% to 23% lower when levied alongside distortionary taxes, depending on the tax reform scenario.[47] The reasons for this change are decomposed below. While some of the difference is driven by the reduced size of the future economy due to tax distortions, the optimal carbon tax-GDP ratio may also be significantly reduced, as shown in Figure 2 and Table 4:[48]

[47] The corresponding variation in peak temperature change is smaller, however, as the distorted economies are smaller and thus require lower carbon taxes to maintain a level of emissions. See also Metcalf (2003).

[48] One of the scenarios ("Green Tax Reform (τ_L Rev. Recycle)") has a slightly higher carbon tax-GDP ratio than the first-best. This is because of the constraint that capital income taxes remain at their BAU level ($\overline{\tau_k} = 34.87\%$). As shown in Appendix A, since this constraint is downwardly binding, and since climate change decreases the marginal product of capital, this gives the planner an additional reason to tax carbon.

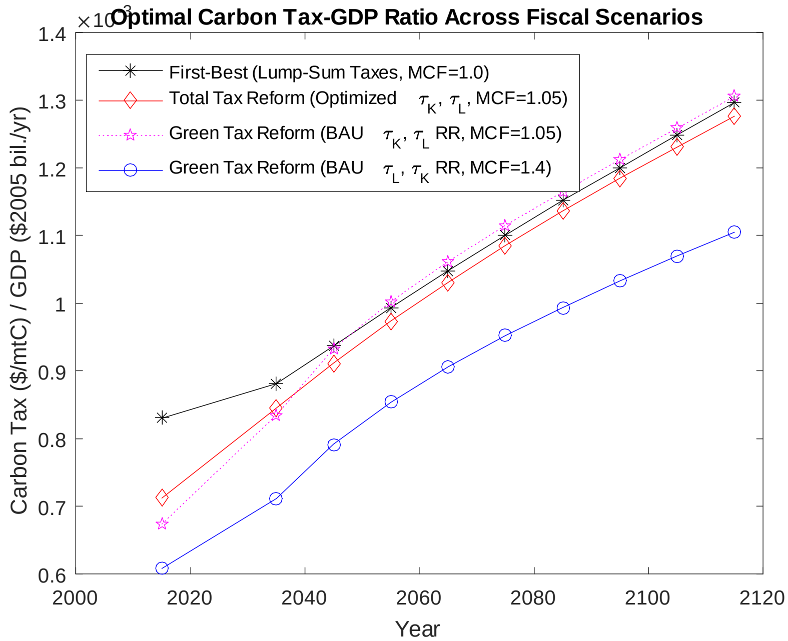

Figure 2

	Fiscal Scenario		Carbon Tax/GDP Ratio ($\times 10^{-3}$)		
	Income Taxes:	Carbon Tax:	2015	2025	2035
(3a)	BAU+ RR(τ_k)	Optimized	0.608	0.711	0.791
(3b)	BAU+ RR(τ_l)	Optimized	0.674	0.835	0.933
(5)	Optimized	Optimized	0.712	0.845	0.911
(6)	First-Best	Optimized	0.830	0.881	0.937

Table 4: Optimal CarbonTax-GDP Ratios

The second result is that a carbon tax yields much larger efficiency gains if its revenues are used to reduce capital income taxes ($27 trillion initial or 0.98% permanent consumption increase) than labor income tax rates ($22 trillion or 0.79%). Intuitively, this is because capital income taxes have a much higher marginal cost of funds (1.4) than labor income taxes (1.05). Consequently, offsetting the former creates larger efficiency gains than the latter. This finding is firmly in line with previous studies such as Goulder (1995), who finds that the non-environmental welfare costs of carbon taxes in the U.S. economy are lower with capital- rather than personal labor income tax revenue recycling (see also Jorgenson et al., 2013).[49]

49 Perhaps surprisingly, the results here also suggest that optimal carbon emissions prices conditional on capital income tax recycling are *lower* than for labor income tax recycling. This is due to the general equilibrium

The third result is that adjusting carbon taxes to the fiscal setting can create sizable welfare improvements. I compare the welfare gains from imposing optimized carbon levies in the BAU income tax scenarios (3a and 3b) to those from carbon taxes estimated in a model that abstracts from distortionary taxes, corresponding to standard practice (runs 4a and 4b). The *additional* welfare gains from adjusting climate policy to the fiscal setting ranges from \$646 billion to \$1.3 trillion (\$2005 lump-sum consumption equivalent) in these scenarios.

