Climate Change Adaptation vs. Mitigation: A Fiscal Perspective

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Abstract

This study explores the implications of distortionary taxes for the tradeoff between climate change adaptation and mitigation. Public adaptation measures (e.g., seawalls) require government revenues, but may increase factor returns by protecting production possibilities. In contrast, mitigation through carbon taxes raises revenues, but interacts with the welfare costs of other taxes. This paper theoretically characterizes and empirically quantifies this tradeoff in a dynamic general equilibrium integrated assessment climate-economy model with distortionary taxation. First, I find that public investments in adaptation to reduce direct utility impacts of climate change (e.g., damages to national parks) should be distorted (reduced) when they are financed through distortionary taxes. The consumption of climate benefits is effectively taxed like other consumption goods. Second, in contrast, public adaptation to reduce production impacts of climate change (e.g., damages to infrastructure) should be fully provided, even when they are financed through distortionary taxes. Third, the central quantitative finding is that the welfare costs of limiting climate policy to adaptation (i.e., failure to enact a carbon price) may be up to twice as high when the distortionary costs of adaptive expenditures are taken into account. The fiscal costs of adaptation may thus add significantly to the welfare costs of un-mitigated climate change.

1 Introduction

Adaptation to climate change is increasingly recognized as an essential policy. In the United States, all Federal agencies have been required to produce climate change adaptation plans since 2009.[1] In addition, numerous states, counties, and cities have been making plans and incurring

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[1] As per Executive Order 13514 (October 5, 2009).

expenditures for climate change adaptation,[2] exemplified by New York City's $20 billion plan announced in the aftermath of Hurricane Sandy.[3] While a growing academic literature has studied the role of adaptation in climate policy,[4] these studies have often abstracted from its fiscal implications. However, many adaptive measures - such as the construction of sea walls - can only be (efficiently) provided by governments (Mendelsohn, 2000). If governments finance adaptation expenditures through distortionary taxes, the associated macroeconomic general equilibrium effects may significantly alter the costs and benefits of competing climate policy options. A large literature[5] has already demonstrated the critical importance of pre-existing taxes for the design of pollution *mitigation* policies, such as carbon taxes or emissions trading schemes (see, e.g., review by Bovenberg and Goulder, 2002). Expanding upon these findings, this paper explores the implications of the fiscal setting for the optimal policy mix between both climate change mitigation and adaptation. Specifically, I first theoretically characterize and then empirically quantify optimal adaptation and mitigation paths in a dynamic general equilibrium integrated assessment climate-economy model (IAM) with government spending requirements, social transfers, and (linear) distortionary taxes.

The increasing policy and academic attention towards climate change adaptation is likely driven by three key factors. First, given the current state of international climate policy, substantial warming is projected by the end of the 21st Century, even with implementation of the Copenhagen Accord (Nordhaus, 2010).[6] Second, due to delays in the climate system, past emissions will continue to cause warming even if greenhouse gas emissions ceased today. Third, adaptation plays a critical role in the fully optimized global climate policy mix (see, e.g., Mendelsohn, 2000) as some adaptation measures are comparatively low-cost. The literature has studied a variety of questions related to climate change adaptation (for a recent literature review, see, e.g., Agrawala, Bosello, Carraro, Cian, and Lanzi, 2011). These include the strategic implications of adaptation in non-cooperative settings (e.g., Antweiler, 2011; Buob and Stephan, 2011; Farn-

[2] For detailed listings of State and local plans in the U.S., see the Georgetown Law School Adaptation Clearinghouse http://www.georgetownclimate.org/adaptation/state-and-local-plans

[3] "Mayor Bloomberg Outlines Ambitious Proposal to Protect City Against the Effects of Climate Change to Build a Stronger, More Resilient New York" New York City Press Release PR- 201-13, June 11, 2013.

[4] Reviewed, e.g., by Agrawala, Bosello, Carraro, Cian, and Lanzi (2011), and discussed in more detail below.

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

[6] Specifically, Nordhaus (2010) predicts warming of $3.5°C$ by the year 2100 in the absence of climate policy, and that implementation of the Copenhagen Accord goals will reduce projected warming to only $3.2°C$ if emissions reductions are limited to wealthy countries.

ham and Kennedy, 2010); interactions between adaptation and uncertainty (Felgenhauer and de Bruin, 2009; Shalizi and Lecocq, 2007; Ingham, Ma, and Ulph, 2007; Kane and Shogren, 2000); comparative statics between macroeconomic variables and optimal adaptation (e.g., Bréchet, Hritonenko, and Yatsenko, 2013); and the optimal policy mix within the context of integrated assessment climate-economy models (e.g., Felgenhauer and Webster, 2013; Agrawala, Bosello, Carraro, de Bruin, De Cian, Dellink, and Lanzi, 2010; Bosello, Carraro, and De Cian, 2010; de Bruin, Dellink, and Tol, 2009; Tol, 2007; Hope, 2006.) There are also many empirical studies estimating the costs and benefits of adaptation in particular sectors, as well as a branch in the literature exploring adaptation behavior from a positive empirical perspective.[7] However, to the best of my knowledge, the academic literature has not formally considered the (differential) implications of the fiscal policy context for the climate change adaptation-mitigation tradeoff.

In the policy realm, numerous groups have voiced concerns about the fiscal impacts of climate change damages and adaptation needs. These include analyses by the U.S. Government Accountability Office (2013), the IMF (2008), and Egenhofer et al. (2010), who provide a detailed literature review, conceptual framework, and several case studies focused on the European Union. Non-governmental organizations such as Ceres have also published reports emphasizing the fiscal costs of climate change (Israel, 2013). Motivated by these concerns and the aforementioned extensive literature on the importance of distortionary taxes for environmental policy design, this study thus seeks to explore climate change costs and the optimal adaptation-mitigation policy mix in a dynamic general equilibrium climate-economy model with fiscal policy. The model essentially integrates the COMET climate-economy model with linear distortionary taxes (Barrage, 2014) with a modified representation of the adaptation possibilities from the AD-DICE framework (2010 version as presented in Agrawala, Bosello, Carraro, de Bruin, De Cian, Dellink, and Lanzi, 2010). I follow AD-DICE in differentiating between adaptation capital investments (e.g., sea walls) and flow expenditures (e.g., increased fertilizer usage). However, as discussed below, the results confirm that climate policy must further differentiate between adaptive capacity to reduce climate change impacts on production (e.g., in agriculture) and direct utility losses from impacts that affect welfare but not production possibilities (e.g., damages to archaeological sites). The model thus accounts for these adaptation types separately. Both the COMET and AD-DICE are based on the seminal DICE/RICE climate-economy models developed by William Nordhaus (e.g., 2008; 2010, 2013), which are among the three models used by the U.S. government to assess the social cost of carbon (Interagency Working Group, 2010). The broader context of this study further includes the rich literatures on (i) macroeconomic climate-economy models (e.g., Golosov,

[7] For reviews and aggregate studies, see, e.g., IPCC WGII (2007); Parry, Arnell, Berry, Dodman, Frankhauser, Hope, Kovats, and Nicholls (2009); World Bank EACC (2010); and Agrawala, Bosello, Carraro, Cian, and Lanzi (2011).

Hassler, Krusell, and Tsyvinski, 2014; van der Ploeg and Withagen, 2012; Gerlagh and Liski, 2012; Acemoglu, Aghion, Bursztyn, and Hemous, 2011; Leach, 2009; etc.) and (ii) integrated assessment models (e.g., PAGE2009, Hope, 2011; FUND 3.7, Tol and Anthoff, 2013; MERGE, Manne and Richels, 2005; etc.), both which have generally abstracted from both distortionary taxes. In addition, the question of optimal adaptation spending from distortionary taxes relates closely to optimal public goods provision in dynamic Ramsey models (e.g., Economides, Park, and Philippopoulos, 2011; Economides and Phlippopoous, 2008; Judd, 1999; etc.).

Before summarizing the results, it should be emphasized that the literature's estimates of aggregate adaptation costs remain highly uncertain and are based on strong simplifying assumptions (Agrawala, Bosello, Carraro, Cian, and Lanzi, 2011). However, the main research question of this paper is how consideration of the fiscal setting *changes* the welfare implications and optimal mix of climate policy. That is, I take the literature's adaptation cost estimates as given, and study how fiscal considerations affect the climate policy prescriptions associated with these cost estimates. The three main results are as follows.

First, public funding of flow adaptation inputs to reduce climate damages in the final goods production sector (e.g., sand bags to reduce storm damage to transport infrastructure) should remain undistorted regardless of the welfare costs of raising government revenues. Intuitively, while it is costly to raise revenues to fund these adaptation expenditures, they effectively 'pay for themselves' by increasing economic output (at the optimum). In fact, it is necessary for the government to dedicate the appropriate level of resources to these adaptation measures so as to ensure that the economy operates efficiently. That is, this first result reflects the well-known property that optimal tax systems must maintain aggregate production efficiency under fairly general conditions (Diamond and Mirrlees, 1971). By noting that public flow adaptation expenditures to reduce production damages are a public input to production, this result also follows directly from studies such as Judd (1999), who finds that public capital inputs to production should be fully provided even under distortionary Ramsey taxation. One caveat to this result is that it holds when income taxes are optimized. If pre-existing fiscal policy is inefficient, third-best considerations apply. Quantitatively, I find that constrained-optimal adaptation to production impacts may be up to 20-25% lower than with fully optimized distortionary taxes, if marginal revenues are raised with capital income taxes.[8] However, in all scenarios considered, I find that the higher the costs of raising public funds (through inefficient taxes), the more heavily adaptation spending should be tilted towards reducing production damages. Again, the core intuition is that such investments yield a productivity gain that can (partly) offset the efficiency

[8] This difference in optimal adaptation reflects both distortions that arise due to interactions between adaptation expenditures and the constraints on fiscal policy that make it inefficient, and general equilibrium differences in output, consumption, etc. across fiscal scenarios.

costs of the tax increases required to fund them.[9]

Second, public funding for both flow and capital adaptation inputs to reduce direct utility losses from climate change (e.g., beach nourishment or flood walls to reduce sea-level rise impacts on archaeological sites) should be distorted when governments have to raise revenues with distortionary taxes. That is, climate change will affect some environmental and cultural goods that may not be of productive value to the economy, but that society nonetheless values, such as cultural treasures, national parks, and biodiversity existence values. However, if raising government revenues creates efficiency costs, the funding of public adaptation to reduce damages to these climate 'consumption goods' should be distorted. Intuitively, this is because the government must distort the consumption of all goods in the economy, and consequently the enjoyment of the pure utility benefits of a healthy climate is effectively taxed as well. Perhaps surprisingly, I find that an intertemporal wedge remains between the marginal rates of transformation and substitution for adaptation capital investments to reduce utility damages from climate change, even when it is optimal to have no intertemporal distortions along other margins (i.e., zero capital income taxes). That is, adaptation capital investments to reduce utility damages from climate change may be optimally distorted even when other capital investments should not be. Quantitatively, I find that optimal flow expenditures on utility adaptation may be reduced by as much as 30-45% if they must be funded through capital income tax increases.

Third, the central quantitative finding is that the welfare costs of relying exclusively on adaptation to address climate change (i.e., without a carbon price) may be up to twice as large when distortionary taxes are used to raise the necessary revenues. At a global level, the welfare costs of relying only on adaptation and of failing to implement a carbon price throughout the 21st Century are estimated to be \$10.8 trillion (\$2005) in a setting without distortionary taxes, \$11.4-12.2 trillion when additional revenues come from labor or optimized distortionary taxes, and \$15.8-20.3 trillion if capital income taxes are used to raise additional funds.

The remainder of this paper proceeds as follows. Section 2 describes the model and derives the theoretical results. Section 3 discuses the quantitative model the calibration of adaptation possibilities. Section 4 provides the quantitative results, and Section 5 concludes.

