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# A GUIDE TO MACROECONOMICS AND CLIMATE CHANGE

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**ABSTRACT**

This paper analyzes the literature that links macroeconomics and climate change. We organize our paper around three themes: (i) loss and damage, which assesses long-run economic costs and non-market impacts from climate change; (ii) mitigation and the energy transition, which evaluates the macroeconomic consequences of shifting away from fossil fuels toward renewable energy; and (iii) adaptation, which explores the economic adjustments necessary to manage heat stress, more frequent severe weather events and rising seas. We discuss macroeconomic frameworks that incorporate these forces as well as empirical estimates that guide their calibration. We suggest areas in which macroeconomic research on climate is needed.

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# 1 Introduction

The world is experiencing increasingly severe consequences of climate change: flooding in 2022 that inundated one-third of Pakistan (Hong et al. 2023), temperatures exceeding 50°C in India (Mandal et al. 2025), and wildfires across Canada in the summer of 2023 that blanketed many United States cities in wildfire smoke for days (Jain et al. 2024). While no individual such event can be attributed solely to climate change, collectively these increasingly common and severe extremes are strongly consistent with climate models (National Academies of Sciences, Engineering, and Medicine 2016).

Driven in part by such events and facilitated by sharply declining prices of renewable power, batteries, and electric vehicles, gradual decarbonization is underway. People, businesses, and governments are just beginning to adapt to the worsening physical damages of climate change. Taken together, the trends of physical damages, decarbonization, and adaptation will likely entail tens of trillions of dollars of redirected capital flows and change the daily lives and economic opportunities faced by billions of people.

These large and enduring changes raise important questions for macroeconomists. They also provide them with opportunities to strengthen and improve society's response to climate change.

Macroeconomists have long been involved in estimating the economic cost of climate change and in assessing optimal climate policy. Both streams date to the seminal work of Nordhaus (1992), who developed the first formal model to integrate climate and macroeconomics: the first integrated assessment model, or IAM. It enabled researchers and practitioners to estimate the monetized damages from climate change, called the social cost of carbon or SCC, and to link the optimal Pigouvian tax on carbon, absent other market failures, to the social cost of carbon.

Since then, and accelerating especially over the past five years, there has been an increasing amount of work at the intersection of climate change and macroeconomics, the topic of this article. For this purpose, we define climate change broadly to encompass both the physical manifestations of climate change and the human and institutional activities driving, experiencing, and responding to those physical changes.

The literature on the macroeconomics of climate change is framed by four major questions, around which we organize this review. First, what are the aggregate economic costs—the loss and damage—of the physical manifestations of climate change? These costs, which include long-run economic losses and non-market damages, are the focus of the SCC and its alternatives. We discuss macroeconomic frameworks that incorporate these elements and how they map into estimates of the SCC. Progress in the measurement of economic losses and non-market impacts such as mortality has led to upward revisions in the SCC. Estimating these costs is extraordinarily challenging: doing so entails extrapolating observed empirically estimated damage functions into the distant future with climate and economic environments never before encountered, then discounting those damages back to the present. Yet such cost estimates are needed to guide the stringency of climate policies, and a great deal of work has gone into their estimation.

This mature literature has yielded a range of estimates of the SCC which, although wide, is sufficiently large to justify many of the climate policies that have actually been considered or adopted. The wide range in part reflects unresolved problems in economics, notably the risk-free rate and equity premium puzzles and other issues around discounting, which have vexed economists for decades. Moreover, a central motivating reason for concern about climate change is deep uncertainty about human and physical systems in a global climate that is outside the range of experience over human civilization, and finding a fully satisfactory way to articulate this deep uncertainty quantitatively remains elusive.

The second framing question is: What are the macroeconomics of the transition to low-carbon sources of energy, that is, the macroeconomics of decarbonization? Because combustion of fossil fuels creates a greenhouse gas externality, the macroeconomics of the transition to low-carbon energy includes the macroeconomics of the suite of mitigation policies enabling the energy transition, the changing means by which energy is produced, and the implications of those changes for labor markets, capital, and productivity. Decarbonization and decarbonization policy can affect inflation, capital accumulation, and productivity growth. Real-world policies are also subject to change, including large changes as have been seen in the United States over the past two decades, which introduces the additional macroeconomic channel of policy uncertainty. Internationally, uncoordinated decarbonization policy is further complicated by coordination problems.[1]

Taken together, the literature on the macroeconomics of decarbonization has resulted in some robust qualitative conclusions: both research and development policy and carbon pricing play important, potentially asynchronous, roles in developing, scaling, then deploying green technologies; predictable implementation of efficient decarbonization policies can incur low macroeconomic costs, both in theory and empirically; and policy vicissitudes and policies with volatile price signals can generate larger macroeconomic costs (although this empirical literature is relatively small and new).

Third, what are the macroeconomics of adaptation? Even under optimal mitigation

[1] Although conventional climate policy operates through regulation or fiscal authorities, a strand of this literature—that we do not address here—examines the capacity and desirability, or not, of a central bank acting as an agent of climate policy.

policy, global temperatures will continue to rise. What does adaptation to a warmer world with rising seas and more frequent and severe weather extremes imply for productivity growth, employment, and output? Although some adaptation will be undertaken privately, there are informational, liquidity, and collective action problems, along with other frictions: policy can facilitate or retard efficient adaptation.

The literature on the macroeconomics of adaptation is small but growing and encompasses changes in sectoral specialization, trade, migration, capital investment and associated policies as possible strategies to cope with climate impacts. The distinction between loss and damage and adaptation can be somewhat fluid, and empirical estimates of climate impacts typically capture some, but not all, adaptation. Still, the distinction is useful for organizing research that aims, on the one hand, to assess costs or, on the other hand, to evaluate candidate adaptation strategies and policies.

Fourth, what are the implications of the answers to the previous three questions for fiscal and monetary policy? In an important speech while Governor of the Bank of England, Carney (2015) categorized the macroeconomic risks from climate change as physical, transition, and liquidity. Physical risks map loosely into the first question above, while transition and liquidity risks map into the second and third questions. Direct physical consequences from climate change, if amplified by market imperfections, could potentially translate to financial system or macroeconomic shocks large enough to be relevant to monetary and fiscal authorities. Arguably more salient, however, are transition risks such as climate policy vicissitudes, trade implications of carbon border taxes, or inflationary effects of energy policies.

The next three sections of the paper address the first three questions in turn. The final section touches the final question, which is the subject of a separate review (Bilal and Stock 2025), and assesses the overall state of the literature and makes suggestions for future research.

There are many excellent complementary recent reviews of the economics of climate change. Each of these reviews focuses in depth on a specific aspect of it. They include economic impacts of temperature (Dell et al. 2014; Lemoine et al. 2025), the social cost of carbon (Bastien-Olvera and Moore 2022; Moore et al. 2024), climate modeling (Dietz et al. 2021b), integrated assessment modeling (Metcalf and Stock 2017; Hassler et al. 2024; Fernández-Villaverde et al. 2024), carbon pricing (Timilsina 2022), discounting (Gollier 2024), wider mitigation policies (Gillingham and Stock 2018; Blanchard et al. 2023), adaptation (Burke et al. 2024; Carleton et al. 2024), the spatial features of climate change (Desmet and Rossi-Hansberg 2024; Balboni and Shapiro 2025), and climate finance (Giglio et al. 2021a). Our paper complements this work by drawing together loss and damage, mitigation and adaptation, thereby providing a comprehensive guide to the interested reader. For space, we necessarily focus our discussion on core issues, seminal papers and recent contributions. The reviews above offer a deeper perspective on their respective topics, and we point to them in the relevant sections of our paper.

# 2 Loss and Damage

The potential damages from climate change are large enough that, historically, their estimation has focused on aggregate output. The leading measure of climate damages is the social cost of carbon (SCC), which is the net present value to society of the incremental monetized damage from an additional ton of carbon dioxide emissions. In models without other frictions such as Nordhaus (1992), the SCC corresponds to the optimal Pigouvian tax on carbon emissions. Under standard cost-benefit analysis for small projects, emissions-reduction policies that are less expensive than the SCC should be implemented, while policies that are more expensive should not.

We structure our discussion around the components of estimates of the SCC. We start with canonical economic damage estimates. Then we discuss the role of heterogeneity, discounting, risk and deep uncertainty. We then cover losses associated with non-market impacts and discuss the climate system.