While these efficiency gains are arguably large, it should be noted that they are modest compared to the overall potential welfare gains of adopting carbon taxes in the twenty-first century (\$21 – \$27 trillion or a 0.76% – 0.98% 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 or 0.82%).[50] These results again highlight that a global *failure* to price carbon appropriately creates extremely costly (intertemporal) distortions.

6.2 Quantitative Results: Decomposition

The changes in optimal carbon taxes due to distortionary fiscal policy are driven by three factors. First, the size of the economy is smaller. As a result, the dollar value of marginal damages from carbon emissions - the social cost of carbon (SCC) - is lower. Second, if the marginal cost of public funds exceeds unity, optimal carbon taxes do not fully internalize the value of marginal damages, as demonstrated above (Proposition 2). Figure 3 illustrates both effects separately for model scenario ($3a$).

effects of climate change and policy, including on the tightness with which the BAU income tax constraints in each scenario bind. See Appendix A.

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

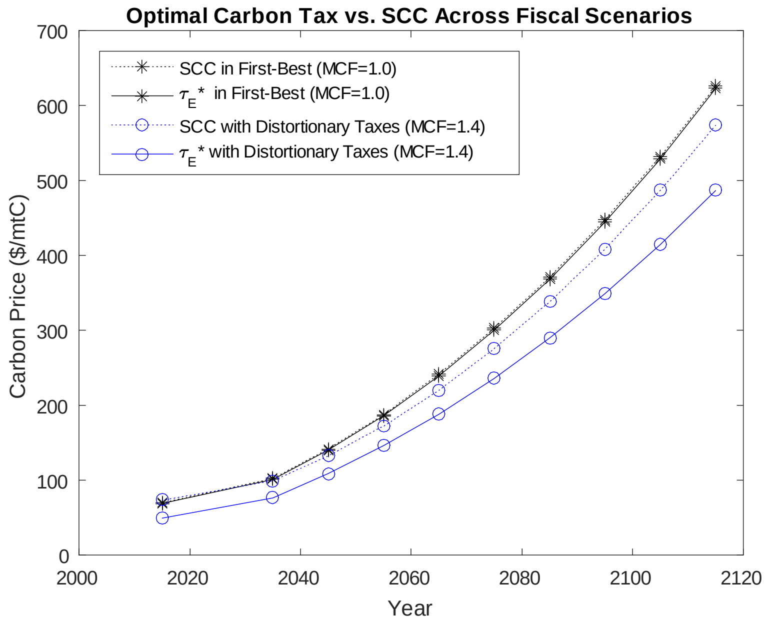

Figure 3

In the first-best setting, the optimal carbon tax τ^*_{Et} equals the SCC (black line with stars). In contrast, taking into account the current distortionary fiscal environment not only lowers the SCC (blue dotted line with circles), but pushes the optimal carbon price below the value of marginal damages (solid blue line with circles).

The fiscal scenario presented in Figure 3 raises marginal revenues from capital income taxes and features a correspondingly high MCF (1.4). In contrast, both the 'fully optimized' and 'BAU capital tax' scenarios raise marginal revenues from labor taxes and feature a low MCF (1.05). Proposition 2 shows that, in the fully optimized case, the relationship between the optimal tax and the SCC is given by expression (24), or:

$$\tau^*_{Et} = SCC_t \left[1 + \theta^u_t \frac{(1 - MCF_t)}{MCF_t} \right] \tag{46}$$

Given that, for climate change, the share of utility damages θ^u_t is modest ($\sim 25\%$), expression (**??**) implies that the optimal carbon tax should be closer to the SCC for the fiscal scenarios with a lower MCF. Figure 4 depicts the optimal carbon tax-SCC ratio (τ^*_{Et}/SCC_t) across all fiscal scenarios, confirming that this is indeed the case.