2 Theoretical Analysis

The analytic framework extends the dynamic COMET (Climate Optimization Model of the Economy and Taxation) model of Barrage (2014) by adding several forms of adaptation. Her

[9] To be more precise, consider the example of labor markets. Increases in labor income taxes create a deadweight loss if they reduce equilibrium employment (further) below efficient levels. Adaptation expenditures can mitigate these labor market effects if they increase the marginal product of labor.

framework builds on the climate-economy models of Golosov, Hassler, Krusell, and Tsyvinski (2014) and Nordhaus (2008; 2011) by incorporating a classic dynamic optimal Ramsey taxation framework as presented by Chari and Kehoe (e.g., 1999). Barrage (2014) solves for optimal greenhouse gas mitigation policies across fiscal scenarios; here we consider adaptation as additional policy lever. Specifically, I consider both adaptation capital and flow inputs as modeled in the 2010 AD-DICE model (Agrawala, Bosello, Carraro, de Bruin, De Cian, Dellink, and Lanzi, 2010). However, I expand upon their framework by separately modeling adaptation to reduce the impacts of climate change on production possibilities and direct utility damages.

To briefly preview the model: an infinitely-lived, representative household has preferences over consumption, leisure, and the environment. In particular, climate change decreases his utility, but these impacts can be reduced through investments in utility adaptation. There are two production sectors. An aggregate final consumption-investment good is produced from capital, labor, and energy inputs. Climate change affects productivity, but the impacts can be reduced through investments in production adaptation. Carbon emissions stem from a carbon-based energy input, which is produced from capital and labor. The government must raise a given amount of revenues as well as funding for climate change adaptation through distortionary taxes on labor, capital, and carbon emissions.[10]

The quantitative model accounts for additional elements such as exogenous land-based emissions, clean energy, population growth, and government transfers. However, these features are omitted from the analytic presentation since they do not affect the theoretical results.

Households

A representative household has preferences over consumption C_t, leisure L_t, climate change T_t, and adaptive capacity to reduce utility damages from climate change Λ_t^u. The household takes both the climate and adaptive capacity as given. That is, adaptation Λ_t^u is publicly provided.

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

Pure utility losses from climate change include biodiversity existence value losses, changes in the amenity value of the climate, disutility from human resettlement, and non-production aspects of health impacts from climate change, as discussed further below. I assume additive separability between preferences over consumption, leisure, and the climate, and that adaptive capacity reduces the disutility from climate change via:[11]

[10] In particular, lump-sum taxes are assumed to be infeasible, in the Ramsey tradition. It is moreover assumed that the revenues raised from Pigouvian carbon taxes are insufficient to meet government revenue needs.

[11] The potential implications of non-separability between pollution, leisure, and consumption are theoretically

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

Intuitively, if adaptive capacity was at 100% ($\Lambda_t^u = 1$), the impacts of any climate change $T_t > 0$ on utility would thus be fully neutralized. Each period, the household allocates his income between consumption, the purchase of one-period government bonds B_{t+1} (at price ρ_t), and investment in the aggregate private capital stock K_{t+1}^{pr}. The household's income derives from net-of-tax (τ_{lt}) labor income $w_t(1 - \tau_{lt})L_t$, net-of-tax (τ_{kt}) and depreciation (δ) capital income $\{1 + (r_t - \delta)(1 - \tau_{kt})\} K_t^{pr}$, government bond repayments B_t, and profits from the energy production sector Π_t. The final consumption good is normalized to be the untaxed good. The household's flow budget constraint each period is thus given by:[12]

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

As usual, the household's first order conditions imply that savings and labor supply are governed by the following decision rules:

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

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

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

Production

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

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

well-known (see, e.g., Schwartz and Repetto, 2000; Carbone and Smith, 2008; or also discussion in Barrage, 2014). However, in line with the literature, I abstract from these issues here as the empirical values of these non-separabilities are essentially unknown.

[12] As in Barrage (2014), I assume that (i) capital holdings cannot be negative, (ii) consumer debt is bounded by some finite constant M via $B_{t+1} \geq -M$, (iii) purchases of government debt are bounded above and below by finite constants, and (iv) initial asset holdings B_0 are given.

where A_{1t} denotes an exogenous total factor productivity parameter. Once again, if adaptive capacity were at 100% ($\Lambda_t^y = 1$) this would imply that climate change impacts on production are fully neutralized. The modeling of climate production impacts as multiplicative factor was pioneered by Nordhaus (e.g., 1991). Production impacts include losses in sectors such as agriculture, fisheries, and forestry, changes in labor productivity due to health impacts, impacts of changes in ambient air temperatures on energy inputs required to produce a given amount of heating or cooling services, etc. (see, e.g., Nordhaus, 2007; Nordhaus and Boyer, 2000).

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

$$\begin{aligned} F_{1lt} &= w_t \\ F_{1Et} &= p_{Et} \\ F_{1kt} &= r_t \end{aligned} \tag{7}$$

Carbon-based energy inputs are assumed to be producible from capital K_{2t} and labor L_{2t} inputs through a constant returns to scale technology:[13]

$$E_t = A_{2t} F_{2t}(K_{2t}, L_{2t}) \tag{8}$$

Given perfect competition, profits from energy production Π_t will be zero in equilibrium:

$$\Pi_t = (p_{Et} - \tau_{Et})E_t - w_t L_{2t} - r_t K_{2t} \tag{9}$$

where p_{Et} represents the price of energy inputs and τ_{Et} is the carbon tax.[14]

Both capital and labor are assumed to be perfectly mobile across sectors. Profit maximization thus implies that prices and marginal factors will be equated:

$$\begin{aligned} (p_{Et} - \tau_{Et})F_{2lt} &= w_t \\ (p_{Et} - \tau_{Et})F_{2kt} &= r_t \end{aligned} \tag{10}$$

[13] As discussed in Barrage (2014), consideration of non-renewable resource dynamics may change the optimal carbon tax level (to capture scarcity rents), but does not interact with the differential optimal policy treatment of production versus utility impacts of climate change. For a detailed discussion in a static setting, see also, e.g., Bento and Jacobsen (2007).

[14] Energy inputs are measured in tons of carbon-equivalent; one unit of energy thus equals one ton of carbon.

Government: Fiscal and Climate Policy

The government faces two tasks: raising revenues to meet an exogenous sequence of expenditure requirements $\{G_t > 0\}_{t=0}^{\infty}$ and choosing an optimal policy mix to address climate change. Following recent work in the adaptation-mitigation literature (e.g., Felgenhauer and Webster, 2013; Agrawala et al., 2010; de Bruin, 2011), I model adaptive capacity in sector i, ${\Lambda_t}^i$, as an aggregate of both adaptation capital $K_t^{\Lambda i}$ (e.g., sea walls) and flow adaptation inputs λ_t^i (e.g., fertilizer):

$$\Lambda_t^i = f^i(K_t^{\Lambda i}, \lambda_t^i) \tag{11}$$

Each period, the government must finance government consumption G_t, bond repayments B_t, flow adaptation expenditures λ_t^i, and net investment in adaptation capital $K_t^{\Lambda,i}$. The government receives revenues from the issuance of new one-period bonds B_{t+1}, by levying taxes on labor, capital income, and carbon emissions. The government's flow budget constraint is thus:

$$G_t + B_t + \lambda_t^y + \lambda_t^u + K_{t+1}^{\Lambda,y} + K_{t+1}^{\Lambda,u} \tag{12}$$

$$\leq \quad \tau_{lt} w_t L_t + \tau_{Et} E_t + \tau_{kt}(r_t - \delta) K_t^{pr} + (1-\delta)(K_t^{\Lambda,y} + K_t^{\Lambda,u}) + \rho_t B_{t+1} \tag{13}$$

The specification (12) differentiates itself from the standard Ramsey setup as in Chari and Kehoe (1999) through the inclusion of carbon taxes and adaptation expenditures, and differs from the climate-economy Ramsey model in Barrage (2014) through adaptation expenditures. Given (12), we can summarize the market clearing conditions for the different capital stocks in the economy at time t :

$$K_t = K_{1t} + K_{2t} + K_t^{\Lambda,y} + K_t^{\Lambda,u} \tag{14}$$

$$= K_t^{pr} + K_t^{\Lambda,y} + K_t^{\Lambda,u} \tag{15}$$

Here, private capital is composed of final good and energy production sector capital: $K_t^{pr} \equiv K_{1t} + K_{2t}$. Specification (14) assumes that, over the model's 10-year time period, capital is mobile across sectors. I moreover impose that depreciation rates are identical across sectors, although this assumption can easily be relaxed. Finally, I assume throughout that the government can commit to a sequence of tax rates at time zero.

Climate System

The quantitative model adopts the DICE representation of the climate system (Nordhaus, 2010). However, for the purposes of this analytic section, let temperature change T_t at time t simply be a function F_t of initial carbon concentrations S_0 and all past carbon emissions:

$$T_t = F_t\left(S_0, E_0, E_1, ..., E_t\right) \tag{16}$$

where:

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

Competitive Equilibrium

A Competitive equilibrium ("CE") in this economy can now be defined as follows:

Definition 1 *A competitive equilibrium consists of an allocation* $\{C_t, L_{1t}, L_{2t}, K_{1t+1}, K_{2t+1},$ $E_t, T_t, \lambda_t^y, \lambda_t^u, K_{t+1}^{\Lambda,y}, K_{t+1}^{\Lambda,u}, \Lambda_t^u, \Lambda_t^y\}$*, 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) adaptive capacity in each sector is feasible given adaptive inputs,

(iv) temperature change satisfies the carbon cycle constraint in every period, and

(v) markets clear.

The social planner's problem in this economy is to maximize the representative agent's lifetime utility (1) subject to the constraints of (i) feasibility and (ii) the optimizing behavior of households and firms. I follow the *primal approach* (see, e.g., Chari and Kehoe, 1999), which solves for optimal allocations after having shown that and how one can construct prices and policies such that the optimal allocation will be decentralized by optimizing households and firms. The optimal allocation - the Ramsey equilibrium - is formally defined as follows:

Definition 2 *A Ramsey equilibrium is the CE with the highest household lifetime utility for a given initial bond holdings* B_0*, initial aggregate private capital* K_0^{pr} *and abatement capital* $K_0^{\Lambda,y}$ *and* $K_0^{\Lambda,u}$*, initial capital income tax* $\overline{\tau_{k0}}$*, and initial carbon concentrations* S_0*.*

Following the standard approach, one can set up the primal planner's problem as follows:

Proposition 1 *The allocations* $\{C_t, L_{1t}, L_{2t}, K_{1t+1}, K_{2t+1}, E_t, T_t, \lambda_t^y, \lambda_t^u, K^{\Lambda,y}, K_t^{\Lambda,u}, \Lambda_t^u, \Lambda_t^y\}$*, along with initial bond holdings* B_0*, initial aggregate private capital* K_0^{pr}*, adaptation capital* $K_0^{\Lambda,y}$ *and* $K_0^{\Lambda,u}$*, initial capital income tax* $\overline{\tau_{k0}}$*, and initial carbon concentrations* S_0 *in a competitive equilibrium satisfy:*

$$F_{1t}(A_{1t}, L_{1t}, K_{1t}, E_t, T_t, \Lambda_t^y) + (1-\delta)K_t \geqslant C_t + G_t + K_{t+1} + \lambda_t^y + \lambda_t^u \tag{RC}$$

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

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

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

$$K_{1t} + K_{2t} + K^{\Lambda,y} + K_t^{\Lambda,u} \leq K_t \tag{KC}$$

$$\begin{aligned} \Lambda_t^y &= f^y(K_t^{\Lambda y}, \lambda_t^y) \\ \Lambda_t^u &= f^u(K_t^{\Lambda u}, \lambda_t^u) \end{aligned} \tag{AdptC}$$

and

$$\sum_{t=0}^{\infty} \beta^t \left[U_{ct}C_t + U_{lt}L_t\right] = U_{c0}\left[K_0^{pr}\left\{1 + (F_{k0} - \delta)(1 - \tau_{k_0})\right\} + B_0\right] \tag{IMP}$$

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: See Appendix. In words, *Proposition 1* implies that any allocation satisfying the conditions (RC)-(IMP) can be decentralized as a competitive equilibrium through some set of prices and policies. I generally assume that the solution to the Ramsey problem is interior and that the planner's first order conditions are both necessary and sufficient. The planner's problem is thus to maximize (1) subject to (RC)-(IMP) (see Appendix).