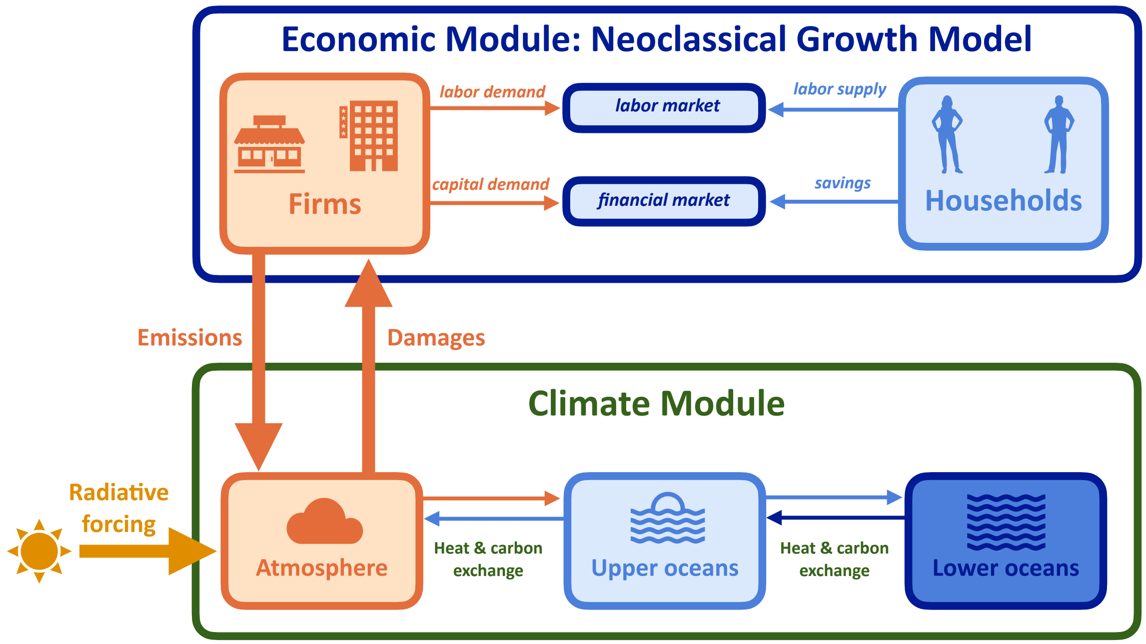
## 2.1 Monetizing Climate Damages: The Social Cost of Carbon

Nordhaus (1992) was the first to integrate climate change into macroeconomic analysis. Many of the frameworks we discuss below, including other integrated assessment models, follow a similar structure. In these frameworks, the calculation of the SCC involves two modules that interact with each other.

The first module is an economic model that maps climatic phenomena to economic fundamentals such as productivity, amenities, capital depreciation or mortality rates. The economic module then maps individual decisions and policy into consumption, output, energy use, welfare, and emissions which feed back to the climate module. The second module is a climate model that maps greenhouse gas emissions into climatic outcomes. Figure 1 describes the typical integrated assessment model diagrammatically.[2] Appendix A details the underlying mathematical structure.

[2]Relative to Figure 1, in DICE heat flows between a combination of the atmosphere and upper oceans on the one hand, and the lower oceans on the other hand, rather than between the three layers separately.

Figure 1: Dynamic Integrated Climate Economy model diagram.




Specifically, Nordhaus (1992) combines a 5-equation representation of the carbon cycle and greenhouse effect with an otherwise standard neoclassical growth model (Cass 1965, Koopmans 1963). In the neoclassical growth model, a representative household (or, equivalently, a unit measure of identical households) decides how much to consume, invest and abatement costs to pay. A representative firm decides how much labor and capital to use. Production leads to emissions. Emissions feed back to temperature, which affects economic activity through productivity losses.

The resulting environment is an economic framework—the dynamic integrated climate economy (DICE) model—in which emissions, warming and economic activity are jointly analyzed. The themes around which this paper is structured broadly follow the various elements of the DICE model described in Appendix A. Our discussion of loss and damage in this section corresponds to measuring and unpacking preferences and the damage function. Our discussion of mitigation in Section 3 corresponds to measurement and microfoundations of the abatement cost curve and technological progress. Our discussion of adaptation in Section 4 amounts to adding more choices and margins to the decision-makers to adjust to a warming world. This structure stands as the core foundation of the SCC and climate change policy analysis, and is reviewed extensively in Metcalf and Stock (2017), Hassler et al. (2024), and Fernández-Villaverde et al. (2024).

Of course, quantifying the SCC requires knowledge of both the economy and of the climate system together with empirical estimates of each of their components, as well as translating future impacts into current dollars. Nordhaus (1992) calibrates his framework based on early damage measures from Cline (1992) and obtains productivity losses of less than 1% per 1°C increase. He finds that optimal warming by 2100 exceeds 3°C. The SCC—which corresponds to the optimal Pigouvian tax—rises from $5 to $20 per ton by 2100.

Generations of economists have since then continuously re-assessed this early set of results. Moore et al. (2024) survey recent estimates of the SCC that range from $100/ton to $240/ton.[3] Over time, the SCC has been updated upward following improved measurement: accounting for persistent impacts and for a broader range of climate impacts, with some recent estimates exceeding $1,000/ton (Bilal and Känzig 2026).

How can we understand this wide range of values? As with any modeling exercise, each module and the associated parameters that enter the SCC is subject to modeling choices and estimation choices. The most prominent ones involve the individual utility function, the social welfare function, estimates of structural damage functions, and the level of aggregation. This flexibility has sparked virulent debate in the profession, with some arguing that it may make integrated assessment models poor guides for policy (Pindyck 2013; Stern et al. 2022). On the other hand, most macroeconomic questions involve as many or even more parameters that researchers must painstakingly identify and estimate.

There has been remarkable progress in modeling and estimation since the inception of the debate surrounding integrated assessment models. A key step was taken by Golosov et al. (2014). They provide a rich yet analytically transparent benchmark to evaluate the role that each of these choices plays. They develop a representative agent framework building on Nordhaus (1992) in which they incorporate a rich specification of energy use in production rather than a simple mitigation cost curve.

The SCC has an analytical expression in this framework: it is increasing in the structural damage function, household patience (related to the discount rate), initial output, the persistence of carbon dioxide in the atmosphere and the climate sensitivity. Crucially, the SCC is independent from the specific details of energy use in production, and is also independent from uncertainty because of logarithmic utility.

The elegant expressions in Golosov et al. (2014) highlight which elements are critical for the SCC. We therefore use the elements of their formula to guide our discussion of SCC

[3] Governmental reports such as U.S. Environmental Protection Agency (2023) and Council of Economic Advisers (2023) report similar estimates of economic damages from climate change.

estimates. Of course, these expressions also necessarily come with some assumptions: in particular, logarithmic utility and full capital depreciation. For that reason, in practice, most estimates of the SCC use numerical methods, and we also highlight below how departing from these assumptions matters. We discuss the economic module extensively and include a shorter discussion of the climate module at the end of this section.

## 2.2 "Top-Down" Damage Estimates

In canonical representative agent frameworks such as Nordhaus (1992), Nordhaus and Boyer (2000), and Golosov et al. (2014), damage functions that map climatic phenomena to economic fundamentals often take the form of a simple relationship between global mean temperature and productivity losses. This damage function can be calibrated to different types of empirical moments, and ultimately determines the cost of carbon. We start by describing the typical range of the cost of carbon, before turning to how it depends on estimates of damage functions.

**Temperature.** The original approach is "top-down": damage functions are directly calibrated to country-level estimates that regress country-level changes in output (GDP) on changes in country-level temperature. Dell et al. (2012) first develop this empirical strategy. Dell et al. (2014) comprehensively review the early underlying panel econometrics which rely on transitory temperature fluctuations to achieve credible identification. These estimates reflect the net effect of country-level temperature on economic activity, inclusive of any adaptation that is taking place within a given year and country in response to transitorily higher temperature (for instance, changes in usage of an installed air conditioning unit) but exclusive of adaptation to long-run changes (for instance, installing a new air conditioning unit). These studies typically find that a transitory 1°C increase in a country's temperature reduces output by 1 to 3% in the short run (e.g. 1 to 2 years).

The use of panel data to estimate damage functions improves on early estimates based on cross-sectional data, which are plagued by omitted variable bias. Still, as discussed in Lemoine et al. (2025), panel estimates are subject to several identification challenges, to which we now turn.

**Growth vs. level effects.** Greenhouse gas emissions today could affect GDP far into the future because of the long persistence of CO2 in the atmosphere. This mechanism is present in the DICE model, and concern about lasting implications for economies and natural systems stem from this long duration. This long duration of CO2 naturally begs the question whether the resulting temperature changes have, themselves, temporary or lasting impacts on GDP. This distinction is crucial. If temperature itself has lasting effects on GDP, emitting CO2 today has compounding effects on economic activity because temperature remains elevated for centuries.