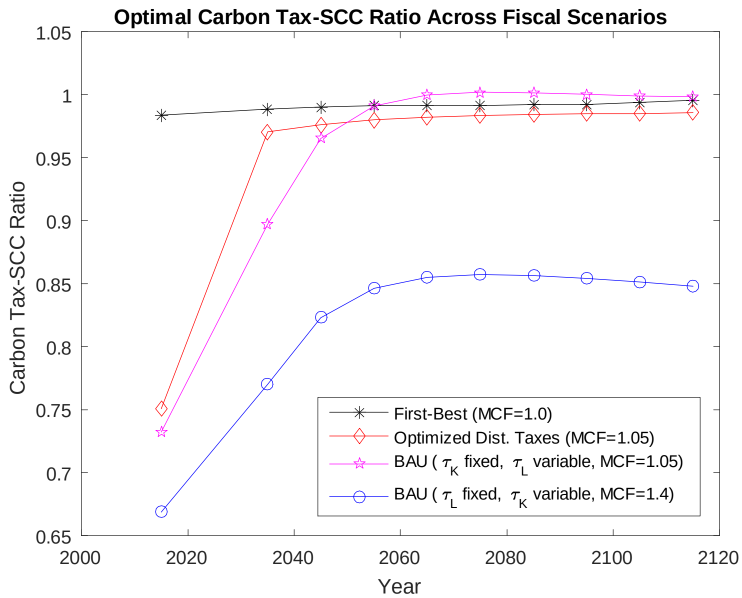

Figure 4

Perhaps surprisingly, the optimal carbon tax in the scenario with fixed BAU capital income taxes (pink line with hexagrams) is slightly above the SCC, despite the fact that $MCF > 1$. This is because of the third factor that determines the τ^*_{Et}/SCC ratio: When factor tax rates are constrained to remain at BAU levels, the planner also considers the impact of climate change on the tightness with which these constraints binds. Since the constraint $\overline{\tau_k} = 34.87\%$ is downwardly binding, and since climate change decreases the marginal product of capital even further away from its optimal level, the planner has an additional reason to tax carbon in this scenario. Appendix A provides a formal characterization of these effects.

One of the central implications of Proposition 2 and (46) is that the ratio of optimal carbon taxes over marginal damages is decreasing in both the MCF, and the share of utility damages. Figure 5 showcases the quantitative significance of these effects.

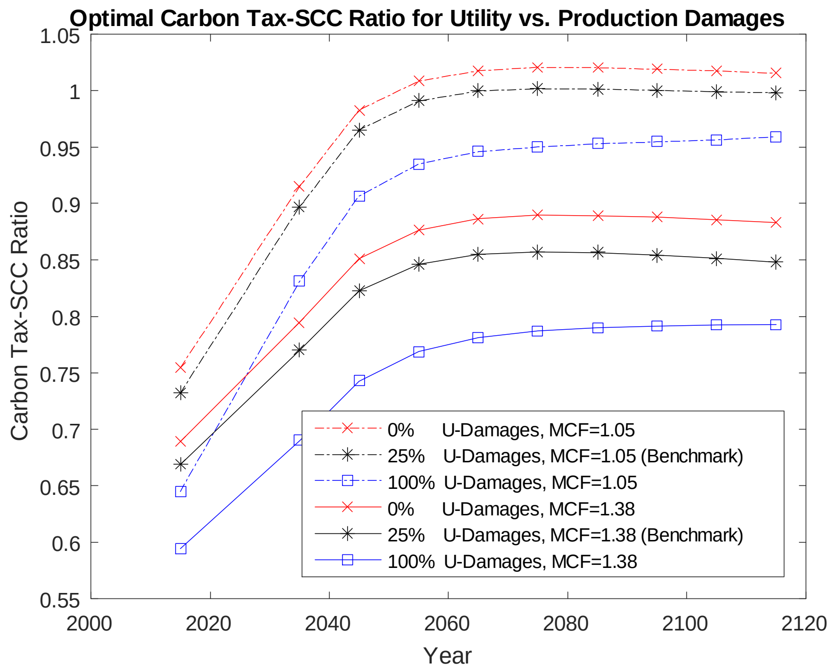

Figure 5

In line with Proposition 2, the results indicate that, for the high MCF scenario ($3a$), the optimal carbon price is 15% to 18% below the SCC (solid lines). However, for the low MCF scenario ($3a$), the optimal carbon price is 2.3% to 10% below the SCC (dash-dotted lines). Similarly, if climate change affects only utility, the optimal carbon price is 10% to 25% below the SCC. However, if climate change affects production possibilities, the optimal price lies only 2.3% to 15% below the SCC. Compared to the estimated benchmark utility damages share of 25%, abstracting from production impacts leads to an under-estimate of the optimal carbon price.