Theoretical Results

Before discussing the results, one more definition is required. The *marginal cost of public funds* (MCF) is a measure of the welfare cost of raising an additional dollar of government revenues. When governments can use lump-sum taxes to raise revenues, then the marginal cost of public funds equals 1, as households give up \$1 in a pure transfer to the government. However, when revenues are raised through distortionary taxes, the costs of raising \$1 will equal \$1 plus the excess burden (or marginal deadweight loss) of taxation. In reviewing the literature, Barrage (2014) calculates the GDP-weighted average MCF estimate across countries and tax instruments to be 1.5, implying that on average \$0.50 is lost for every \$1 of revenue raised. Following the literature, I formally define the marginal cost of funds as the ratio of public to private marginal utility of consumption:

$$MCF_t \equiv \frac{\lambda_{1t}}{U_{ct}} \tag{17}$$

where λ_{1t} is the Lagrange multiplier on the resource constraint (RC) in the planner's problem.

The wedge between the marginal utility of public and private income thus serves as a measure of the distortionary costs of the tax system.

Given (17), we can state the theoretical results. Consider first the optimal provision of flow adaptation inputs to reduce production damages from climate change (e.g., fertilizer subsidies, sand bags, mosquito control sprayings, etc.):

Result 1 *Public funding of flow adaptation inputs to reduce climate impacts on final goods production should remain undistorted regardless of the welfare costs of raising revenues. That is, productive flow adaptation expenditures should be fully provided at the optimum.*

Before discussing this result in further detail, it is important to define the notion of "undistorted" public goods provision. The actual dollar amount of optimal spending will differ across fiscal settings. However, Result 1 implies that there is no "wedge" (or distortion) in the optimality condition for spending on flow adaptation inputs to reduce production damages from climate change: the government should spend resources on these adaptation goods until the additional benefit of avoided output losses equals the marginal adaptation cost. More formally, as shown in the Appendix, the optimal policy equates the marginal rate of transformation between C_t and adaptive capacity Λ_t^y through expenditures on flow adaptation inputs λ_t^y ($\mathrm{MRT}^{f_t^y}_{C_t,\Lambda_t^y}$) and avoided output losses from climate change in the final goods sector ($\mathrm{MRT}^{F_{1t}}_{C_t,\Lambda_t^y}$):

$$\underbrace{(-F_{1Tt}D(T_t))}_{\mathrm{MRT}^{F_{1t}}_{C_t,\Lambda_t^y}} = \underbrace{\frac{1}{f^y_{\lambda_t}}}_{\mathrm{MRT}^{f_t^y}_{C_t,\Lambda_t^y}} \tag{18}$$

Here, F_{1Tt} denotes the marginal output losses due to a change in temperature at time t, and $D(T_t)$ is the damage function. The left-hand side of (18) thus measures the increase in the final consumption good available due to a marginal increase in adaptive capacity in the final goods sector (Λ_t^y). Conversely, the right-hand side represents the marginal rate of transformation between the consumption good C_t and adaptive capacity through flow adaptation expenditures λ_t^y.[15] While condition (18) will be evaluated at different allocations depending on the tax system, it ensures that there is no wedge distorting the provision of flow adaptation at the optimum. (Importantly, this result stands in contrast to other adaptation expenditures, as discussed below.) Intuitively, while it is costly for the government to raise revenues, at the optimal level these adaptation expenditures 'pay for themselves' by increasing output (and thereby also expanding

[15] Specifically, one unit of the final consumption good is required to increase flow adaptation expenditures by one unit, which, in turn, increases adaptive capacity through its marginal product in the adaptation production function, $f^y_{\lambda_t}$.

the bases of labor and capital income taxes). This result follows from the well-known property that optimal tax systems maintain aggregate production efficiency under fairly general conditions (Diamond and Mirrlees, 1971). By noting that adaptation expenditures constitute a public input to production, this result likewise follows from studies such as Judd (1999), who finds that public flow productive inputs should always be fully provided, regardless of the distortionary costs of raising revenues.

Next, and in contrast, consider the provision of flow adaptation expenditures to reduce utility impacts of climate change (e.g., beach nourishment to maintain public parks). While these expenditures increase utility, they do not yield a productivity benefit that could counteract the macroeconomic costs of raising the revenues required to fund them. Consequently, I find that the optimal provision of these adaptation expenditures is distorted proportionally to the marginal cost of raising public funds. More specifically, as shown in the Appendix, the optimality condition governing these expenditures is given by:

$$\underbrace{\frac{(-U_{Tt}T_t)}{U_{ct}}}_{\text{MRS}_{C_t,\Lambda_t^u}}\underbrace{\frac{1}{MCF_t}}_{\text{wedge}} = \underbrace{\frac{1}{f^u_{\lambda_t}}}_{\text{MRT}^{f_t^u}_{C_t,\Lambda_t^u}} \tag{19}$$

The first term on the left-hand side of (19) is the household's marginal rate of substitution (MRS) between consumption and adaptive capacity to reduce climate change utility impacts. The right-hand side equals the marginal cost of increasing this adaptive capacity, or the marginal rate of transformation (MRT) between consumption and adaptive capacity (through increased flow expenditures λ_t^u). However, contrary to equation (18) here there is a wedge between the MRS and MRT at the optimum.

Result 2 *Public funding of flow adaptation inputs to reduce direct utility losses from climate change should be distorted if governments raise revenues with distortionary taxes. That is, the provision and thus consumption of the climate adaptation good should be effectively taxed alongside the consumption of other final goods.*

Intuitively, the wedge in (19) can be thought of as an implicit tax on the consumption of the climate adaptation good. Just like any final good in this economy, utility adaptation will be 'taxed' by being less-than-fully provided (compared to the first-best setting).

Both Result 1 and Result 2 are closely related to a set of findings in the environmental tax interaction literature regarding the internalization of environmental impacts affecting utility versus production (Bovenberg and van der Ploeg, 1994; Williams, 2002; Barrage, 2014). These studies find that the optimal pollution tax internalizes production externalities 'fully' (without a wedge), whereas a large literature has demonstrated that utility damages are 'less-than-fully' internalized (with a wedge) when there are other, distortionary taxes (see, e.g., review by Bovenberg and Goulder, 2002). However, as shown by Barrage (2014), additional considerations apply in a dynamic setting with stock pollutants. As discussed below, I similarly find that the optimal policy rules governing investment in adaptation capital may differ from those for flow adaptation expenditures described above.

Consider first the household's decision to invest in private capital. The marginal rate of transformation between consumption in periods t and $t+1$ based on private capital investments in final goods production is given by:

$$MRT^{K_{1t}}_{C_t,C_t+1} = \frac{1}{F_{k_{t+1}} + (1-\delta)} \tag{20}$$

The household's marginal rate of substitution between C_t and C_{t+1} is moreover given by:

$$MRS_{C_t,C_{t+1}} = \frac{\beta U_{ct+1}}{U_{ct}} \tag{21}$$

Investment decisions in private capital are undistorted if $MRT^{K_{1t}}_{C_t,C_t+1} = MRS_{C_t,C_{t+1}}$. As can readily be seen from a simple comparison of (20), (21), and the household's Euler Equation (4), undistorted investment margins require effective capital income taxes (τ_{kt+1}) to be zero. As is well-known, it is indeed desirable for the government to leave private investment decisions undistorted in a wide range of settings (see, e.g., Chamley, 1986; Judd, 1985; Atkeson, Chari, and Kehoe, 1999, Acemoglu, Golosov, Tsyvinski, 2011, etc.). Here, I find that this condition determines optimal climate change adaptation investments as well.

One the one hand, public investments in adaptation capital to reduce the *output losses* from climate change (e.g., sea walls to protect productive infrastructure) transform consumption in period t into output in period $t+1$. Giving up 1 unit of C_t to invest in adaptation capital $K^{\Lambda,y}_{t+1}$ increases adaptive capacity in the output sector at time $t+1$ by $f^y_{K_t+1}$ units. In terms of the final consumption good, this investment thus yields a return of $f^y_{K_t+1} \cdot D(T_{t+1})\widetilde{F_{1t+1}}(.)$ units, plus the undepreciated capital. The MRT between C_t and C_{t+1} based on investments in production adaptation capital is thus given by:

$$MRT^{K\Lambda y}_{Ct,Ct+1} = \frac{1}{f^y_{K_t+1} D(T_{t+1})\widetilde{F_{1t+1}}(.) + (1-\delta)} \tag{22}$$

As shown in the Appendix, the optimal policy mix equates the returns to investing in private and public capital, (20) and (22), respectively. Importantly, this implies that public investment in production adaptation capital is undistorted ($MRT^{K\Lambda y}_{C_t,C_{t+1}} = MRS_{C_t,C_{t+1}}$) whenever investment decisions in private capital are undistorted (i.e., when the government optimally sets capital income taxes to zero).

Result 3 *The optimal policy in period $t > 0$ features undistorted (full) public investment in adaptation capital to reduce production damages from climate change if the optimal policy leaves private capital investment undistorted (zero capital income tax). In this case, the government should invest fully in production adaptation capital even though the necessary revenues are raised with distortionary taxes.*

The intuition for this result is simple: if the structure of the economy is such that it is optimal not to distort productive investments, then this holds true for both private and public capital. The implementation of this undistorted allocation requires a zero effective capital income tax as well as full public provision of productive adaptation capital.

Finally, consider on the other hand investments in adaptation capital to reduce utility damages. In contrast to productive adaptation capital, the return to these investments consists of future environmental quality, rather than future consumption. That is, the relevant intertemporal margin is between C_t and $-T_{t+1}$.[16] With regards to the MRT, giving up 1 unit of C_t to marginally increase utility adaptation capital $K^{\Lambda,u}_{t+1}$ decreases the effective amount of temperature change entering the utility function by f^u_{Kt+1}, and thus increases the climate amenity by a total of $-T_{t+1}f^u_{Kt+1}$ units. In addition, this investment will leave $(1-\delta)K^{\Lambda,u}_{t+1}$ units of the consumption-investment good after depreciation. Denominated in equivalent units of the climate amenity, the value of this leftover capital after an increase in $K^{\Lambda,u}_{t+1}$ by one unit equals $\frac{(1-\delta)U_{ct+1}}{-U_{Tt+1}}$. In sum, the MRT is thus:

$$MRT^{K\Lambda u}_{C_t,T_{t+1}} = \frac{1}{-T_{t+1}f^u_{Kt+1} + \frac{(1-\delta)U_{ct+1}}{-U_{Tt+1}}} \tag{23}$$

The representative agent's MRS between C_t and $-T_{t+1}$ is conversely given by:

$$MRS_{C_t,T_{t+1}} = \frac{\beta U_{Tt+1}}{U_{ct}} \tag{24}$$

Equating (23) and (24) and rearranging terms, one can see that, in order for investments in utility damages adaptation capital to be undistorted, it must be the case that:

[16] Here, as temperature change T_{t+1} denotes an environmental bad, the reduction (or negative) of this bad $-T_{t+1}$ represents an improvement in environmental quality, or the environmental good.

$$
\begin{aligned}
MRS_{C_t,T_{t+1}} &= MRT^{K\Lambda u}_{C_t,T_{t+1}} \\
&\Leftrightarrow \\
\frac{U_{ct}}{\beta U_{ct+1}} &= (1-\delta) + \frac{(-U_{Tt+1}T_{t+1})}{U_{ct+1}} f^u_{Kt+1} \qquad (25)
\end{aligned}
$$

As shown in the Appendix, the government's optimality condition does not generally coincide with (25) when revenues are raised through distortionary taxes. That is, when the marginal cost of public funds exceeds unity ($MCF_{t+1} > 1$), public investment in adaptation capital to reduce climate change utility damages is distorted at the optimum. For example, if preferences take one of the commonly used constant elasticity forms (27)-(28), the government's optimality condition for utility adaptation investment for $t > 1$ becomes (see Appendix):

$$
\frac{U_{ct}}{\beta U_{ct+1}} = (1-\delta) + \left[\frac{(-U_{Tt+1}T_{t+1})}{U_{ct+1}} \frac{1}{MCF_{t+1}} f^u_{K_{t+1}} \right] \qquad (26)
$$

Comparing (25) and (26) thus demonstrates that the planner's optimality condition (26) features a wedge between the MRS and MRT. Intuitively, this is because the planner values the household's future climate change disutility based on the public marginal utility of income, whereas the household values his disutility based on his private marginal utility of consumption. Distortionary taxes create a deadweight loss in the transfer of income from households to the government. Consequently, the public and private marginal utilities of income diverge, and the optimal provision of public utility adaptation capital is distorted. The wedge in (26) also corresponds to an implicit tax on utility adaptation capacity, which is taxed (distorted) at the optimum just like all other consumption goods. As before, the contrast to output adaptation capital emerges because the optimal policy leaves productive investments and intermediate goods undistorted, and imposes all distortions on the consumption side of the economy. To summarize:

Result 4 *The optimal policy at time $t > 1$ leaves investment in adaptation capital to reduce direct utility impacts from climate change distorted if governments raise revenues through distortionary taxes (if $MCF_{t+1} > 1$). In addition, optimal investment in utility adaptation capital remains distorted even if it is optimal for there to be no distortions on investment in private capital (no capital income tax) and public adaptation capital to reduce production impacts of climate change.*

Finally, the four theoretical results can be formally summarized by the following proposition.