The debate around whether, over the long run, a temperature increase has a long-run effect on the log level of GDP or alternatively on the growth rate of GDP has vexed the literature on estimating climate damages. Because of compounding, over a century of climate change, levels v. growth specifications imply dramatically different evolutions of GDP. A notable early example is Moore and Diaz (2015), who calibrated damage functions in fully specified integrated assessment frameworks to the estimated impact of temperature on output from Dell et al. (2012). Under a growth rate specification, they estimate a SCC of $220/ton and 2100 output losses that range from 10 to 40% across countries under 4.5°C warming, i.e. 2-10% per 1°C on average; under a levels specification, the SCC is $33/ton.

The possibility of long duration impacts creates a deep challenge for empirical estimation of damage functions. Because those functions are estimated on a handful of decades of data, any inference about the distant future requires estimating dynamic causal effects (impulse response functions) at horizons comparable to and exceeding the span of the data. For horizons greater than the span of the data, those impulse response functions are not identified nonparametrically, and so can be estimated only by imposing some parametric or other restriction. Increasing the number of cross-sectional units in panel data might improve estimates of short-run dynamics but cannot help with long-run dynamics. Moreover, inference on objects such as impulse response functions is typically nonstandard at horizons that are proportional to the sample size (Richardson and Stock 1989). In many problems in empirical macroeconomics, such as estimating the effect of monetary policy on the economy, the problem of long-run impacts can be sidestepped by focusing on relatively short business cycle horizons, but this convenience is not available in the economics of climate change.

The literature has broadly adopted two approaches to estimating the long-run dynamic causal effect of temperature on GDP. One has been to use low-dimensional lag specifications in panel models, either through imposing zero dynamics outside some window as in Dell et al. (2012) or, less commonly, by assuming a parametric functional form as in Kahn et al. (2021). In both, the long-term effects are necessarily identified from short-term dynamics. A separate issue is that the growth specification, when addressed as a hypothesis testing problem, entails testing a zero restriction in a panel data regression (that the level of temperature does not enter a specification for the growth of GDP), so a Type II error leads to adopting a growth specification. Newell et al. (2021) avoid the Type II problem by using a cross-validation framework to assess 800 panel data specifications found in and inspired by the literature, and find that the levels models have better forecasting performance. Their analysis does not, however, address the problem of the dynamical assumptions implicit in the short-lag models in the literature.

A second approach is to use longer lags for the impulse responses, then to rely on other theory to guide long-term effects. Nath et al. (2024) use panel local projections to estimate a 10-year impulse response function of output to country-level temperature fluctuation. They then rely on economic growth theory, the theory of technology diffusion, and the historical evidence of the stability of the spread of log GDP across countries in long time series to suggest that there is little historical evidence to support long-term growth effects of temperature: given the dispersion of temperature, it would induce cross-country divergence. Bilal and Känzig (2026) take a similar approach—estimating a 10-year impulse response function—using purely time series data, and obtain impacts that are consistent with persistent level effects.

On net, our reading of the literature suggests that the evidence favors persistent level effects rather than growth effects or entirely transitory level effects, with the caveat that this long-run effect is unidentified so its estimation must entail a mix of theory and judgment. Quantitatively, these papers find output losses of about 2-3% per permanent 1°C increase on average.

**Nonlinearities and functional form.** Conventional wisdom holds that climate change will hurt already-hot countries but might help some currently-cold countries, for example by opening up northern regions to farming and development. Building on the panel approach, Burke et al. (2015) propose evidence that temperature has nonlinear effects on output by interacting temperature fluctuations with the baseline level of country temperature. Most panel data analyses since then have investigated nonlinear effects and typically find U-shaped responses, with optimal temperatures to be around those in the United States.

The nonlinear aspects of this literature also have issues. One is the concern about selection of a preferred functional form on the basis of substantial pretesting, potentially resulting in overfitting and spurious nonlinearities. Newell et al. (2021) examine this concern and find limited evidence for nonlinearities using their cross-validation approach which penalizes overfit models. Another concern, recently raised by Jones et al. (2026), is that non-climate trends that differ by region could be correlated with baseline temperature, in which case they would confound estimates of the nonlinearities. This potentially important insight suggests a full reassessment of nonlinear effects is in order.

**Weather vs. climate.** The standard panel data approach to estimating the impact of temperature on output includes year and country fixed effects and thus relies on local, country-level temperature variation. This empirical strategy leverages local temperature fluctuations that are plausibly exogenous; in this sense, these estimates can have good internal validity for estimating the short-run effect of local temperature fluctuations on local economic activity (with the caveat of the comments above on nonlinearities). The challenges to this approach concern external validity and entails two leaps of faith that characterize the 'weather vs. climate' debate. The first, which we discuss in this section, is that the effect of changes in local temperature (weather) accurately and comprehensively summarize global climate change (climate). The second, which we discuss together with adaptation in Section 4, is that one can extrapolate the effect of small and unanticipated transitory changes in weather to infer the effect of large and permanent anticipated changes in climatic conditions.

Why is the first leap of faith indeed a leap of faith? In practice, climate change is summarized by changes in global mean temperature. Global mean temperature includes ocean surface temperature, which is a key determinant of a myriad of climatic phenomena that may be only weakly correlated with local temperature. Tropical storms, hurricanes and droughts are just a few examples. In principle, one could include all these manifestations in damage estimates. In practice, it is difficult to enumerate, measure and estimate the economic impact of the entire range of weather phenomena.

Bilal and Känzig (2026) address this challenge. They directly estimate the impact of a shock to global temperature on world output in the time series. By looking at long-term ramifications of this shock, they identify fluctuations in global climatic conditions rather than in local weather. To the extent that adaptation responses, such as trade and financial flows, are measured in GDP, the resulting estimates are net of any short- to medium-run adaptation at the global level. They obtain a SCC in excess of \$1,000/ton, compared to about \$150/ton for local temperature holding everything else fixed. These costs correspond to 22% output losses per 1°C in the long run under global temperature, compared to 3% per 1°C under local temperature. These differences are consistent with a geophysical interpretation: quantitatively, ocean surface temperature and extreme weather events account for the majority of the gap between global and local temperature estimates.

**Natural disasters and weather extremes.** Consistent with the results in Bilal and Känzig (2026), some of the costliest direct manifestations of climate change are likely natural disasters and extreme weather. Examples include extreme heat, wind, precipitation, flooding, droughts, and hurricanes.

The literature concerning the effect of specific extreme weather events on economic activity is broad and has conflicting results. In an important early estimate, Hsiang and Jina (2014) used cross-country panel data and estimated that hurricane strikes cause substantial economic losses. Similarly, in panel data on U.S. counties, Deryugina (2017a) finds that hurricane strikes reduce employment. Using a nonlinear vector autoregression model, Kim et al. (2025) find that extreme weather has negative aggregate effects on the United States economy, although the effects, while statistically significant, are quite small. In contrast, in a panel setting across United States counties, Roth Tran and Wilson (2025) find the opposite: natural disasters tend to improve economic activity.

Differences in the sign of the effect could be due to econometric choices such as differences in controls for background demographic trends, governmental aid, and reconstruction efforts, given that pre-trends are not always reported. Differences in sign could also be due to the nature of the disaster and whether it is defined as objective physical measures or reported measures. In theory, a medium-run positive regional effect on GDP is possible because rebuilding is counted as output. In any event, the range of estimates in this literature is large, the effects could be context-specific, depending for example on the prevalence of social and private insurance, and we do not consider this literature resolved.

A nascent literature uses reduced-form estimates of the impact of extreme events to calibrate structural models. Bakkensen and Barrage (2025) quantify the role hurricane strikes for growth across multiple countries. They find annual growth reductions between 0.01 and 0.1 percentage point due to climate change. Bilal and Rossi-Hansberg (2025) combine county-level estimates of extreme heat and coastal storms to estimate productivity, amenity and capital depreciation impacts in a structural model of the United States at the county level. They find that coastal storms are at least as important as heat stress for the United States.

## 2.3 "Bottom-Up" Damage Estimates

A natural complement to the "top-down" approach that we discussed so far is the so-called "bottom-up" approach to damage estimation. It entails estimating separate damage functions for an impacted economic sector or outcomes, some of which might be market outcomes (e.g., agricultural output) while others are non-market (e.g., mortality), where the non-market outcomes are valued in a way that reflects their welfare impact (e.g., the value of a statistical life).[4]

**Market outcomes.** Agricultural productivity losses are a prominent component in the SCC for two reasons. First, agricultural yields drops precipitously when temperature exceeds crop-specific thresholds and precipitation falls, making agriculture a sector that is particularly exposed to climate change. Schlenker and Roberts (2009) and Schlenker and Lobell (2010) use econometric panel methods to estimate the impact of climate change on agricultural productivity. Among other crops, they find that corn yields are largely unaffected until temperature reaches 25-30°C, and then drop by 2% for any additional day over 35°C. These estimates imply that moderate climate change is expected to reduce agricultural yields by more than 30% worldwide by 2100. Blanc and Schlenker (2017) survey this large literature.