7 Conclusion

This paper considers the optimal taxation of carbon jointly with distortionary revenue-raising taxes. Specifically, I theoretically characterize and then quantify optimal carbon taxes as a part of fiscal policy in a dynamic general equilibrium climate-economy model. The three main results of the paper can be summarized as follows:

First, I demonstrate a theoretical link between the optimal taxation of carbon and capital income. If the government optimally sets capital income taxes to zero, then the optimal carbon tax to internalize production losses from climate change is the Pigouvian tax, even if labor markets are distorted. Intuitively, this is because setting carbon taxes below Pigouvian rates 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. A planner seeking to reduce intertemporal distortions should thus be concerned not only with capital income tax reform, but also with climate policy.

Second, I theoretically motivate and then quantify a distinction between production and direct utility impacts of climate change. On the theoretical side, the intuition for this result is that utility damages reflect the value of the climate as final consumption good. Conversely, production damages reflect the value of the climate as an environmental capital input to production. The optimal climate policy internalizes these damages differently. Building on the seminal climate change impact estimates underlying the DICE model (Nordhaus, 2008), I estimate that 75% of climate change impacts from $2.5°C$ warming affect production; 25% affect utility directly. I further find that abstracting from these production impacts and climate-economy feedback effects leads to an underestimate of the optimal carbon tax.

Third, I quantify optimal carbon tax schedules across fiscal scenarios. Compared to the setting with lump-sum taxes commonly considered in the literature and the policy realm, I find that optimal carbon levies are $6-23\%$ lower when there are other, distortionary taxes. Intuitively, this is both because the social cost of carbon is $3-7\%$ lower as taxes decrease future output, and because the optimal carbon price is $4-18\%$ below the social cost of carbon. The results further suggest that adjusting carbon taxes in this way increases the welfare gains from climate policy by around \$1 trillion in the BAU income tax scenario. Recycling carbon tax revenues through capital income taxes is found to provide substantial additional efficiency gains. The total welfare gains from optimized carbon taxes in the twenty-first century are estimated to be extremely large (\$21 − \$27 trillion initial consumption change or a 0.75-1% permanent consumption increase), depending on revenue recycling and the fiscal scenario.

As this paper presents a relatively simple benchmark setting for both fiscal and climate policy, it invites several potential extensions. First, I find that optimal climate policy adjustments to the fiscal setting depend not only on the levels but also on the reasons for pre-existing tax distortions. This paper focuses on a Ramsey setting with linear taxes, an infinitely lived representative agent, and full commitment. Climate policy design under alternative fiscal frameworks giving rise to different optimal tax structures is thus an interesting area for future research.

Second, this paper focuses on a deterministic setting as a natural benchmark. Climate-economy models are increasingly incorporating different kinds of uncertainty. For example, Lemoine and Traeger (2014) find that consideration of uncertainty over tipping points in the climate system increases near-term optimal carbon taxes by 25-40% in the baseline. Lontzek et al. (2015) find even higher initial optimal carbon tax increases due to tipping points, but that subsequent carbon prices grow more slowly than in the deterministic benchmark. Whether and how the dynamic implications of tipping point would interact with distortionary taxes is unclear. Some recent studies consider climate and economic uncertainty jointly, with Cai, Judd, and Lontzek (2015) showing that both factors can significantly increase optimal carbon prices. Again, however, it is an open question how accounting for tax distortions would interact with these factors. Finally, several studies have focused on climate policy and business cycles (Heutel, 2012; Fischer and Springborn, 2011). A stochastic version of the COMET could thus consider uncertainty in yet another direction: fiscal fluctuations. Chari and Kehoe (1999) find that optimal labor, capital, and asset taxes vary differentially in response to fiscal shocks. It would correspondingly be interesting to study the optimal response of carbon taxes to fiscal shocks, particularly in light of this paper's finding that optimal capital and carbon taxes are linked.