Corollary 1 *If preferences are of either commonly used constant elasticity form,*

$$U(C_t, L_t, T_t, \Lambda_t^u) = \frac{C_t^{1-\sigma}}{1-\sigma} + \vartheta(L_t) + h(T_t(1-\Lambda_t^u)) \tag{27}$$

$$U(C_t, L_t, T_t, \Lambda_t^u) = \frac{(C_t L_t^{-\gamma})^{1-\sigma}}{1-\sigma} + h(T_t(1-\Lambda_t^u)) \tag{28}$$

then, after period $t > 1$:

(i) investment in private capital should be undistorted (the optimal capital income tax is zero),

(ii) investment in public adaptation capital to reduce climate change production damages should be undistorted;

(iii) investment in public adaptation capital to reduce direct utility damages in period t should be distorted in proportion to the marginal cost of public funds in period $t+1$;

(iv) public flow adaptation expenditures to reduce production damages should be undistorted (satisfy productive efficiency);

(v) public flow adaptation expenditures to reduce direct utility damages in period t should be distorted in proportion to the marginal cost of public funds in period t; and:

(ii) the optimal carbon tax is implicitly defined by:

$$\tau_{Et}^* = \tau_{Et}^{Pigou,Y} + \frac{\tau_{Et}^{Pigou,U}}{MCF_t} \tag{29}$$

Proof: See Appendix. Intuitively, the proof follows straightforwardly from Results $1-4$.

The expression implicitly defining the optimal carbon tax (29) is identical to the one presented by Barrage (2014) for this model without adaptation.[17,18] That is, the need for additional government revenue to finance adaptation does not change the formulation defining the optimal carbon tax. Intuitively, this is because carbon taxes in this model fall on energy inputs, which are an intermediate good. Consequently, carbon is not a desirable tax base beyond revenues from corrective taxes (see, e.g., Diamond and Mirrlees, 1971; also discussion by Goulder, 1996).

The theoretical results presented in this section are limited to qualitative statements based on implicit expressions. In order to solve the model and assess the quantitative importance of the fiscal context for the optimal adaptation-mitigation policy mix and the welfare costs of climate change, the next section describes the numerical implementation of the model.

[17] Of course, the value of the optimal tax will differ between the models as (29) is evaluated at different allocations.

[18] In a static setting, an analogous expression differentiating production and utility impacts was also been derived by Bovenberg and van der Ploeg (1994) and Williams (2002).

3 Quantitative Analysis in Integrated Assessment Climate-Economy Model

3.1 COMET Overview

In order to assess the quantitative importance of fiscal considerations for climate policy, I integrate adaptation as policy lever into the Climate Optimization Model of the Economy and Taxation (COMET) presented by Barrage (2014). The COMET builds on the seminal DICE climate-economy model of Nordhaus (see, e.g., 2008, 2010, etc.). It is a global dynamic general equilibrium growth model with two production sectors: a final consumption-investment good is produced using capital, labor, and energy inputs, and energy is produced from capital and labor. Production further depends on the climate. There is both clean and carbon-based energy. Consumption of the latter leads to carbon emissions which accumulate in the atmosphere and change the climate. The climate system is modeled as in DICE, with three carbon reservoirs (lower ocean, upper ocean/biosphere, atmosphere) and an exogenous path of projected land-based emissions. The COMET also adapts DICE's projections of population growth and technological progress in both final goods production and clean energy production. The COMET differs from DICE in several key ways to incorporate a simple representation of fiscal policy. First, households have preferences over consumption, leisure, and the climate (separably). A globally representative government faces the dual task of raising revenues and addressing climate change. The government can issue bonds and impose linear taxes on labor, capital income, and carbon. It faces an exogenous sequence of government consumption requirements and household transfer obligations. These are calibrated based on IMF Government Finance Statistics to match globally representative government spending patterns. See Barrage (2014) for details.

The COMET focuses on the policies that would be pursued by a global welfare-maximizing planner. Importantly, the calibration nonetheless captures heterogeneity across countries in terms of expected climate change impacts, adaptation costs, average tax rates, etc. However, strategic interactions across countries are not considered. The reason for this focus is twofold. First, with regards to mitigation policy, d'Autume, Schubert, and Withagen (2011) formally demonstrate that, even though countries may have heterogeneous distortionary tax systems, the optimal global carbon tax is still uniform across countries when lump-sum redistribution between nations is possible. Indeed, the international community has set up mechanisms for such transfers, most notably the Green Climate Fund under the United Nations Framework Convention on Climate Change (UNFCCC).[19] In reality, political constraints may of course prevent the optimal uniform global carbon price from being implemented. Heterogeneous climate adaptation efforts across

[19] For details, see Green Climate Fund website at: http://news.gcfund.org/

countries may further exacerbate coordination failures (see, e.g., Antweiler, 2011; Buob and Stephan, 2011). I abstract from these strategic considerations and study the global planner's solution as it still represents the ideal benchmark against which other, third-best policies or inefficient equilibria should arguably be compared. While this paper's focus is thus strictly on the interaction of fiscal considerations and the climate adaptation-mitigation tradeoff, further consideration of the triple-interaction with strategic incentives is likely an interesting area for future research.

Another restriction is that I focus on public adaptation efforts. In reality, climate change adaptation involves both public and private actions (Mendelsohn, 2000). However, in the COMET this assumption is without loss of generality to the extent that private adaptation costs are borne by (competitive) firms in expenditures of the final consumption-investment good. This is because an increase in government expenditure changes the economy's aggregate resource constraint equivalently to a loss of aggregate output by one unit. It should be noted that this may no longer hold if the model incorporated, for example, multiple sectors with heterogeneous adaptation possibilities, or a non-Cobb Douglas production structure where adaptation efforts could have different complementarities with labor versus capital. The focus on public adaptation is also not without loss of generality to the extent that adaptation costs are actually borne by households. The resulting non-separability between household preferences over climate change, consumption, and leisure would be expected to change the results, as prior research on optimal emissions taxes and non-separability has shown (see, e.g., Schwarz and Repetto, 2002; Carbone and Smith, 2008). I consequently exclude adaptation to climate change impacts on the value of leisure time use, as those are unambiguously private (see AD-DICE 2010).[20] For the remaining sectors, I focus on adaptation costs borne by the public as those are likely much larger in magnitude than household-level adaptation costs.

3.2 Modeling Adaptation

The central quantitative challenge of this paper is to incorporate adaptation into the COMET. This extension necessitates (i) replacing the COMET's net (of adaptation) damage functions with gross damage functions, (ii) adding adaptive capacity production functions, and (iii) expanding the government's choice set to include adaptation expenditures. Several issues arise in the calibration of adaptation cost functions. First, bottom-up studies are limited both in terms of sectors and regions covered. In addition, bottom-up studies often do not report their results in sufficiently comparable metrics to enable integration into a single cost function. Finally, estimating adaptation costs in certain sectors, such as for biodiversity preservation, is extremely

[20] That is, for time use impacts, I exclude the estimated adaptation costs and retain *net* damages in the cost and damages aggregation based on AD-DICE 2010.

difficult (see, e.g., UNFCCC, 2007). Consequently, existing aggregate adaptation cost functions are highly uncertain and require many simplifying assumptions (see also discussion by Agrawala et al., 2011).

The literature has dealt with this challenge in several ways. A number of studies rely on cost functions backed out from the DICE/RICE model family. The DICE damage function (Nordhaus and Boyer, 2000) uses adaptation-inclusive cost estimates in certain sectors, such as agriculture. An approach pioneered by de Bruin, Dellink, and Tol (2009) thus seeks to split the DICE net damages into gross damages, residual damages, and adaptation costs. The authors calibrate the model such that the benchmark results duplicate the DICE optimal net damages path, and match other moments derived from the literature.[21] Other studies focus on adaptation in sectors where good cost estimates are available. For example, the FUND model (Tol, 2007) represents sea-level rise adaptation based on available cost estimates for measures such as building dikes. Finally, the PAGE model (Hope et al., 1993; Hope, 2006, 2011) features exogenous adaptation variables which can reduce climate damages in several ways. In this paper, I use a modified version of the adaptation cost and gross damages estimates underlying the AD-DICE/-RICE model as detailed in Agrawala, Bosello, Carraro, de Bruin, de Cian, Dellink, and Lanzi (2010). The authors combine a backing-out procedure based on DICE/RICE with results from other adaptation studies (e.g., Tan and Shibasaki (2003) on agriculture) and modelers' judgment to provide adaptation cost estimates across the sectors and regions of the RICE model. The key innovation required to use their estimates in this study is to separately estimate adaptation and gross damage functions for production and utility damages, as demonstrated by the theoretical results.

In order to provide separate estimates for production and utility damages, I disaggregate the AD-DICE estimates according to the same criteria as outlined in Barrage (2014):

[21] As discussed by Agrawala, Bosello, Carraro, Cian, and Lanzi (2011), additional studies based on this approach include Bahn et al. (2010), Hof et al. (2009), and Bosello et al. (2010).

Impact/ Adaptation 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

Two categories require further disaggregation. First, health impacts affect both production and utility as losses, as disease-adjusted years of life lost from climate-sensitive diseases decrease both work and leisure time endowments. The COMET consequently converts these time losses into an equivalent TFP change from a reduction in the global labor time endowment, and values the non-work share of time loss at standard figures for the value of statistical life (see Barrage (2014) for details). I follow the same approach here to convert the gross damage estimates presented by Agrawala et al. (2010) into gross production and utility losses from climate change health impacts. Second, catastrophic impacts are also assumed to affect both production possibilities and utility directly. I assume that the relative importance of production/utility impacts of a severe climate event in each region is proportional to the relative importance of production/utility impacts across the other sectors outlined in Table 1.[22] I weigh both damages and adaptation costs in each region by its predicted output share in the 2010-RICE model (Nordhaus, 2011) in 2065, when climate change is projected to reach the calibration point of $2.5°C$[23] in the business-as-usual (BAU) scenario. Re-aggregating and re-weighting (i) gross damages, (ii) optimal adaptation expenditures, and (iii) optimal adaptation effectiveness estimates presented by Agrawala et al. (2010) across regions and sectors in this way leads yields:[24]

[22] However, as in Barrage (2014), *time use* values are excluded from the calculation of the distribution of catastrophic impacts across production/utility damages, as such severe events are assumed to affect predominantly the other impact sectors.

[23] Mean atmospheric surface temperature change over pre-industrial levels.

[24] The total gross damages of 2.92% implied by the results exceed Agrawala et al.'s (2010) figure of 2.25%. This is in part because I weigh countries' impacts based on their predicted 2065 global output shares, giving a higher weight to developing nations than 2010 shares.