Second, agriculture plays an important role in understanding the regional patterns of climate change impact: most low- and middle-income countries have large agricultural sectors, so are highly exposed, and many of these countries are in already-hot parts of the globe and are especially susceptible to further warming and impacts on the sector. Integrating agricultural damage functions into an integrated assessment model, Moore et al. (2017) and Rennert et al. (2022) find that worldwide agricultural losses account for a partial "agricultural" SCC of up to $84/ton.

Temperature appears to affect a broad set of industries beyond agriculture. Using standard panel methods in a sample of 28 Caribbean countries, Hsiang (2010) finds that losses associated with a 1°C increase reach 2.4% in non-agriculture, while they are only 0.1% in agriculture. Somanathan et al. (2021) estimate that an increase of 1°C in all days of the year lowers annual output by 2% in Indian manufacturing plants. With similar methods, Wilson (2017) finds broad-based damages from temperature across United States counties.

How important are non-agricultural losses relative to agricultural losses? To answer this question, Conte et al. (2021) consider a two-sector environment, and Cruz (2024) uses six-sector framework, both at the regional level. They estimate industry-specific damage functions in a broad set of countries by matching reduced-form panel estimates that relate local temperature changes to productivity. Driven by larger empirical estimates in agriculture, they find that agricultural losses are three times non-agricultural losses.

That losses are largely concentrated in agriculture is broadly consistent with the estimates based on country-level temperature that we discussed in Section 2.2. However, esti-

[4] Confusingly, in the climate change literature, these bottom-up categories are sometimes referred to as sectors, although some are economic sectors (agriculture, energy use) while others are not (mortality, sea level rise).

mates based on global temperature suggest that impacts extend well beyond agriculture. Significant economic impacts of global temperature fluctuations in high-income countries that rely less on agriculture are difficult to rationalize without broad-based damages. One possible explanation is that weather extremes beyond local temperature affect other industries relatively more, or that input-output linkages amplify sectoral shocks. A large literature in macroeconomics studies the role of input-output networks for aggregate economic activity, starting with Hulten (1978), and recently revived by Baqaee and Farhi (2019). With few exceptions (Zappala 2024), the role of input-output networks in the transmission of climate shocks remains largely unexplored.

**Non-Market outcomes.** Climate change impacts not only market outcomes typically included in integrated assessment models such as output, investment and consumption, but also non-market outcomes that have critical importance for welfare: the amenity valuation of various locations, mortality, violent crime, civil unrest and migration. These outcomes directly affect individual well-being, but do not directly appear in output.

A large empirical literature evaluates the impact of rising temperature on mortality. Deschênes and Greenstone (2011) find that each additional day above 32°C increase mortality rates by 0.1% in the United States. Burgess et al. (2017) find that this impact is six times larger in developing countries. Based either on estimates from the literature or original estimates, Bressler (2021), Rennert et al. (2022), and Carleton et al. (2022) find that the global mortality-induced (partial) SCC ranges from $36/ton to $221/ton. Health co-benefits from reducing emissions—reductions in particulate matter exposure—can be substantial and are frequently overlooked in SCC calculations.

The literature evaluating other non-market outcomes is relatively less developed. Dell et al. (2012), Ranson (2014) and Hsiang et al. (2017) find significant effects of temperature on crime, violence, and political instability. The welfare effects of biodiversity loss related to a changing climate are difficult to estimate and are frequently absent from cost of carbon calculations. All these channels may be correlated with each other, partly causing or caused by economic contractions. Avoiding double-counting is therefore important.

Originally, integrated assessment models have not included non-market impacts of climate change. Over time and as discussed above, SCC assessments have incorporated some of these channels using standard monetization methods. Crime and political instability are more difficult to monetize without more structure but may account for some of the costliest consequences of climate change. We hope that future assessments of the cost of carbon will incorporate monetizations of these consequences of a changing climate.

## 2.4 Heterogeneity

Representative agent frameworks have the virtues of simplicity, transparency, and ease of simulation. A central feature of climate change, however, is that it has unequal impacts that vary by region, sector/industry and type of household. This observation has two implications.

First, as is illustrated by the foregoing discussion of agriculture, regionally heterogeneous incidence is key to estimate climate impacts. Internal consistency requires specifying a structural model (an integrated assessment model) at the same level of resolution as the estimated impacts. Second, even if aggregate damages were equal to their representative agent value in a model that features heterogeneity, their welfare impact and the corresponding SCC may differ widely in the presence of heterogeneity in incomes.

**Geography.** The impact of climate change varies not only by sector, but also by region. While Sweden will likely experience agricultural productivity benefits from additional warming, the opposite will presumably hold in Mali. As we already alluded to, Dell et al. (2012) and Burke et al. (2015) find that warmer, low-income countries tend to experience larger negative effects of climate change, while colder, high-income countries can gain from it. Taking spatial variation into account is key to accounting accurately for losses and damage from climate change.

To assess climate impacts across countries, Nordhaus and Yang (1996) introduce the Regional Integrated Climate Economy (RICE) model, which extends the Nordhaus (1992) framework to a regional setting. Countries do not interact through trade in goods or capital nor through migration: they only interact through the global climate, which is a function of all countries' emissions.[5]

Spatially disaggregated economic models can now be specified at much finer resolution due to recent progress in modeling techniques; see Redding and Rossi-Hansberg (2017) for a review of the spatial economics literature. Modern frameworks incorporate migration, both across and within international borders, trade in goods and capital, and dynamic, micro-founded decision-making. They incorporate parameters that control productivity losses from local average temperature or extreme heat exposure, amenity losses, capital depreciation losses from storms, and land losses from slow-onset sea level rise.

Modeling spatial disaggregation has three benefits. First, it permits a more accurate representation of climate impacts, for instance sea level rise, productivity and amenity losses, at a fine grid cell level (Desmet et al. 2021; Krusell and Smith 2023). Second, it in-

[5]See Hassler and Krusell (2012) for a version with a continuum of regions and a closed form solution.

troduces damage parameters at spatial resolutions that mirror the resolution of empirical analysis by matching estimates of the impact of temperature or weather extremes at the grid cell or county level (Cruz and Rossi-Hansberg 2024; Bilal and Rossi-Hansberg 2025). Third, it lets researchers quantify the role of adaptation by reallocating goods, labor and capital across space, to which we return in more detail in Section 4. The present welfare cost of moderate climate change ranges from 1% to 5% across these studies.

Desmet and Rossi-Hansberg (2024) summarize the role of geography for loss and damage. With spatially disaggregated impacts, averaging damage functions at coarser resolutions can underestimate losses if impacts are concentrated on few but dense locations. They find that accounting for regional heterogeneity at the 1° x 1° latitude and longitude grid cell level can nearly double the cost of climate change relative to a country-level or world-level representation.

**Income and households.** So far, our discussion implicitly assumed that a dollar is worth the same to individuals working in different industries or residing in different locations. In practice, individuals in lower income countries may value a given dollar more than individuals in higher income countries to the extent that utility is concave and that markets are incomplete. If lower income countries are also more exposed to climate impacts, the covariance between marginal utility and damages implies that a utilitarian social welfare function leads to higher aggregate damages.

A long tradition of work finds that inequality increases the SCC. Fankhauser et al. (1997) develop this idea with standard welfare economics theory. Nordhaus (2014) incorporates it in a version of Nordhaus and Yang (1996). Anthoff and Emmerling (2019) extend this approach to distinguish between inequality aversion between time periods and across locations and household types. Quantitatively, incorporating concave utility or explicit inequality aversion across countries and/or household types tends to double the SCC relative to a reference level where inequality is ignored (i.e. linear utility).

Within industries, locations and countries, households with different characteristics may be differentially exposed to climatic shocks. For instance, lower income households might be more exposed to climate shocks because they work in industries that are themselves more exposed, such as agriculture or construction. The degree of asset market incompleteness then determines how these differences in income and exposure map into and correlate with marginal utilities. This equilibrium link between income, savings and marginal utility is largely absent from the papers that we discussed above.

The vast literature that evaluates the role of household heterogeneity and incomplete markets for macroeconomic aggregates (Huggett 1993; Aiyagari 1994) is just starting to be used to unpack the SCC. Kubler (2025) shows theoretically that optimal carbon prices can differ from the SCC when markets are incomplete, with possibly large deviations. We view the calibration of such frameworks as posing an important set of open questions. Empirical estimates that measure climate impacts by groups of households are not widely available, and incorporating them into structural models with household heterogeneity to evaluate the SCC is an open challenge.