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

A Appendix A

A.1 Proof of Proposition 2

Step 1: Derive General Optimal Carbon Tax Expression (20)

The planner's problem is defined by Proposition 1. In particular, splitting the implementability constraint into its time-zero and lifetime summation components, including the latter in the maximand, and defining the resulting function $W_t = W(C_t, L_t, T_t, \phi) \equiv U(C_t, L_t, T_t) + \phi \left[U_{ct} C_t + U_{lt} L_t\right]$, the planner's is given by:

$$\begin{aligned}
&\max \sum_{t=0}^{\infty} \beta^t [\underbrace{U(C_t, L_t, T_t) + \phi \left[U_{ct} C_t + U_{lt} L_t\right]}_{\equiv W_t}] \qquad \text{(A.1)} \\
&-\phi \left\{U_{c0} \left[K_0 \left\{1 + (F_{k0} - \delta)(1 - \tau_{k_0})\right\}\right]\right\} \\
&+\sum_{t=0}^{\infty} \beta^t \lambda_{1t} \left[\left\{A_t(T_t) \widetilde{F_{1t}}(L_{1t}, E_t, K_{1t})\right\} + (1 - \delta) K_t - C_t - G_t - K_{t+1}\right] \\
&+\sum_{t=0}^{\infty} \beta^t \xi_t [T_t - \digamma_t(S_0, E_0, E_1, ...E_t)] \\
&+\sum_{t=0}^{\infty} \beta^t \lambda_{lt} \left[L_t - L_{1t} - L_{2t}\right] \\
&+\sum_{t=0}^{\infty} \beta^t \lambda_{kt} \left[K_t - K_{1t} - K_{2t}\right] \\
&+\sum_{t=0}^{\infty} \beta^t \omega_t \left[F_{2t}(A_{Et}, K_{2t}, L_{2t}) - E_t\right]
\end{aligned}$$

Combining the planner's FOCs for energy E_t, sectoral labor supplies L_{1t} and L_{2t}, and temperature change T_t at $t > 0$ yields the following optimality condition for carbon energy usage:

$$\begin{aligned}
F_{Et} - \frac{F_{1lt}}{F_{2lt}} &= \frac{1}{\lambda_{1t}} \sum_{j=0}^{\infty} \beta^j \xi_{t+j} \frac{\partial T_{t+j}}{\partial E_t} \qquad \text{(A.2)} \\
&= \frac{1}{\lambda_{1t}} \sum_{j=0}^{\infty} \beta^j \left[U_{Tt+j} + \lambda_{1t+j} F_{Tt+j}\right] \frac{\partial T_{t+j}}{\partial E_t}
\end{aligned}$$

Intuitively, $(A.2)$ shows that the wedge between the marginal product of energy (F_{Et}) and its private production cost $\left(\frac{F_{1Lt}}{F_{2Lt}}\right)$ is given by the present discounted value of the externality costs of carbon emissions. In order to find a carbon tax τ_{Et} that can decentralize $(A.2)$, consider the energy producer's profit-maximization condition (12):

$$(p_{Et} - \tau_{Et}) F_{2lt} = w_t$$

Invoking competitive equilibrium prices based on (8) and (12) and rearranging leads to:

$$F_{Et} - \frac{F_{1lt}}{F_{2lt}} = \tau_{Et} \tag{A.3}$$

Comparing the decentralized behavior of firms $(A.3)$ with the planner's optimality condition $(A.2)$ shows that the optimal allocation can be decentralized by a carbon tax equal to the right-hand side of $(A.2)$. Finally, separating production and utility damages, multiplying the latter by U_{ct}/U_{ct} and invoking the definition of the MCF (16), yields the general optimal carbon tax expression (20):

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

Step 2: Refine Optimal Carbon Tax for Preferences (21)-(22)
First, note that the utility damages term in the right-hand side of $(A.4)$ already equals:

$$\begin{aligned} &\frac{1}{MCF_t}\sum_{j=0}^{\infty}\beta^j \left[\frac{-U_{Tt+j}}{U_{ct}}\right]\frac{\partial T_{t+j}}{\partial E_t} \\ = \; &\frac{\tau_{Et}^{Pigou,U}}{MCF_t} \end{aligned}$$

in the general case, as per the definition of $\tau_{Et}^{Pigou,U}$ (18). Next, the planner's optimality condition for consumption C_t for $t > 0$ yields:

$$\lambda_{1t} = W_{ct}$$

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

$$W_{ct} = C_t^{-\sigma}[1 + \phi(1-\sigma)] = U_{ct}[1 + \phi(1-\sigma)]$$

Similarly, for preferences (22),

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

Consequently, for either type of preferences, we have that:

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

Finally, based on $(A.5)$, proving that the production damages term in $(A.4)$ reduces to $\tau_{Et}^{Pigou,Y}$ follows identically from the proof of Proposition 3.