COMET Adaptation Calibration Moments at 2.5°C		
	Production (Y)	Utility (U)
Gross Damages (% GDP)	2.2%	0.7%
Total Adaptation Cost (% GDP)	0.47%	0.15%
Adaptation Effectiveness (% Damages Avoided)	52%	60%
Residual Damages	1.1%	0.3%

Table 2: Disaggregated Adaptation Estimates

I use these moments to calibrate gross damages and adaptation as follows. The AD-DICE model represents gross damages (as a fraction of GDP) as $GD = \alpha_1 T_t + \alpha_2 T_t^{\alpha_3}$. I maintain this functional form for both production and utility damages, but scale them by parameters θ^y and θ^u, respectively, to imply the appropriate gross damage values from Table Table (2) (see Appendix for parameter values). Net output is given by:

$$Y_t = \left(\frac{1}{1 + (1 - \Lambda_t^y) \cdot \theta^y [\alpha_1 T_t + \alpha_2 T_t^{\alpha_3}]} \right) \cdot A_t \widetilde{F_1}(K_{1t}, L_{1t}, E_t) \tag{30}$$

where Λ_t^y represents adaptive capacity (the fraction of damages reduced) as in the theoretical model. Similarly, disutility from climate change is modeled according to:

$$U = u(C_t, L_t) + \frac{1}{1-\sigma} \left(\frac{1}{1 + (1 - \Lambda_t^u) \cdot \theta^u \left[\alpha_1 T_t + \alpha_2 T_t^{\alpha_3}\right]} \right)^{1-\sigma} \tag{31}$$

As in Barrage (2014), the functional form of $h((1 - \Lambda_t^u) T_t)$ is chosen to ensure that the implied temperature risk aversion coefficient (as defined by Weitzman, 2010) from utility damages is equivalent to what it would be from a consumption loss. Finally, I assume the following specification of adaptation technology (for $i = y, u$) :

$$(1 - \Lambda_t^i) = \frac{1}{1 + \beta_A^i \lambda_t^i} \tag{32}$$

It should be noted that (32) models all adaptation expenditures as a flow (λ_t^i). Previous drafts of this paper provide results for a version of the model differentiating between flow and capital inputs in a CES adaptation production structure. However, this specification raised significant computational concerns, such as strong starting point sensitivity of the results.[25] Given that our present understanding of adaptation technologies is still characterized by deep uncertainties,

[25] This issue likely reflected areas of flatness in the objective function with regards to some of the adaptation choices due to the modeling and parameterization of adaptation costs and effectiveness (such as the COMET's putty-putty structure (implying adaptation capital malleability), and the degree of substitutability between adaptation capital and flow inputs assumed in the literature)).

I thus focus on the simplified and computationally robust specification (32). The parameters β_A^i ($i = y, u$) are then calibrated to match key moments from the results presented in Table 2, the AD-DICE model, and the COMET model without adaptation and distortionary taxes (see Appendix). Intuitively, the parameters are chosen such that when the model is run without distortionary taxes, it aligns with both (i) the optimal adaptation estimates based on the re-aggregation of AD-DICE described in Table 2, and (ii) optimal mitigation estimates from the COMET without distortionary taxes. In other words, the parameters are calibrated such that the results align with the literature when the model is run with the literature's benchmark assumption that there are no distortionary taxes.

3.3 Remainder of the COMET: Summary

The parameterization of the remainder of the COMET is as described in Barrage (2014), and can be summarized as follows. Both the final consumption good and energy inputs are produced from a Cobb-Douglas technology, with output shares taken from the literature and estimated based on U.S. energy sector production data, respectively. Preferences over consumption and leisure take a standard CES shape with a pure rate of social time preference equal to 1.5% per year ($\beta = 0.985$), an inverse intertemporal elasticity of substitution $\sigma = 1.5$, and a Frisch elasticity of labor supply of 0.78 (based on Chetty, 2011). Productivity growth, population growth, clean energy production costs, and the representation of the carbon cycle and climate system are all taken from the DICE model (Nordhaus, 2008). Estimates of public revenue requirements and spending on social transfers are based on IMF Government Finance Statistics. Finally, baseline effective tax rates are based on the GDP-weighted averages of cross-country estimates by Carey and Rabesona (2002), implying a 35.19% labor-consumption wedge, and a 43.27% capital income wedge. However, as noted below, I also consider slightly lower capital income taxes and higher labor income taxes as this improves both the plausibility and internal consistency of predicted tax rates.

4 Quantitative Results

The analysis focuses on five central fiscal scenarios:

1. A "First-Best" scenario without distortionary taxes, where the government can raise revenues through lump-sum taxation. This is the benchmark scenario in that the integrated assessment and adaptation literatures typically assume no distortionary taxes.

2. A "Optimized" scenario with fully optimized distortionary taxes.

3. A "BAU Labor tax, Adjustable Capital tax" scenario where labor income tax rates are held fixed at baseline levels (35.19%). Energy tax[26] revenues can be used ("recycled") to reduce capital income taxes and/or to finance adaptation expenditures. Conversely, the capital income tax can be decreased based on carbon tax revenues, and/or increased to finance additional adaptation expenditures.[27]

4. A "Alternative BAU Labor Tax, Adjustable Capital tax" scenario that is identical to (3) but allows a slightly higher BAU labor tax (36.58%) so as to yield constrained optimal capital income tax rates closer to the empirically motivated baseline levels than the very high rates resulting from scenario (3).

5. A "BAU Capital Tax, Adjustable Labor tax" scenario where capital income tax rates are held fixed at modified baseline levels (39.35%). Energy tax revenues can be used to reduce labor income taxes and/or to finance adaptation expenditures. Conversely, labor income taxes can be decreased based on carbon tax revenues, and/or increased to finance additional adaptation expenditures.[28]

In addition, I run a "No Carbon Tax" version of each of these scenarios. These runs impose the additional restriction that the planner cannot enact carbon taxes throughout the 21st Century.[29] Table 3 summarizes the quantitative results:

[26] Both clean and carbon-based energy inputs can now be taxed in the model. The "carbon tax" is defined as the excess level of the carbon-based energy tax over the clean energy tax (as both are measured in tons of carbon-equivalent). However, clean energy subsidies are restricted to zero in all scenarios.

[27] Capital income taxes are restricted to be constant after the initial period.

[28] Labor income tax rates are restricted to be constant after the initial period.

[29] All scenarios permit optimized carbon pricing after the year 2115 in order to avoid using the smooth, convex damage function of the model to evaluate the very large temperature change that would be associated with a "no carbon taxes at all" scenario.

Fiscal Scenario	Capital Tax (avg.) 2025-2215	Labor Tax (avg.) 2025-2215	Carbon Tax $\$/mtC$ 2015	MCF Avg. 2025-2215	T_t C° Max	Adaptation Avg. 2025-2215 Y	U
1a. First-Best	0%	0%	80	1.00	2.99	50%	52%
1b. First-Best, No Carbon Tax[a]	0%	0%	0	1.00	4.20	62%	62%
2a. Optimized	4%[a]	42%	68	1.07	3.06	51%	51%
2b. Optimized, No C-Tax	7%	43%	0	1.07	4.20	61%	60%
3a. BAU $\overline{\tau_l}$, Adj. τ_k	53%	35%	51[b]	2.50[c]	2.79	38%	28%
3b. BAU $\overline{\tau_l}$, Adj. τ_k, No C-Tax	54%	35%	0	2.69[c]	3.86	51%	40%
4a. Alt. BAU $\overline{\tau_l}$, Adj. τ_k	43%	37%	56[d]	1.80[c]	2.80	41%	36%
4b. Alt. BAU $\overline{\tau_l}$, Adj. τ_k, No C-Tax	44%	37ˆ	0	1.86[c]	3.89	54%	49%
5a. BAU $\overline{\tau_k}$, Adj. τ_l	39%	37%	60	1.06[f]	3.11	52%	52%
5b. BAU $\overline{\tau_k}$, Adj. τ_l No C-Tax	39%	38%	0	1.06[f]	4.34	63%	62%

[a] No carbon tax until 2115 after which optimal carbon pricing is permitted.

[a] Consists of $\tau_{k,2025} = 51\%$ followed by $\sim 0\%$ (except for pre-simulation period $T = 2215$; see Barrage (2014) for details.)

[b] Carbon tax is difference btwn. total taxes on carbon energy ($134/t in 2015, $179 in 2025, etc.) and taxes on clean energy ($82/t in 2015, $103 in 2025, etc.). All energy is taxed because it increases the marginal product of labor thus tightening the labor income tax constraint.

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

[d] Carbon tax is difference btwn. total taxes on carbon energy ($109/t in 2015) and taxes on clean energy ($53/t in 2015).

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

Table 3: Main Results

First, as expected, the most efficient income tax structure raises most revenues from labor income taxes, after an initial period of high capital income taxation (Scenario 2). In contrast, requiring the planner to maintain business-as-usual labor income taxes and raising additional revenues from capital income taxes is associated with a high cost of funds (Scenarios 3,4).

Second, in line with previous quantitative studies of optimal carbon taxes in the presence of other taxes (e.g., Goulder, 1995, Bovenberg and Goulder, 1996, etc.), I find that the optimal carbon price is lower, the higher the pre-existing tax burden. Figure 1 displays optimal carbon tax schedules across fiscal scenarios over time:

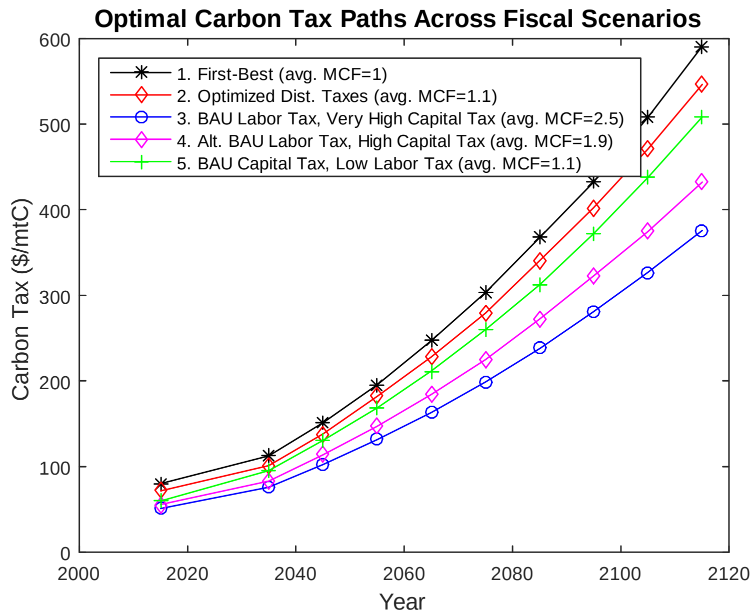

Figure 1

Intuitively, the reason for this finding is that carbon taxes exacerbate the welfare costs of other taxes by shrinking their bases (e.g., by reducing labor supply), as demonstrated in the long-standing literature on this topic (see, e.g., review by Bovenberg and Goulder, 2002). The results displayed in Figure 1 are moreover close to the ones obtained in Barrage (2014) for the model without adaptation, confirming the theoretical result that the need for additional tax revenues to (endogenously) fund public climate change adaptation efforts does not alter the optimal carbon tax formulation (expression (29)). Again, this is due to the well-known public finance result that taxes on intermediate inputs should not be used to raise revenues (above and beyond those from corrective or pure profits taxes).

Before discussing optimal adaptation, it is important to note that the lower carbon tax schedules of the more distortionary fiscal scenarios do not necessarily lead to more climate change. Indeed, optimal peak temperature change is lowest in the most distortionary scenario (3a) with the lowest carbon taxes, as can be seen in Table 3. This is because output and energy demand are both lower in the more distorted economy. Consequently, a lower carbon price is needed to achieve a given level of emissions than in a more efficient economy with higher output.