## 2.5 Discounting

Whether in representative or heterogeneous agent frameworks, calculating the SCC requires discounting damages that occur in the future back to the present. How best to do so has produced an enduring and at times heated debate. The reason is simple: the bulk of the stream of climate damages associated with emitting one ton of carbon occurs decades or centuries into the future. As a result, small changes in the discount rate can imply large shifts in the SCC. For instance, Rennert et al. (2022) show that changing the discount rate from 3% annually to 2% annually shifts the SCC from $80/ton to $185/ton.

Long-horizon discounting raises important conceptual and practical issues. These issues correspond to two distinct approaches to discounting, one theory-driven, the other data-driven. Both confront philosophical questions and longstanding challenges in asset pricing. Gollier (2024) offers a comprehensive discussion of these issues.

**Theory-driven discounting.** At a conceptual level, a core disagreement is whether to use a pure rate of time preference that reflects the impatience of individuals or social preferences over time, in particular over different generations. On the one hand, preferences of current generations incorporate the well-being of future generations if individuals are altruistic with respect to their children. In that case, a social welfare function that reflects current generations discounts the future at the private rate of time preference. On the other hand, the classic normative, veil of ignorance argument suggests that all generations, present and future, be equally weighted. In that case, the social welfare function uses a zero pure rate of time preference.

This conceptual distinction underpins much of the debate surrounding the discount rate. The Stern (2006) review argues for a discount rate just above 1% based on a near-zero pure rate of time preference, yielding a large SCC. Contemporaneous and subsequent work debates this choice (Weitzman 2007; Nordhaus 2007), ultimately settling on values closer to the risk-free interest rate.

The choice of the appropriate rate of time preference reflects ethical choices that extend beyond the scope of economic theory alone. Importantly, this debate is relevant for any investment that has long-lived benefits—transportation infrastructure, schools, hospitals, research and development, and so on—although the time scales associated with climate change are even longer because atmospheric carbon decays more slowly than physical capital depreciates.

Two additional factors affect the appropriate value of the discount rate. The first is economic growth. When the economy grows over time and utility is concave, future individuals or generations will have lower marginal utility and care less about consumption changes. The effective discount rate is then the rate of time preference plus the growth rate divided by the elasticity of intertemporal substitution. This is the Ramsey discounting formula, which tends to increase the discount rate relative to the rate of time preference.[6]

The second force is risk. When the economy is risky, even absent climate change, standard asset pricing theory indicates that the proper discount rate typically requires a downward adjustment. If risk increases sufficiently rapidly as the horizon recedes, then the discount rate declines with the horizon (Gollier 2024). Moreover, if climate risk is correlated with economic risk, the discount rate used to evaluate emitting one ton of carbon should be further adjusted for the so-called "climate beta." Dietz et al. (2018) clarify that this correlation is mainly driven by two opposing forces: risk in technological growth and risk in climate damages and climate sensitivity. They find that technological growth tends to dominate, implying that carbon abatement projects pay out more in states of the world with high consumption. Thus, they have a positive risk premium and require an additional upward adjustment in the discount rate.

There would be no practical debate surrounding discounting in the calculation of the SCC (besides the choice of the social rate of time preference) if standard model parametrizations rationalized observed market rates of return. If this were the case, it would suffice to shift market rates of returns by the chosen social rate of time preference to appropriately discount climate damages.

The challenge is that there are important discrepancies between market rates of returns and what standard models imply (Mehra and Prescott 1985; Weil 1989), which the field of asset pricing has not yet resolved. The risk-free rate puzzle is that a 2% annual risk-free rate is difficult to reconcile with the Ramsey discount rate formula in standard parametrizations, with the downward risk adjustment via the Ramsey version with a

[6] An important and often under-appreciated exception arises when climate damages also scale with economic activity as in many estimates and formulations. In that case, transforming the problem to a stationary one implies that the effective discount rate subtracts one from the elasticity of substitution, as in Gordon and Shapiro (1956). The effective discount rate can then fall below the rate of time preference.

stochastic discount factor, the Consumption Capital Asset Pricing Model (CCAPM), making little difference. The equity premium puzzle is that a 5 percentage point premium for risky equities requires substantially more risk aversion than what microeconomic studies measure.

These difficulties with standard models have led some climate researchers to replace the CCAPM isoelastic preferences with other preferences, mainly Epstein and Zin (1990) preferences (Cai and Lontzek 2019; Van den Bremer and Van der Ploeg 2021). While these preferences dissociate risk aversion from the elasticity of intertemporal substitution, they still require an unusually large risk aversion to rationalize risk premia and therefore do not fully solve the challenges associated with the equity premium puzzle.

**Data-driven discounting.** Given ambiguities around consumption-based discounting, an alternative is to use observed market rates directly. Nordhaus (2007) argues for discount rates consistent with empirical stock market returns. Dietz et al. (2018) argue that this it is likely too high, because the stock market carries a larger risk premium than carbon abatement. Others have used empirical risk-free rates (Rennert et al. 2022), which likely carry too little of a risk premium relative to carbon abatement, a criticism that also applies to using quite low very long-term market rates (Giglio et al. 2021b).

As Weitzman (1998) pointed out, because market rates are stochastic and the discount factor is a nonlinear transformation of the discount rate, the expected discount factor is less than the discount factor based on the mean interest rate by Jensen's inequality. Bauer and Rudebusch (2023) simulate an empirically estimated process for the U.S. Treasury bond rate and obtain a declining discount rate. This argument provides a purely empirical complement to the declining discount rate derived in Gollier (2024) based on Ramsey pricing with increasing uncertainty at longer horizons. An important weakness of this approach, however, is that it too does not capture the climate beta.

These underlying challenges continue to fuel the debate. As is now clear, discounting is a thorny issue for the cost of carbon. There is no resolution yet, but not for a lack of trying: rather, the problem is that there is no clear resolution to the underlying long-standing challenges in asset pricing and social choice theory.

## 2.6 Risk and Deep Uncertainty

Stepping back, the task at hand is to extrapolate local relationships estimated from a few decades of data into an uncharted future of temperatures under which humanity has never lived. The range of possibilities is vast, and the role of risk and uncertainty goes far beyond the circumscribed discussion in Section 2.5.

At an evaluation level, estimates of the SCC based on integrated assessment models depend on many objects that are not known with certainty: the climate sensitivity, future economic growth (through discounting), economic damages from warming, and so on. A common way to quantify this uncertainty is to use Monte-Carlo simulation: sample parameters from a distribution–either derived from expert elicitation or estimated–and evaluate the distribution of outcomes across runs of a deterministic integrated assessment model. This approach is useful and practical, but ultimately unsatisfying because it falls short of incorporating risk and uncertainty consistently with decision theory.

We now discuss how to incorporate climate risk and uncertainty consistently with agent expectations, which complements reviews by Pindyck (2011) and Lemoine and Rudik (2017). We henceforth refer to risk in the traditional sense: a known probability distribution over warming scenarios, the climate sensitivity, damage functions, and so on. We refer to deep uncertainty as an unknown probability distribution over these same variables.

**Risk.** With risk-averse individuals, standard expected utility theory implies that the expected welfare cost of risky losses is larger than the welfare cost of the average losses. Therefore, risk tends to increase the SCC.

Van den Bremer and Van der Ploeg (2021) derive analytical formulas using a first-order perturbation in an integrated assessment economy with Epstein and Zin (1990) preferences. They clarify how risk, risk aversion and intertemporal substitution affect the SCC. They reach similar conclusions to Dietz et al. (2018): risk matters primarily through its effect on the discount rate and through the correlation between climate impacts and consumption growth.

Most analyses of the role of risk are based on thin-tailed distributions for tractability. However, the cost of carbon can become infinite when the risk of a catastrophic outcome has a thick enough tail and the coefficient of relative risk aversion is larger than one. This result is the 'dismal theorem' in Weitzman (2009) and Weitzman (2014). Given the possibility that risk makes the SCC infinite, quantifying its impact appears crucial.

Cai and Lontzek (2019) incorporate risk in technological growth, damages and the climate sensitivity in an otherwise standard integrated assessment model using well-established global computational methods in dynamic stochastic general equilibrium models. They find that adjusting the SCC for risk can change it by a factor of two. They explore the role of risky tipping points and, in their calibration, find that they can increase the cost of carbon by 60% today, because agents are motivated to avoid the tipping point, after which the SCC goes down because it is too late. In contrast, SCC estimates using nonstochastic integrated assessment models with damages augmented by tipping points provide lower marginal increases in the SCC due to tipping points (Dietz et al. 2021a).