A.2 Exogenously Fixed Capital Tax Rates

The planner's problem is now given by (A.1) with the addition of capital tax constraints (34) with associated Lagrange multipliers Ψ_t :

$$-\sum_{t=0}^{\infty}\beta^t\Psi_t\left[\underbrace{\frac{U_{ct}}{\beta U_{ct+1}}-[1+(1-\overline{\tau_k})(F_{kt+1}-\delta)]}_{\equiv\chi_t}\right] \tag{A.6}$$

With χ_t as defined in $(A.6)$, the planner's first order condition with respect to temperature change T_t after $t>0$ implies the following marginal welfare cost of temperature change in period t, ξ_t :

$$-U_{Tt}-\lambda_{1t}F_{Tt}+\frac{1}{\beta}\Psi_t\chi_{Tt-1}=\xi_t$$

Here, χ_{Tt-1} reflects the derivative of the capital tax constraint with respect to T_{t-1}. The marginal welfare cost of climate change thus consists of utility damages U_{Tt}, production damages F_{Tt} (valued at the public marginal utility of income λ_{1t}), plus an additional term reflecting the degree to which temperature change relaxes or tightens the capital tax constraint. In our setting:

$$\chi_{Tt}=(-1)\frac{\partial^2 F_{1t}}{\partial K_t\partial T_t}$$

If the government would ideally set capital taxes below $\overline{\tau_k}$, $\Psi_t>0$, and since we are assuming that T_t negatively affects all marginal products, $\chi_{Tt}>0$, and hence marginal welfare costs of temperature change are *higher* than without the capital tax constraint. Intuitively, this is because *temperature change decreases the marginal product of capital, and thus exacerbates the capital income tax constraint.*

Similarly, combining the planner's FOCs for energy E_t and sectoral labor supplies L_{1t} and L_{2t} at $t>0$ yields the following optimality condition for carbon energy:

$$F_{Et}-\frac{\omega_t}{\lambda_{1t}}=\frac{1}{\lambda_{1t}}\left[\sum_{t=0}^{\infty}\xi_{t+j}\frac{\partial T_{t+j}}{\partial E_t}+\frac{1}{\beta}\Psi_t\chi_{Et-1}\right] \tag{A.7}$$

Expression $(A.2)$ shows that the wedge between the marginal product of energy (F_{Et}) and its production cost $\left(\frac{\omega_t}{\lambda_{1t}}\right)$ is now given by the present discounted value of the social cost of carbon emissions (ξ_{t+j}), plus a term to account for the effects of energy usage on the capital income tax constraint, $\Psi_t\chi_{Et-1}$. Note that:

$$\chi_{Et}=(-1)(1-\overline{\tau_k})\frac{\partial^2 F_{1t}}{\partial K_t\partial E_t}$$

If capital and energy are complements in final goods production, $\chi_{Et}<0$. If the planner would ideally want to set capital taxes below $\overline{\tau_k}$, $\Psi_t>0$, and the social cost of energy consumption is adjusted *downwards* due to its impacts on the capital tax constraint in (A.7), ceteris paribus. Intuitively, *higher energy use increases the marginal product of capital, and thus counteracts the* *exogenously given capital income tax.* Finally, the marginal cost of energy production ω_t is now also adjusted to reflect the impact of changes in labor supply L_t and its allocation between the two production sectors (L_{1t}, L_{2t}) on the capital tax constraint. Combining the corresponding FOCs yields:

$$\omega_t = \lambda_{1t} \underbrace{\frac{F_{l1t}}{F_{2lt}}}_{\substack{\text{Private MC of} \\ \text{energy production}}} - \underbrace{\frac{\Psi_{t-1}\chi_{l1t-1}}{\beta F_{2lt}}}_{\substack{\text{Capital tax} \\ \text{constraint inter-} \\ \text{action adjustment}}}$$

where:

$$\chi_{l1t} = (-1)(1-\overline{\tau_k})\frac{\partial^2 F_{1t}}{\partial K_{1t}\partial L_{1t}}$$

If capital and labor are complements in final goods production then $\chi_{l1t} < 0$. If the planner would want to set capital taxes below $\overline{\tau_k}$, $\Psi_t > 0$, and the social cost of energy production is thus adjusted *upwards* to reflect the decrease in the marginal product of capital (and thus the tightening of the capital income tax constraint) associated with allocating labor away from final goods production and towards energy production.