Finally, the results for optimal adaptation across fiscal scenarios can be summarized as follows. First, optimal adaptation against utility damages is lower, the higher the cost of raising public funds. For example, if the government has to raise additional funds from (effective) capital income taxes at a marginal cost of funds of 1.8, it should provide adaptation expenditures to reduce utility damages by only 36% on average, compared to 52% in the scenario with lump-sum taxation (Scenarios 4 and 1 in Table 3). This finding is in line with the theoretical result that, in choosing utility adaptation expenditures, the government should leave a wedge between the marginal rates of substitution and transformation in proportion to the marginal cost of public funds (see expression (19)). Figure 4 displays the evolution of utility adaptation (in % of damages avoided) across fiscal scenarios over the 21st Century:

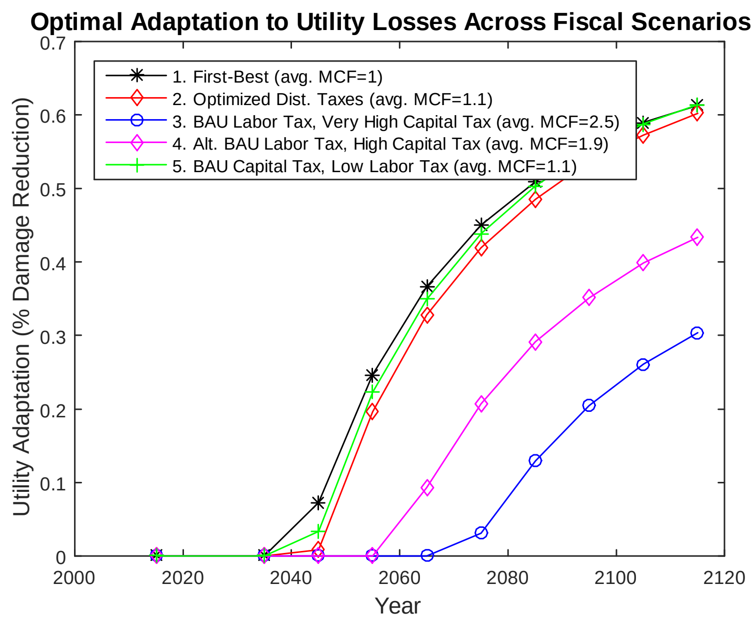

Figure 4

Next, for adaptation to reduce *output* losses from climate change, optimal provision is essentially unaffected by the presence of fully optimized distortionary taxes (i.e., 50% vs. 51% in Scenarios 1a and 2a of Table 3). This finding reflects the theoretical Result 1 that optimal provision of flow adaptation expenditures to guard against production damages should be fully provided even when revenues are raised with (optimized) distortionary taxes (see equation (18)).[30] Figure 5 displays optimal adaptation to output damages over time:

[30] Actual adaptation levels may still vary across fiscal scenarios due to differences in the allocations at which the planner's optimality condition is evaluated.

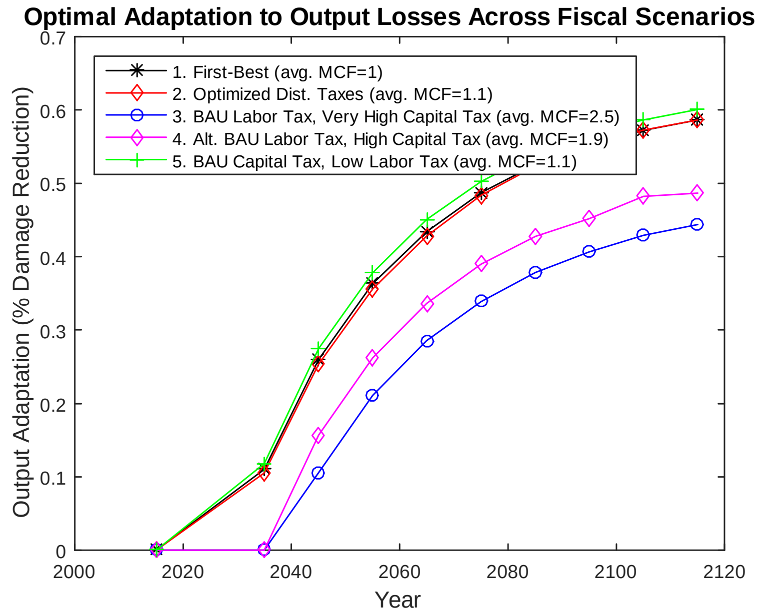

Figure 5

Perhaps surprisingly, in the scenarios with non-optimal tax policy, even productive adaptation is lower, the higher the cost of public funds. There are two potential reasons for this result. The first is that the optimality condition governing productive adaptation (18) must be modified to account for these expenditures' interactions with the additional constraints on the planner that give rise to sub-optimal tax policy (e.g., keeping labor income taxes at sub-optimally low levels). The second is that the general equilibrium differences across scenarios are larger in these more distorted settings, and consequently the adaptation level that solves even the basic optimality condition (18) may differ more from the first-best baseline case.

Importantly, however, the effect of the fiscal setting on optimal adaptation is much weaker for output than utility damages. Considering again the example where the government must raise additional revenues from (effective) capital income taxes with a MCF of 1.8, average output adaptation is 18% lower than in the first-best setting, whereas utility adaptation is reduced by over 30% (Scenarios 4 and 1 in Table 3). Figure 6 shows how the ratio of optimal utility vs. output adaptation (both in % of damages avoided) evolves over time across fiscal scenarios. Throughout the 21st Century it appears that governments facing more distortionary tax systems should prioritize adaptation to guard against output losses associated with climate change over adaptation to reduce non-productive utility damages. However, both should be provided in all fiscal scenarios considered.

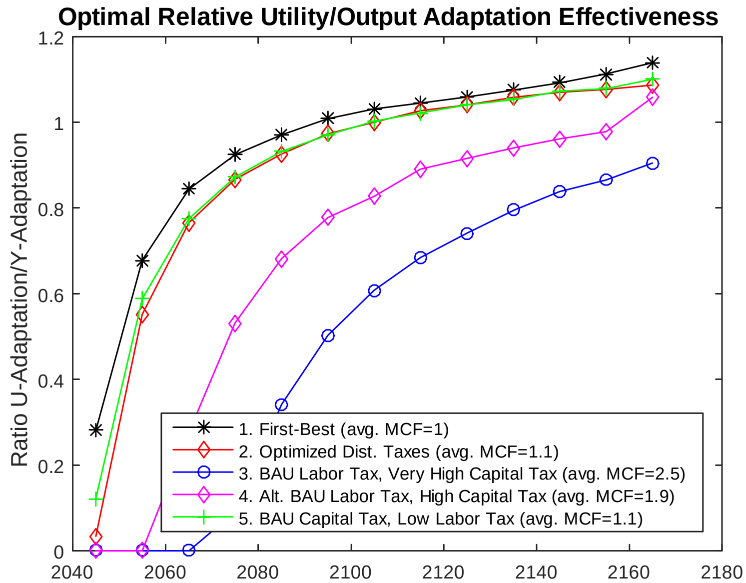

Figure 6

4.0.1 Welfare Effects of Relying on Adaptation as Climate Policy

Many of the current climate change policy efforts in the United States (and other countries) focus on adaptation rather than mitigation. As a final quantitative exercise, I thus compute the global welfare costs of failing to engage in mitigation over the 21st Century, and of pursuing an adaptation-only policy. For each fiscal scenario, these calculations compare welfare with optimized carbon taxes (Scenarios a) to the "No Carbon Tax" case (Scenarios b). Welfare is measured as the change in initial period aggregate consumption (ΔC_{2015} in \$2005) in the no-carbon tax scenarios that produces the same utility as the optimal climate policy allocation. Table 4 provides the results.

Policy Scenario: Income Taxes:		Carbon Tax:	ΔWelfare[1] $2005 tril.
1a.	First-Best	None (until 2115)	-
1b.	First-Best	Optimized	$10.8 tril.
2a.	Optimized	None (until 2115)	-
2b.	Optimized	Optimized	$12.2 tril.
3a.	BAU $\overline{\tau_l}$ (35%), Adj. τ_k	None (until 2115)	-
3b.	BAU $\overline{\tau_l}$ (35%), Adj. τ_k	Optimized	$20.3 tril.
4a.	Alt. BAU $\overline{\tau_l}$ (37%), Adj. τ_k	None (until 2115)	-.
4b.	Alt. BAU $\overline{\tau_l}$ (37%), Adj. τ_k	Optimized	$15.8 tril.
5a.	BAU $\overline{\tau_k}$ (39%), Adj. τ_l	None (until 2115)	-
5b.	BAU $\overline{\tau_k}$ (39%), Adj. τ_l	Optimized	$11.4 tril.
[1]Equivalent variation change in agg. initial consumption ΔC_{2015}			

Table 4: Welfare Costs of Adaptation-Only Policy

The results suggest that the welfare costs of addressing climate change only through adaptation may be almost twice as large when adaptation has to be financed through distortionary taxes. In the first-best setting with lump-sum taxation, the welfare costs of failure to engage in carbon taxes over the 21st Century are estimated to be $10.8 trillion ($2005). If additional revenues are raised through labor income taxes or an optimized tax mix, the cost of the adaptation-only policy increases to $11.4-12.2 trillion. Worse yet, if adaptation has to be financed through capital income taxes, the welfare costs of failing to price carbon increase to $15.8-20.3 trillion. It should be noted that these results also apply to *effective* capital income taxes, such as corporate income taxes. Analyses that ignore the fiscal costs of climate change adaptation may thus greatly underestimate the welfare costs of un-mitigated climate change. And while the adaptation production functions used in this study are subject to large quantitative uncertainty, these results arguably presents at least a notable warning that the public financing of climate change adaptation expenditures warrants further attention.

5 Conclusion

Adaptation to climate change impacts is increasingly recognized as a critical public policy issue. Even countries that have been unable to implement broad-based carbon pricing, such as the United States, are working towards integrated adaptation policies, as exemplified by President Obama's *Task Force on Climate Preparedness and Resilience*. A growing academic literature has explored the tradeoffs between adaptation and mitigation (reviewed by Agrawala, Bosello, Carraro, Cian, and Lanzi, 2011).

This study revisits this question from a fiscal perspective. In particular, when governments raise revenues through distortionary taxes, the fiscal costs of climate policy become welfare-relevant. On the one hand, public financing for adaptive capacity requires government revenues. On the other hand, mitigation policies such as carbon taxes raise revenues, but are also well-known to exacerbate the welfare costs of other taxes (see, e.g., Goulder, 1996; Bovenberg and Goulder, 2002). I therefore use a dynamic general equilibrium climate-economy model with linear distortionary taxes to theoretically characterize and empirically quantify these tradeoffs.

First, I find that both flow and capital adaptation expenditures to reduce direct utility impacts of climate change (e.g., biodiversity existence value losses) are distorted in a setting with distortionary taxes. The quantitative results suggest a decrease in optimal utility adaptation of up to 30-45% when it is financed through capital income taxes, compared to a first-best setting with lump-sum taxation.

Second, adaptation to reduce climate change impacts on final goods production should be fully provided to maintain productive efficiency, regardless of the welfare costs of raising government revenues. This result follows directly from studies such as Judd (1999), and is based on the well-known property of Ramsey tax systems that they maintain aggregate production efficiency under fairly mild conditions (Diamond and Mirrlees, 1971). This result may not hold if income taxes are inefficient, as third-best interactions may then make it desirable for the government to distort even productive adaptation expenditures. However, quantitatively I find that the effect of distortionary taxes is smaller for output than for utility adaptation. In all scenarios considered, the optimal policy for governments facing a higher cost of raising public funds is to focus those scarce resources relatively more on productive adaptation expenditures.

Third, the quantitative analysis suggests that the welfare costs of relying exclusively on adaptation to address climate change (i.e., without a carbon tax) may be up to twice as large in a setting with distortionary taxes. The estimated global welfare costs of an adaptation-only policy throughout the 21st Century is $10.8 trillion in a setting without distortionary taxes, $11.4-12.2 trillion when additional revenue comes from labor or optimized distortionary taxes, and $15.8-20.3 trillion when capital income taxes are used to raise additional funds ($2005). While these figures are based on highly uncertain adaptation cost estimates, they nonetheless show that the fiscal setting warrants further attention in considering the tradeoff between climate change adaptation and mitigation.

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6 Appendix

6.1 Proof of Proposition 1

This proof follows closely the one presented by Barrage (2014), but adds the adaptation variables of this study. In addition, let Ω_t denote public transfers to households. These are not in the analytic model above but are featured in the quantitative COMET model and thus incorporated in the proof here.