**Deep uncertainty.** So far we discussed risk as if the outcomes of the climate system and of the economy had known distributions. In practice, these are far from known with certainty. Large-scale climate models deliver a non-trivial range of climate sensitivities. Many climatic phenomena are at best partially modeled and imperfectly understood. For instance, the speed of the Greenland and West Antarctic ice sheet melting is the subject of much debate. We do not know the probability distribution of the coastal flooding that would result. Similarly, we do not know the effect of, say, 3°C warming on biodiversity and the resulting effect on ecosystems, ecosystem services, and agriculture. Much of the concern surrounding climate change can be traced back to the unknown probability of such concerning but unquantified catastrophic events.

This type of uncertainty justifies using ambiguity-averse decision-making setups that have deep roots in decision theory (Gilboa 1987; Hansen and Sargent 2001; Maccheroni et al. 2006). In that case, individuals or society evaluate uncertainty according to either the worst case scenario or a smoother penalty for uncertainty. Ambiguity aversion can substantially raise the cost of carbon as society endogenously places more weight on more adversarial scenarios.

Barnett et al. (2020) and Olijslagers and Wijnbergen (2024) incorporate ambiguity aversion over features such as climate damages and the climate system in integrated assessment models. In illustrative calibrations, they find that ambiguity aversion increases the SCC by more than 50%.

Many of the papers above highlight uncertainty surrounding the climate sensitivity. Our view is that the range of possible values for the climate sensitivity is relatively tight compared to the range of possible values for most economic parameters in general, and in particular compared to uncertainty surrounding other inputs to the SCC that operate through discounting (e.g. growth) or economic losses (e.g. tipping points, ecosystem collapse, and catastrophic damages).

It is not obvious how to choose the parameters that govern the social degree of ambiguity aversion, nor the appropriate set of distributions that govern ambiguity. Still, this small and difficult literature gets to the core of some of the most profound concerns about climate change.

## 2.7 The Climate Module

We make two brief remarks on the climate module; see Hsiang and Kopp (2018), Dietz et al. (2021b), and Folini et al. (2024) for extensive reviews of the climate science and how it interacts with the economic module.

First, most economists use small-scale, simplified climate models because large-scale models are extremely computationally intensive even on their own. If paired with the typical but additional fixed point problem involved in finding an equilibrium in an economic model, the problem becomes computationally intractable.

Second, for many applications of interest, simplified climate models that relate worldwide emissions to global mean temperature together seem to suffice (Folini et al. 2024), at least if one uses a modern simplification like the FAIR model. When regional impacts are needed, statistical downscaling that projects local weather on global mean temperature can often provide a useful first pass, as in Cruz and Rossi-Hansberg (2024) for instance.

# 3 Mitigation

A direct way to avoid escalating climate damages is to reduce emissions of greenhouse gases. Because neither households nor firms internalize the effect of their greenhouse gas emissions on the rest of the economy, emissions reduction policy, known as mitigation policy, has an important role to play.

Most mitigation policies operate through relative prices at the level of an industry or firm—think fuel economy standards or renewable portfolio standards—so much of the literature on mitigation policy consists of microeconomic and partial equilibrium studies. The macroeconomic approach to climate policy and to the transition to low-carbon energy sources—the "energy transition"—complements and indeed guides this microeconomic approach. In this section, we start by laying out the organizing principles of the macroeconomics of mitigation. We then discuss energy use, carbon pricing, international coordination.

## 3.1 Macroeconomics and Mitigation

Three features characterize the macroeconomic approach to mitigation and the energy transition. First, the perspective and tools of modern dynamic macroeconomics are ones of dynamic optimization. This approach was present in the seminal work of Nordhaus (1992), where the greenhouse gas externality is the only market failure and setting a carbon tax equal to the SCC is the solution to a dynamic welfare optimization problem. With more market failures, the optimal dynamic policy involves multiple instruments. Most importantly, as shown by Acemoglu et al. (2012), when an innovation externality is included, the solution to the dynamic optimization problem involves both research and development subsidies and a carbon tax, where the timing of the two in general can differ; in particular, the research and development subsidy initially develops low-carbon technologies and the carbon tax subsequently incentivizes their deployment.

This dynamic perspective differs sharply from program-level policy evaluations, which typically examine the costs and benefits of a project one at a time and do not consider spillovers and do not treat a given policy as a step in a sequence of policies towards a dynamical goal. Hahn et al. (2024) review microeconomic mitigation policy studies and take an initial step towards incorporating dynamic spillovers into a program evaluation framework. In brief, the dynamic macroeconomic approach asks what is the optimal sequence of policies to maximize welfare in a warming world; the microeconomic program evaluation approach asks whether a particular policy, taken in isolation, has benefits that exceed costs. In general, these two approaches complement each other but can yield different policy prescriptions.[7]

Second, the objects considered by the macroeconomic approach aggregate ones: GDP, aggregate employment, labor productivity, and so forth. The virtue of the aggregate approach is that it incorporates spillovers and general equilibrium effects, for example in the DICE model, the aggregate impacts of the reduced capital accumulation arising from a carbon tax. That said, this aggregate approach makes identification more challenging.

Third, the empirical tools are largely those of macroeconomics, often having origins in monetary economics. These include calibrated dynamic optimization models and time series methods estimating the dynamic causal effects of shocks such as a carbon tax shock.

These three features are present throughout the evolution of the literature on the macroeconomics of mitigation policies, which tracks the evolving broader understanding of the climate problem and the technological environment. Over the course of the twentieth century and for at least the first ten years of this century, there were few economical alternatives to the use of fossil fuels for energy, so the main way to reduce emissions of carbon dioxide was simply to use less energy. Unsurprisingly, economists initially gravitated to carbon taxation, which introduces a Pigouvian tax or another carbon pricing mechanism to internalize the carbon externality (Nordhaus 1977).

In hindsight, economists' fondness for Pigouvian pricing arguably led to an underappreciation of the importance of developing low-carbon energy sources and the absence

[7] A parallel line of work provides rich representations of energy systems, consumption and emissions, that studies dynamically optimal or constrained decarbonization pathways, e.g. Edmonds and Reilly (1983). Jebaraj and Iniyan (2006) review the earlier stage of this body of work.

of innovation in early macro-climate models such as DICE. In practice, prompted by the energy crisis of the 1970s there were multiple low-carbon research and development and deployment policies, notably in the United States, Germany, and especially China, along with deployment subsidies for nuclear energy. Now, wind and solar generation, paired with storage to address intermittency, are competitive with fossil thermal generation in many parts of the world, and battery electric vehicles are already cost-competitive with internal combustion engine vehicles on a full cost of ownership basis for several vehicle classes. Although some of those developments stem from technological change in other sectors, research and development and commercialization policies also played an important role (Nemet 2019).

The literature on the macroeconomics of carbon pricing is the most mature, followed by innovation and areas of relatively recent heightened attention including international agreements, carbon border taxation, and implications of the energy transition for labor, capital, and productivity. The organization of the rest of this section follows this arc. In keeping with the theme of how dynamic macroeconomics provides a unique and important starting point for climate policies, we begin with a discussion of lessons from the theory of the management of exhaustible resources.

## 3.2 Energy Use

The theory of exhaustible resources addresses the question of the optimal rate of extraction of a finite resource, taken here to be oil. The core insights, which date to Hotelling (1931), are: (i) barring externalities, it is socially optimal to asymptote towards using all the world's oil as long as it is economical to do so, (ii) the oil price rises as the resource becomes scarce, and (iii) future oil market developments affect prices and optimal depletion rates today—for example, an announced future carbon tax will in theory reduce prices today to deplete before the tax takes effect (the so-called "green paradox"). Decentralized exploitation in general will not follow the socially optimal path; depending on the structure of property rights and other production distortions, there can be under- or -over-extraction (Stiglitz 1976; Bohn and Deacon 2000). Nonetheless, absent intervention, private entities (or state enterprises) will "leave it in the ground" only if extraction costs exceed what the market will bear.

These key insights change if there is technical progress (e.g., more efficient extraction), discovery of new reserves, or more efficient use of the resource (e.g., vehicle fuel economy). If so, the use of the resource is extended and prices rise more slowly, supporting long-run economic growth. If there is directed technical change—that is, if technical progress is stimulated and directed by rising prices—then innovation can dynamically offset gradual depletion of oil. Hassler et al. (2021) find that, even when the static elasticity of substitution between energy and other factors is close to zero, technical change implies that the long-run elasticity of substitution between fossil fuels and other factors is unity.

This dynamical perspective highlights the challenge of ending the use of fossil fuels, and brings to the fore the conditions under which doing so is even desirable. A carbon tax in isolation shifts the timing of fossil fuel production and consumption but not the total quantity—and thus, not cumulative emissions or temperature rise (Heal and Schlenker 2019). Of course, this outcome may still be optimal from a standard Pigouvian cost-benefit perspective adopted in most integrated assessment models such as Golosov et al. (2014).