Overall, combining the planner's FOCs leads to the following implicit expression for optimal carbon taxes in this setting, conditional on all other taxes being set optimally:

$$\begin{aligned} \tau^*_{Et} \;=\; & \sum_{j=0}^{\infty}\left[\underbrace{\frac{U_{Tt+j}}{\lambda_{1t}}}_{\text{Utility damages}} + \underbrace{\frac{\lambda_{1t+j}}{\lambda_{1t}}F_{Tt+j}}_{\text{Output damages}} - \underbrace{\frac{1}{\beta}\frac{\Psi_{t+j}}{\lambda_{1t}}\chi_{Tt-1+j}}_{\substack{\text{Temperature change} \\ \text{impact on } \overline{\tau_k} \text{ constraint}}}\right]\frac{\partial T_{t+j}}{\partial E_t} \\ & - \underbrace{\frac{1}{\beta}\frac{\Psi_{t-1}}{\lambda_{1t}}\chi_{Et-1}}_{\substack{\text{Energy use} \\ \text{impact on } \overline{\tau_k} \text{ constraint}}} + \underbrace{\frac{1}{F_{2lt}}\frac{1}{\beta}\frac{\Psi_{t-1}}{\lambda_{1t}}\chi_{l1t-1}}_{\substack{\text{Energy production cost} \\ \text{impact on } \overline{\tau_k} \text{ constraint}}} \end{aligned} \tag{A.8}$$

There are thus several countervailing forces affecting the optimal carbon tax formulation in a setting with exogenously given, suboptimal capital income tax rates. Which effect dominates is ex-ante ambiguous. The two energy use terms in (A.8) moreover indicate that even clean energy should be taxed or subsidized depending on its effects on capital returns. The quantitative results in our setting suggest that all types of energy should be taxed in this setting, but that carbon emissions levies are lower due to the capital income tax constraint (see Section 6).

B Appendix B

B.1 Calibration of Preferences for Climate Change

The goal of the calibration is to find a parameter α_0 such that the disutility of $2.5C^\circ$ climate change - a standard calibration point in the literature (e.g., Nordhaus, 2010) - is equivalent to the utility loss resulting from 0.49% output damages. Given the chosen preference specification

(42), the total utility change from $2.5C^{\circ}$ warming utility damages is given by:

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

Analogously, the total utility change from a consumption loss of $D(2.5^{\circ})$ can be approximated:[51]

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

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 $D(2.5^{\circ})$. Consumption levels $C_{2.5^{\circ}C}$ are taken from a modified business-as-usual (BAU) run of the 2010 DICE model.[52] Labor supply $l_{2.5^{\circ}C}$ is set at the baseline COMET value, since the BAU scenario represents the idea of no tax reform. The benchmark COMET specification (with distortionary taxes) has $\alpha_0 = .000235$. Finally, note that one can easily show that the temperature risk aversion coefficient (Weitzman, 2010) implied by utility function (42) is given by:

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

for utility damages. Similarly, for consumption losses in (B.2) with $(1 - D(2.5^{\circ})) = \frac{1}{1+\theta T_t^2}$ as assumed for production damages in (41), we one can easily derive that:

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

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

B.2 Computation

In order to numerically solve the planner's infinite horizon problem, I follow a similar though slightly different approach as Jones, Manuelli, and Rossi (1993), also employed in Barrage (2014b). First, I optimize over all allocations for T periods as well as over the continuation

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

[52] Specifically, I deactivate the sea level rise module and use the slightly older damage function parameters whose calibration includes sea level rise. In addition, I 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 expenditure in the COMET.

gross savings rate for period T. In the benchmark calibration, $T = 25$, representing 250 years. In contrast to studies such as Jones, Manuelli, and Rossi (1993), however, one cannot impose a balanced growth path after some terminal period T in the current setting. The reason is that full effects of carbon emissions in late periods would not be accounted for due to lags in the climate system between emissions and warming. In addition, a balanced growth path requires that the climate be in steady state, that is, that carbon concentrations have stabilized. Given the assumption that clean energy backstop technologies will become fully cost competitive by the year 2255 (Nordhaus, 2010), industrial carbon emissions will stop at the latest thereafter, allowing the climate to gradually reach a new steady state.

After the last direct optimization period $T > 2255$, I thus use the continuation gross savings rate as well as the period T labor supply and period T factor distribution across sectors (i.e., the share of capital allocated to energy and final goods production) to simulate the economy and climate for another 100 years. Finally, after this additional 100 years (generally 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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