Before proceeding, it is useful to write out the firm's and household's first order conditions. Given the appropriate convexity assumptions, I can assume that the solution to the problem is interior. Let γ_t denote the Lagrange multiplier on the consumer's flow budget constraint (3) in period t, his first order conditions are given by:

$[C_t]$:

$$\gamma_t = \beta^t U_{ct} \tag{33}$$

$[L_t]$:

$$\frac{-U_{lt}}{U_{ct}} = w_t(1-\tau_{lt}) \tag{34}$$

$[K_{t+1}^{pr}]$:

$$\gamma_t = \beta\gamma_{t+1}\left\{1+(r_{t+1}-\delta)(1-\tau_{kt+1})\right\} \tag{35}$$

$[B_{t+1}]$:

$$U_{ct}\rho_t = \beta U_{ct+1} \tag{36}$$

The climate variable T_t and utility adaptation Λ_t^u do not enter his problem directly because he takes both values as given, and because of the additive separability in preferences we have assumed in (2).

Next, the final goods producer's problem is to select L_{1t}, K_{1t}, and E_t to solve:

$$\max F_{1t}(L_{1t}, K_{1t}, E_t, T_t, \Lambda_t^y) - w_t L_{1t} - p_{Et}E_t - r_t K_{1t}$$

where the firm takes the climate T_t and public adaptation Λ_t^y as given.

Defining F_{jt} as the first derivative of the production function with respect to input j, the firm's FOCs are:

$$\begin{aligned} F_{1lt} &= w_t \\ F_{1Et} &= p_{Et} \\ F_{1kt} &= r_t \end{aligned} \tag{37}$$

The energy producer's problem is to maximize:

$$\max(p_{Et}-\tau_{Et})E_t - w_t L_{2t} - r_t K_{2t}$$

subject to:

$$E_t = F_{2t}(L_{2t}, K_{2t})$$

With FOCs:

$$\begin{aligned} (p_{Et} - \tau_{Et})F_{2lt} &= w_t \\ (p_{Et} - \tau_{Et})F_{2kt} &= r_t \end{aligned} \tag{38}$$

Proof Part 1: If the allocations and initial conditions constitute a competitive equilibrium, then the constraints (RC)-(IMP) are satisfied. In a competitive equilibrium, the consumer's FOCs (33)-(36) must be satisfied. Multiplying both sides of (35) by K_t gives:

$$\left[\gamma_t - \gamma_{t+1}\left\{1 + (r_{t+1} - \delta)(1 - \tau_{kt+1})\right\}\right] K^{pr}_{t+1} = 0 \tag{39}$$

Equivalently, for bond holdings, we find:

$$\left[\gamma_t \rho_t - \gamma_{t+1}\right] B_{t+1} = 0 \tag{40}$$

Next, consumer optimization dictates that the transversality conditions must hold in a competitive equilibrium:

$$\begin{aligned} \lim_{t\to\infty} \gamma_t B_{t+1} &= 0 \\ \lim_{t\to\infty} \gamma_t K^{pr}_{t+1} &= 0 \end{aligned} \tag{41}$$

Lastly, the consumer's flow budget constraint (3) holds in competitive equilibrium. Multiplying both sides of the flow budget constraint in each period by the Lagrange multiplier γ_t leads to:

$$\gamma_t \left[C_t + \rho_t B_{t+1} + K^{pr}_{t+1}\right] = \gamma_t \left[w_t(1 - \tau_{lt})L_t + \left\{1 + (r_t - \delta)(1 - \tau_{kt})\right\} K^{pr}_t + B_t + \Omega_t + \Pi_t\right] \tag{42}$$

As discussed above, the assumptions of perfect competition and constant returns to scale in the energy sector imply that equilibrium profits will be equal to zero.[31] Summing equation (42) over all t thus yields:

$$\sum_{t=0}^{\infty} \gamma_t \left[C_t + \rho_t B_{t+1} + K^{pr}_{t+1} - w_t(1 - \tau_{lt})L_t - \left\{1 + (r_t - \delta)(1 - \tau_{kt})\right\} K^{pr}_t - B_t - \Omega_t\right] = 0 \tag{43}$$

[31] One can formally confirm this by substituting the energy producer's FOCs for labor and capital inputs into the definition of energy sector profits:

$$\Pi_t = (p_{Et} - \tau_{Et})F(K_{2t}, L_{2t}) - F_{l2t}(p_{Et} - \tau_{Et})L_{2t} - F_{kt}(p_{Et} - \tau_{Et})K_{2t}$$

If $F(K_{2t}, L_{2t})$ exhibits constant returns to scale, then by Euler's theorem for homogenous functions, $(F(K_{2t}, L_{2t}) = F_{l2t}L_{2t} + F_{k2t}K_{2t})$, and the profits expression reduces to zero.

All terms relating to capital and bond holdings after period zero cancel out of equation (43) out as can be seen by substituting in from (39), (40) and the transversality conditions (41). We thus end up with:

$$\sum_{t=0}^{\infty}\gamma_t\left[C_t - w_t(1-\tau_{lt})L_t - \Omega_t\right] = \gamma_0\left[K_0^{pr}\left\{1+(r_0-\delta)(1-\tau_{k_0})\right\}+B_0\right] \tag{44}$$

Finally, one can substitute out for the remaining prices γ_t, $w_t(1-\tau_{lt})$, and r_0 in (44) from the consumer's and firm's FOCs in order to obtain the implementability constraint (IMP):

$$\sum_{t=0}^{\infty}\beta^t\left[U_{ct}C_t + U_{lt}L_t - U_{ct}\Omega_t\right] = U_{c0}\left[K_0^{pr}\left\{1+(F_{k0}-\delta)(1-\tau_{k_0})\right\}+B_0\right] \tag{45}$$

We have demonstrated that the implementability constraint is satisfied in a competitive equilibrium.

The last step is where adaptation comes into play directly. We need to show that the final goods resource constraint (RC) holds in competitive equilibrium. Start by adding up the consumer and government flow budget constraints (3) and (12) with the addition of transfers to households Ω_t in each. Canceling redundant terms on each side leaves:

$$G_t + \lambda_t^y + \lambda_t^u + K_{t+1}^{abt} + C_t + K_{t+1}^{pr} = w_tL_t + \tau_{Et}E_t + \Pi_t + (1-\delta+r_t)K_t^{pr} + (1-\delta)K_t^{abt}$$

Next, invoking the definition of energy sector profits, substituting in based on the labor and capital market clearing conditions, and substituting in for factor prices based on the energy producer's FOCs (38) changes the RHS to:

$$G_t + \lambda_t^y + \lambda_t^u + K_{t+1}^{abt} + C_t + K_{t+1}^{pr} = w_tL_{1t} + p_{Et}E_t + r_tK_{1t} + (1-\delta)K_t^{pr} + (1-\delta)K_t^{abt} \tag{46}$$

By Euler's theorem for homogenous functions, (46) becomes the resource constraint, as desired:

$$G_t + \lambda_t^y + \lambda_t^u + K_{t+1}^{abt} + C_t + K_{t+1}^{pr} = Y_t + (1-\delta)K_t^{pr} + (1-\delta)K_t^{abt} \tag{47}$$

Finally, the carbon cycle constraint (CCC) and the energy producer's resource constraint (ERC) hold by definition in competitive equilibrium.

Direction: If constraints(RC)-(IMP) are satisfied, one can construct competitive equilibrium. I proceed with a proof by construction. First, set factor prices as equal to their marginal products evaluated at the optimal allocation:

$$\begin{aligned} F_{1lt} &= w_t \\ F_{1Et} &= p_{Et} \\ F_{1kt} &= r_t \end{aligned} \tag{48}$$

These factor prices are clearly consistent with profit maximization in the final goods sector, as needed in a competitive equilibrium. Next, set the return on bonds based on the consumer's intertemporal first order conditions for bond holdings (36):

$$\rho_t = \beta U_{ct+1}/U_{ct}$$

Again, this price is obviously consistent with utility maximization. Proceed similarly in setting the labor income tax based on the household's labor supply and consumption FOCs:

$$\begin{aligned} -U_{lt}/U_{ct} &= (1-\tau_{lt})F_{lt} \\ 1+\frac{U_{lt}/U_{ct}}{F_{lt}} &= \tau_{lt} \end{aligned}$$

Next, let the tax rate on capital income for each time $t > 0$ be defined by the household's Euler equation and the firm's capital holdings FOC:

$$\begin{aligned} U_{ct} &= \beta U_{ct+1}\left\{1+(F_{1kt+1}-\delta)(1-\tau_{kt+1})\right\} \\ \tau_{kt+1} &= 1-\frac{U_{ct}/\beta U_{ct+1}-1}{(F_{1kt+1}-\delta)} \end{aligned}$$

As before, being defined by the consumer and firm's FOCs these tax rates will clearly be consistent with utility and profit maximization.

Proceeding in the same manner, define the carbon tax based on the energy and final goods producers' FOCs (38) and (37) as:

$$\tau_{Et} = p_{Et} - \frac{F_{1lt}}{F_{2lt}}$$

Finally, in order to construct bond holdings in period t, multiply the consumer budget constraint (3) by its Lagrange multiplier γ_t and sum over all periods *from period t onwards*:

$$\sum_{s=t}^{\infty}\gamma_s\left[C_s+\rho_s B_{s+1}+K^{pr}_{s+1}-w_s(1-\tau_{ls})L_s-\left\{1+(r_s-\delta)(1-\tau_{ks})\right\}K^{pr}_s-B_s-\Pi_s-\Omega_t\right]=0 \tag{49}$$

The consumer's FOCs and transversality conditions (41) must necessarily hold in a competitive equilibrium, indicating that all future terms relating to capital and bond holdings in (49) cancel out. We are thus left with:

$$\sum_{s=t}^{\infty}\gamma_s\left[C_s-w_s(1-\tau_{ls})L_s-\Pi_s-\Omega_t\right]+\gamma_t\left\{1+(r_t-\delta)(1-\tau_{kt})\right\}K^{pr}_t=\gamma_t B_t \tag{50}$$

Use the agent's and the firms' FOCs once again to substitute out prices in equation (50) finally leads to:[32]

$$\sum_{s=t}^{\infty}\frac{\beta^{s-t}U_{cs}}{U_{ct}}\left[C_s+\frac{U_{ls}}{U_{cs}}L_s-\Omega_s\right]+\frac{U_{ct-1}}{\beta U_{ct}}K^{pr}_t=B_t$$

Given allocations, this equation defines the unique bond holdings that are consistent with a

[32] For the capital return in period t, note that the substitution derives from:

competitive equilibrium.

Since the prices and policies defined as outlined above are all based on household and firm optimality conditions, they are clearly consistent with utility and profit maximization. It thus remains to be shown that the constraints necessary for competitive equilibrium are satisfied as well. First, the final goods resource constraint, the carbon cycle constraint, the energy production resource constraints, and the factor market clearing conditions for labor and different capital types all hold by assumption. If we can show that the consumer budget constraint is satisfied, then by Walras' law it follows that the government budget constraint must be satisfied also. Following the standard line of reasoning (see, e.g., Chari and Kehoe, 1999), we can note the following. First, only the consumer's competitive equilibrium-budget constraint is relevant to show that our constructed prices, bond holdings, and policies are constitute a competitive equilibrium. In a competitive equilibrium, the household's intertemporal budget constraint must hold, along with the consumer's FOCs and the consumer's transversality conditions. Consequently, (39) and (40) must hold in a competitive equilibrium as well . However, as shown in the first part of this proof, at the prices selected above, the consumer's competitive equilibrium-budget constraint is identical to the implementability constraint, which holds by assumption. The competitive equilibrium budget constraint at the chosen prices is thus satisfied, as was to be shown □.