If society adopts a net-zero target or the goal of phasing out fossil fuels, instead of standard cost-benefit considerations—for instance because of uncertainty about catastrophic damages and ambiguity aversion—the Hotelling logic leaves few options. One option is the development of low-cost low-carbon alternatives: wind and solar power generation outcompeting coal, or electric vehicles outcompeting internal combustion engine vehicles. Adoption of low-carbon technologies are supported by a carbon price (Kellogg 2024). Another option is to remove supply from the market, the focus of supply-side policies (Sinn 2008; Harstad 2012; Prest 2022).

### 3.3 Carbon Pricing Frameworks

Regardless of the particular path of fossil fuel resources, the Pigouvian approach to align private and socially efficient emissions is carbon pricing. A carbon tax serves to reduce emissions through two channels: the direct channel makes emissions more expensive, and the substitution channel changes the relative price between emitting and non-emitting technologies (e.g., coal v. solar generation). Stiglitz et al. (2017) provide a broad overview of the goals and means of carbon pricing.

In practice, cap-and-trade systems, intensity standards, and portfolio standards have been implemented more broadly than carbon taxes. All are implicit carbon pricing schemes although that term is commonly used only for carbon taxes and quantity-based cap-and-trade. Conceptually, these schemes are closely related and many carbon pricing policies can be interpreted as combinations of carbon taxes and output subsidies (Fischer and Newell 2008).

Cap-and-trade and carbon taxes are equivalent under certainty in a static model. Both instruments provide contemporaneous incentives to reduce emissions, based on their price: the tax rate or the price of tradeable carbon allowances. When there is uncertainty, a classic result by Weitzman (1974) shows that quantity instruments perform better than price instruments if and only if marginal benefits of the regulated good are more concave than marginal costs.

Timilsina (2022) comprehensively surveys the literature on carbon taxes. We complement their survey by summarizing the economics of carbon pricing through the lens of macroeconomic frameworks.

### 3.3.1 The Impacts of Carbon Pricing

The results in Golosov et al. (2014) indicate that the optimal carbon price does not depend on the economy's reliance on energy. However, economic mitigation costs do depend on the effect of carbon pricing on energy use and thus emissions, as well as on output and employment. We first discuss estimates of the elasticity of emissions to carbon prices, and next discuss estimates of the elasticity of economic activity to carbon prices.

**Carbon pricing and emissions.** How responsive are carbon emissions to carbon pricing in practice? Studies at the country or at the firm level have found broadly consistent estimates. Metcalf and Stock (2023) use country-level panel techniques across European Union countries and find that a country-level $40 per ton carbon price leads to cumulative emissions reductions of 4 to 6% when 30% of the economy is covered, amounting to a 13 to 20% reduction within the covered sector. Using matched difference-in-differences design at the firm level, Colmer et al. (2024) find similar elasticities for the European Emissions Trading System prices: 14-16% emissions reduction for $20-40 carbon prices. These estimates are consistent with medium-run energy price elasticities for the different sector and with the carbon price transmitting through standard demand channels. Large energy simulation models suggest significantly higher long-run price effects are possible as low-cost non-emitting alternatives become available, so that a substitution channel for the provision of energy services is available as well as the direct demand channel.

**Carbon pricing and economic activity.** Because carbon pricing raises energy prices and the marginal cost of production, it could be accompanied by adverse effects on output and employment. Of course, it might also incentivize innovation that reduces the cost of energy in the long run, resulting in at most moderate effects on economic activity. Shapiro and Metcalf (2023) study this trade-off in a model with green energy, highlighting that substitution towards green energy is key in mitigating the possible adverse effects of rising carbon prices.

The empirical literature overall finds limited evidence of such adverse effects on output, employment and inflation, with a few important exceptions. Metcalf and Stock (2023) and Colmer et al. (2024) find that even substantial increases in carbon taxes lead to little or no losses in output or employment growth in the European Union. Similarly, using a country-level panel approach, Konradt and Weder di Mauro (2023) find no evidence of effects of carbon taxes on aggregate inflation, though some evidence on energy price increases. However, some estimates point to larger costs of carbon pricing. Using high frequency time series methods based on regulatory updates for the European Union Emissions Trading System, Känzig (2023) finds evidence of a starker trade-off between carbon pricing and economic activity, possibly because his approach accounts for general equilibrium effects of carbon pricing including response by monetary authorities. Reconciling the effect of carbon pricing inferred from panel estimates and time-series estimates appears to be an important topic for future research.

The estimates of carbon pricing can be put in perspective with work estimating the impact of energy price fluctuations on economic activity. While this literature is too vast to be summarized here, we point to a few recent papers. Using time series methods and OPEC announcements as an external instrument for energy price changes, Känzig (2021) suggests that output reacts less to energy price changes than to carbon prices. Similarly, Moll et al. (2023) and Chiacchio et al. (2023) show theoretically and empirically that the energy price spikes that followed Russia's invasion of Ukraine led to only moderate economic losses, if any at all. These estimates highlight the importance of substitution through technology and openness to trade.

**Risk.** In cap-and-trade systems, allowance prices frequently exhibit large fluctuations. For example, in 2023-2024 the price of emissions permits under the European Emissions Trading System ranged from 54 euros/ton to 102 euros/ton. Such fluctuations discourage investment. In theory, a virtue of carbon taxes is the certainty of the carbon tax schedule over time. In practice, however, carbon taxes have faced large swings in political support, so seemingly stable tax schedules face political risk. For both taxes and cap-and-trade, the impact of uncertain carbon pricing may differ from the case with certainty beyond the reasons highlighted in Weitzman (1974). This risk can discourage investment as they provide different dynamic investment incentives, as indicated by standard investment theory (Dixit and Pindyck 1994) and modeled in the context of tradeable emissions projects by Aldy and Armitage (2022) and broad mitigation policy risk by Fried et al. (2022).

### 3.3.2 Temperature targets and carbon budgets

Absent uncertainty and other market failures, carbon taxes or equivalent emission trading systems implement the first-best allocation. They can also be used to achieve what would be a second-best objective from the perspective of standard cost-benefit analysis: for instance, achieve a given climate path to stay under a predetermined temperature target (Ploeg 2018).

One of the earliest—perhaps the earliest—analytical articulations of a temperature target is Nordhaus (1975), reprinted as Nordhaus (2019), who suggested that, "As a first approximation, it seems reasonable to argue that the climatic effects of carbon dioxide should be kept well within the normal range of long-term climatic variation" which, combined with historical evidence, leads to a 2°C to 3°C target.

In accordance with the United Nations Paris climate framework, the European Union now tends to use a temperature ceiling target: it sets a carbon budget to avoid warming above 2°C. Given this temperature target, in theory carbon emissions can be analyzed in a Hotelling framework of finite resource exhaustion, adjusted to take into account increasing marginal abatement costs and, in principle, endogenous technical change in green technologies.

Temperature targets have been extensively studied in integrated assessment models, although usually by evaluating them against optimal carbon prices in a cost-benefit approach. Nordhaus (1992) and Nordhaus and Boyer (2000) reach the conclusion that temperature targets imply larger mitigation costs than optimal carbon prices. Although emissions and temperature targets are closely related, they are not identical. Lemoine and Rudik (2017) show theoretically that temperature targets achieve lower mitigation costs than emissions targets because of warming lags inherent to the climate system.

Outside this integrated assessment model literature, the economics literature on temperature targets and carbon budgets is incomplete, especially given the real-world importance of such targets. One open political economy question is why temperature targets are so widely adopted in practice. Another open question is whether there are formal economic frameworks that would lead to choosing a temperature target over a standard marginalist cost-benefit approach.

### 3.3.3 International Coordination

In a world with multiple countries making decisions, pricing carbon confronts three additional challenges, that fall broadly under the umbrella of coordination failures. The first is the free-riding problem: any given country bears only a fraction of the consequences of its carbon emissions, and thus may not find it beneficial to engage in unilateral decarbonization. The second is carbon leakage: carbon pricing in one country leads emissions-intensive economic activity to relocate to other countries. The third consists of general equilibrium fossil fuel price adjustments in response to mitigation in a subset of countries. We discuss these failures in turn.

**Free riding.** The free-riding problem is the most prominent coordination failure in climate policy. Any individual country experiences a fraction of climate damages relative to the entire world. However, its greenhouse gas emissions warm the entire world and thus cause climate damages in all other countries. Therefore, any given country internalizes only a fraction of the greenhouse gas externality and engages in less decarbonization than what a global planner would decide.

Nordhaus and Yang (1996) first formalized the free-riding problem in a multi-region integrated assessment model. They find that non-cooperative, unilateral carbon policy leads to substantially lower carbon prices than global cooperation, although the resulting difference in emissions is moderate under their calibration.