6.2 Proof of Theory Results

The social planner's problem is given by:

$$
\begin{aligned}
& \gamma_t \left[r_{kt}(1-\tau_{kt}) + (1-\delta) \right] K_t^{pr} \\
= \quad & \beta^t U_{ct} \left[\frac{U_{ct-1}}{\beta U_{ct}} \right] K_t^{pr} \\
= \quad & \beta^{t-1} U_{ct-1} K_t^{pr}
\end{aligned}
$$

$$
\begin{aligned}
&\max_{k}\sum_{t=0}^{\infty}\beta^{t}[\underbrace{[v(C_t,L_t)+h[(1-\Lambda_t^u)T_t]+\phi\,[U_{ct}C_t+U_{lt}L_t]]}_{\equiv W_t} \\
&+\sum_{t=0}^{\infty}\beta^{t}\lambda_{1t}\left[\begin{array}{c}\left\{[1-D(T_t)(1-\Lambda_t^y)]\cdot A_{1t}\widetilde{F_{1t}}(L_{1t},E_t,K_{1t})\right\}+(1-\delta)K_t \\ -C_t-K_{t+1}-G_t-\lambda_t^y-\lambda_t^u\end{array}\right] \\
&+\sum_{t=0}^{\infty}\beta^{t}\xi_t[T_t-\digamma_t(S_0,E_0,E_1,...E_t)] \qquad (51) \\
&+\sum_{t=0}^{\infty}\beta^{t}\lambda_{lt}\,[L_t-L_{1t}-L_{2t}] \\
&+\sum_{t=0}^{\infty}\beta^{t}\lambda_{kt}\left[K_t-K_{1t}-K_{2t}-K^{\Lambda,y}-K_t^{\Lambda,u}\right] \\
&+\sum_{t=0}^{\infty}\beta^{t}\omega_t\,[F_{2t}(A_{Et},K_{2t},L_{2t})-E_t] \\
&+\sum_{t=0}^{\infty}\beta^{t}\eta_{yt}\left[f^{y}(K_t^{\Lambda,y},\lambda_t^y)-\Lambda_t^y\right] \\
&+\sum_{t=0}^{\infty}\beta^{t}\eta_{ut}\left[f^{u}(K_t^{\Lambda,u},\lambda_t^u)-\Lambda_t^u\right] \\
&-\phi\left\{U_{c0}\left[K_0\left\{1+(F_{k0}-\delta)(1-\tau_{k_0})\right\}\right]\right\}
\end{aligned}
$$

The associated first-order conditions for periods $t>0$ are as follows:
$[E_t]$:

$$\lambda_{1t}F_{Et}-\sum_{t=0}^{\infty}\xi_{t+j}\frac{\partial T_{t+j}}{\partial E_t}=\omega_t \qquad (52)$$

$[T_t]$:

$$U_{Tt}+\lambda_{1t}F_{1Tt}=\xi_t \qquad (53)$$

$[L_t]$:

$$U_{lt}=-\lambda_{lt}$$

$[L_{2t}]$:

$$\lambda_{lt}=\omega_t F_{2lt} \qquad (54)$$

$[L_{1t}]$:

$$\lambda_{1t}F_{1lt}=\lambda_{lt} \qquad (55)$$

Conditions (52)-(55) can be used to derive an expression implicitly defining the optimal carbon tax. Specifically, combining (54) and (55) yields:

$$\frac{\lambda_{1t}F_{1lt}}{F_{2lt}}=\omega_t \qquad (56)$$

Combining (56) with the FOCs for energy inputs (52) and temperature change T_t (53), we obtain:

$$F_{Et} - \sum_{j=0}^{\infty} \beta^j \left[\frac{U_{Tt+j}}{\lambda_{1t}} + \frac{\lambda_{1t+j}}{\lambda_{1t}} F_{1Tt+j} \right] \frac{\partial T_{t+j}}{\partial E_t} = \frac{F_{1lt}}{F_{2lt}} \tag{57}$$

Comparison between (57) and the energy firm's optimality condition (10) at equilibrium factor prices (which are equated with marginal products), it thus immediately follows that the optimal carbon tax is implicitly defined by:

$$\tau_{Et}^{\star} = \sum_{j=0}^{\infty} \beta^j \left[\frac{U_{Tt+j}}{\lambda_{1t}} + \frac{\lambda_{1t+j}}{\lambda_{1t}} F_{1Tt+j} \right] \frac{\partial T_{t+j}}{\partial E_t} \tag{58}$$

In words, expression (58) is the present value sum of all future marginal utility and production damages associated with an additional ton of carbon emissions in period t. This expression is analogous to the one derived in Barrage (2014); however it will be evaluated at a different allocation due to the introduction of adaptation possibilities.

Next, consider the following additional FOCs for the planner's problem, again for $t > 0$:

$[\Lambda_t^u]$:

$$-U_{Tt} T_t = \eta_{ut} \tag{59}$$

$[\lambda_t^u]$:

$$\lambda_{1t} = \eta_{ut} f_{\lambda_t}^u \tag{60}$$

$[\Lambda_t^y]$:

$$\lambda_{1t} D(T_t) \widetilde{Y}_t = \eta_{yt} \tag{61}$$

where $\widetilde{Y}_t$ denotes gross output (before climate damages).

$[\lambda_t^y]$:

$$\lambda_{1t} = \eta_{yt} f_{\lambda_t}^y \tag{62}$$

Combining (59)-(60) yields the optimality condition for public provision of flow adaptation inputs λ_t^u :

$$\frac{-U_{Tt} T_t}{\lambda_{1t}} = \frac{1}{f_{\lambda_t}^u} \tag{63}$$

$$\frac{(-U_{Tt} T_t)/U_{ct}}{MCF_t} = \frac{1}{f_{\lambda_t}^u} \tag{64}$$

Multiplying the left-hand side of (63) by U_{ct}/U_{ct} and invoking the definition of the MCF in (17) thus yields the desired result of equation (19).

Similarly, combining (61)-(62) yields the optimality condition for flow adaptation inputs for production damages λ_t^y :

$$D(T_t) \widetilde{Y}_t = \frac{1}{f_{\lambda_t}^y} \tag{65}$$

Finally, consider the planner's FOCs relating to optimal adaptation capital for $t > 0$:

$[K_t^{\Lambda,y}]$:

$$\lambda_{kt} = \eta_{yt} f^y_{K_t}$$

$[K_t^{\Lambda,u}]$:

$$\lambda_{kt} = \eta_{ut} f^u_{K_t}$$

$[K_{t+1}]$:

$$\lambda_{1t} = \beta\lambda_{1t+1}(1-\delta) + \beta\lambda_{kt+1} \tag{66}$$

$[K_{1t}]$:

$$\lambda_{1t} F_{1kt} = \lambda_{kt} \tag{67}$$

Based on these equations, we can derive intertemporal optimality conditions for the economy's capital stocks. First, for private productive capital, combining (66) and (67) yields the standard optimality condition:

$$\frac{\lambda_{1t}}{\beta\lambda_{1t+1}} = (1-\delta) + F_{1kt+1} \tag{68}$$

Next, for production adaptation, we have that:

$$\lambda_{1t} = \beta\lambda_{1t+1}(1-\delta) + \beta\left[\eta_{yt+1} f^y_{K_t+1}\right] \tag{69}$$

Substituting in based on the shadow value of production adaptation (61), equation (69) becomes:

$$\frac{\lambda_{1t}}{\beta\lambda_{1t+1}} = (1-\delta) + \left[D(T_{t+1})\widetilde{Y_{t+1}} f^y_{K_t+1}\right] \tag{70}$$

Comparing the optimality conditions for private and public adaptation capital in the final output sector, (68) and (70), respectively, we see that the returns to these investments are equated at the optimum. Consequently, if investments in private capital are left undistorted by the optimal tax code, then public spending in productive adaptation capital should likewise be undistorted.

In contrast, for utility adaptation capital, the first order conditions yield:

$$\lambda_{1t} = \beta\lambda_{1t+1}(1-\delta) + \beta\left[\eta_{ut+1} f^u_{K_{t+1}}\right]$$

Again substituting in based on the shadow value of utility adaptation from (60) leads to:

$$\begin{aligned} \lambda_{1t} &= \beta\lambda_{1t+1}(1-\delta) + \beta\left[(-U_{Tt+1}T_{t+1})\, f^u_{K_{t+1}}\right] \\ &= \beta\lambda_{1t+1}(1-\delta) + \lambda_{1t+1}\beta\left[\frac{(-U_{Tt+1}T_{t+1})}{\lambda_{1t+1}} f^u_{K_{t+1}}\right] \end{aligned}$$

Consequently, invoking again the definition of the MCF in (17) leads to the desired result:

$$\frac{\lambda_{1t}}{\beta\lambda_{1t+1}} = (1-\delta) + \left[\frac{(-U_{Tt+1}T_{t+1})}{U_{ct+1}} \frac{1}{MCF_{t+1}} f^u_{K_{t+1}}\right] \tag{71}$$

As derived in the text, the condition for an undistorted margin for investments in utility adaptation capital is given by:

$$\frac{U_{ct}}{\beta U_{ct+1}} = (1-\delta) + \frac{(-U_{Tt+1}T_{t+1})}{U_{ct+1}} f^u_{Kt+1}$$

For public investment in utility adaptation capital, a wedge in the form of $(1/MCF_{t+1})$ thus remains in the optimality condition (71) even if other investments are undistorted and $\frac{\lambda_{1t}}{\beta\lambda_{1t+1}} = \frac{U_{ct}}{\beta U_{ct+1}}$. That is, as is well known, with constant elasticity preferences of the commonly used forms,

$$U(C_t, L_t, T_t, \Lambda^u_t) = \frac{C_t^{1-\sigma}}{1-\sigma} + \vartheta(L_t) + h(T_t(1-\Lambda^u_t)) \tag{72}$$

$$U(C_t, L_t, T_t, \Lambda^u_t) = \frac{(C_t L_t^{-\gamma})^{1-\sigma}}{1-\sigma} + h(T_t(1-\Lambda^u_t)) \tag{73}$$

for periods $t > 1$, we have that $\frac{\lambda_{1t}}{\beta\lambda_{1t+1}} = \frac{U_{ct}}{\beta U_{ct+1}}$. Consequently, investment in private capital should be undistorted and capital income taxes should be optimally set to zero, as can be readily seen from substituting $\frac{\lambda_{1t}}{\beta\lambda_{1t+1}} = \frac{U_{ct}}{\beta U_{ct+1}}$ into the private capital optimality condition (68) and comparing it with the household's Euler Equation. However, even in this case, the wedge $(1/MCF_{t+1})$ remains in the optimality condition for public investments in utility adaptation capital (71).

6.3 Adaptation Calibration Details

The parameter values used to calibrate the gross damage and adaptation sector functions (equations (30)-(32) in the text) and the sources for their values are as follows:

Parameter	Value	Source
α_1	0.003	AD-DICE
α_2	0.0014	Match 2.92% total gross damages (AD-DICE) at 2.5°C given α_3, α_1
α_3	3	AD-DICE
θ^y	0.7480	Match gross Y-damages of 2.2% at 2.5°C
θ^u	0.0779	Match WTP to avoid gross U-damages as 0.0072% of GDP at 2.5°C
β^y_A	176.76	Adjusted to match baseline moments (Table 5)
β^u_A	703.59	Adjusted to match baseline moments (Table 5)

At these values, running the COMET without distortionary taxes - that is, allowing lump-sum taxation as is the standard assumption in this literature, including the AD-DICE model - yields the following results:

Moment	Target	COMET	Target Source:
Opt. max temperature change ($^{\circ}C$)	2.96	2.99	COMET without dist. taxes and without adaptation (Barrage 2014)
Opt. $Y-$adaptation effect at $\sim 2.5^{\circ}C$	52%	49%	Re-aggregation of AD-DICE Damages
Opt. $U-$adaptation effect at $\sim 2.5^{\circ}C$	60%	46%	Re-aggregation of AD-DICE Damages
Opt. Y-adaptation cost at $\sim 2.5^{\circ}C$ (% GDP)	0.47%	0.56%	Re-aggregation of AD-DICE Damages
Opt. U-adaptation cost at $\sim 2.5^{\circ}C$ (% GDP)	0.16%	0.12%	Re-aggregation of AD-DICE Damages
Opt. Carbon Tax ($\$/mtC$ in 2015)	70	80	COMET without dist. taxes and without adaptation (Barrage 2014)

Table 5: COMET Adaptation Calibration Targets and Results