Trade policy is often viewed as a partial solution to the free-riding problem: it provides a possible enforcement mechanism to influence other countries in a non-cooperative setting. The idea originates in Markusen (1975), who uses a simple trade model to show that tariffs can be used to reduce other countries' production of a globally harmful externality such as carbon dioxide.

Building on this idea, Nordhaus (2015) formalizes the idea of a "climate club", where countries in the club would impose high carbon prices and countries outside the club would be incentivized to participate through trade policy. In a static framework with a limited number of regions, Nordhaus (2015) finds that large climate clubs are sustainable only if the social cost of carbon remains low enough, which in his calibration turns out to be around \$50. At a higher level, trade sanctions on defecting members become too costly for remaining club members, and the club disintegrates. Climate clubs are thus less powerful precisely when they are the most needed. In a dynamic setting, recurrent renegotiation can also help to sustain coalitions (Battaglini and Harstad 2016).

A partial remedy to the free-riding problem arises at high costs of carbon—for instance above \$1,000—because empirical abatement cost curves tend to be initially close to flat and rise steeply only close to full decarbonization. In that case, Bilal and Känzig (2025) show that the domestic cost of carbon (DCC, costs born by individual countries) is high enough for large economies that it exceeds mitigation policy costs, making broad unilateral decarbonization cost-effective for the United States and for the European Union.

**Carbon leakage.** The second most prominent coordination failure in climate policy is carbon leakage. In an international setting, any level of carbon pricing—unilaterally or globally efficient—in a given country or climate club incentivizes emissions-intensive production to relocate to third party countries. Emissions-intensive goods may then be imported back into the country that initially imposed the carbon price. The resulting allocation counteracts any domestic emissions benefits of carbon pricing, while relocating economic activity away from the country pricing carbon. The leakage problem can compound with the free-riding problem by exacerbating the costs of trade sanctions necessary to keep a climate club in place.

Carbon border adjustments or other trade-based policies can solve the leakage problem. Carbon border adjustments impose tariffs on carbon-intensive imports to the same degree as domestic carbon prices, thereby nullifying the incentives to shift emissions-intensive production abroad and import it back to the pricing country. Weisbach et al. (2023) show theoretically that domestic demand and supply carbon taxes are jointly necessary to alleviate the leakage problem, which lead to an implicit tariff on carbon.

Carbon border adjustments in a given country can also incentivize its trading partners to adopt their own carbon pricing system, and thus also address the free-riding problem. Indeed, trading partners may find it preferable to impose a carbon pricing mechanism and retain its revenue rather than letting the country imposing the carbon border adjustment collect the proceeds. Cicala et al. (2023) show theoretically how to design tariffs on carbon-intensive imports to maximize adoption of carbon-saving technologies abroad. In line with this body of work, the European Union has started rolling out a Carbon Border Adjustment Mechanism, that imposes a tariff on the carbon content of imports (European Commission 2021).

Are carbon border adjustments effective in practice, and do they achieve more or less emissions reductions relative to hypothetical climate clubs? Clausing et al. (2025) assess quantitatively the impact of the European carbon adjustment mechanism. They find that it improves competitiveness and limits leakage without penalizing low-income countries. Farrokhi and Lashkaripour (2025) compare climate clubs and carbon border adjustment mechanisms in a quantitative trade model. They find that climate clubs can be more effective than carbon border adjustment mechanisms because most emissions are not embedded in traded goods. However, in practice trade policy is often far from these second-best benchmarks, with historically lower tariff rates on carbon-intensive industries around the world (Shapiro 2021).

**Fossil fuel price response.** The third type of international spillovers of carbon policy arises through general equilibrium fossil fuel price adjustments. Sinn (2008) argues that demand-side policies such as carbon pricing enacted by a subset of countries are ineffective if supply does not react strongly to demand. In the extreme, if fossil fuel supply is fixed, a demand reduction by some countries is exactly offset by an increase in demand from other countries due to falling prices. This is another version of the Hotelling conundrum discussed above. The extent to which fossil fuel prices respond in general equilibrium to mitigation policies remains an unsettled question.

## 3.4 Innovation and Technological Progress

The promise of technological progress in providing green energy services makes innovation policy a powerful complement to carbon pricing. From a first-best perspective, carbon pricing is necessary regardless of the presence of innovation. But because of the knowledge spillover externality, spurring innovation in low-carbon technologies requires an additional set of policies. Blanchard et al. (2023) and Bistline et al. (2023) review how green innovation policies complement carbon pricing.

### 3.4.1 Directed Innovation

A long tradition in economics develops theories of innovation (Romer 1990; Grossman and Helpman 1991; Aghion and Howitt 1992). Knowledge is a public good, so firms can only capture a fraction of the benefits that innovation brings to society in the form of research and development or learning by doing. Therefore, market forces may provide insufficient incentives for innovation in general and for low-carbon technologies in particular. A carbon price that is too low further exacerbates the problem both because it weakens the signal for directed technical change and inadequately incentivizes adoption. But suboptimal investment can persist even if the carbon price is set right. Newell (2010) reviews the associated literature in the context of climate change.

Like market activity, innovation flows towards sectors where marginal returns are highest: technical change is directed, but the allocation across sectors needs not be efficient (Acemoglu 2002). Early analyses of endogenous technological change in integrated assessment models find modest emissions reductions and lower carbon prices because directed technical change in emissions-scarce industries substitutes for abatement (Goulder and Schneider 1999; Popp 2004).

Four implications emerge collectively from the next generation of tractable theories of directed technical change with clean and dirty energy (Acemoglu et al. 2012; Acemoglu et al. 2016; Hassler et al. 2021). First, optimal policy features both carbon taxes and green innovation subsidies as these are distinct externalities. Second, when clean and dirty energy sources are sufficiently substitutable, temporary innovation policies can permanently redirect innovation to green energy and reduce long-run emissions because of path-dependence. Third, fossil fuel scarcity contributes to directed technical change. Fourth, a higher elasticity of substitution between green and carbon-intensive energy sources implies lower optimal carbon taxes.[8]

Evidence on prices and industry evolution suggest that carbon-saving innovations are directed by market forces. Early work by Popp (2002) indeed finds that energy patent applications respond positively to energy price shocks. Subsequent work has confirmed and refined this conclusion. Aghion et al. (2016) obtain similar results for green patenting in the auto industry, and Moscona and Sastry (2022) estimate that agricultural patents respond to exposure to extreme temperatures in the United States. Even then, historical evidence suggests that carbon-saving innovation tends to outperform forecasts (Way et al. 2022).

In practice, most clean energy technologies generate power, which is highly tradable within a regional power grid, less tradable across regions, and essentially not tradable across grid boundaries. Innovations in clean energy will therefore have to grapple with the uneven distribution of renewable potential across regions. Arkolakis and Walsh (2023) stress the importance of local comparative advantage in renewable potential together with electric grid transmission costs for the development of clean energy. They provide a spatial theory of clean growth and find that despite large heterogeneity and lower tradability, renewable-induced price declines have large beneficial effects for households.

### 3.4.2 Diffusion of Technology

Because knowledge and technology diffuse across regional, country and industry borders (Eaton and Kortum 1999; Keller 2004), green technological progress is a powerful instrument to reduce carbon emissions across the globe. Pigato et al. (2020) provide an extensive review of green technology diffusion with an emphasis on developing countries.

In principle, green innovation subsidies in one country can have important spillovers to other countries. Hémous (2016) develops a theory of technology diffusion with multiple countries and demonstrates that green innovation subsidies alleviate environmental

[8]Energy sources with intermediate carbon intensity have more nuanced implications: they can either increase or lower emissions along the energy transition. Acemoglu et al. (2023) analyze the shale gas boom in the United States with a model of directed technical change. They find that despite short-run reductions in emissions, the United States is pushed into a fossil fuel trap in which innovation is directed away from renewables.

degradation in the presence of international diffusion. Building on this idea quantitatively, Barrett (2021) find that international diffusion can halve long-run warming in a multi-region integrated assessment model with green innovation and diffusion. For the solar sector specifically, Gerarden (2023) develops a structural model and highlights the key role played by German subsidies in the worldwide adoption of solar panels.

### 3.5 Factor Market Reallocation

In most frameworks discussed so far, the reallocation of production inputs—labor, capital—is assumed to occur frictionlessly between green and carbon-intensive industries. In practice, large factor market reallocation can be difficult and protracted. For instance, the rise of Chinese import penetration in the United States has left many communities persistently exposed to joblessness (Autor et al. 2013). Given that the green transition implies a comparable change in the comparative advantage of industries and regions, it may well share some of these features.

**Labor.** Potentially millions of jobs are in industries reliant on high emissions-intensity activity in the United States. These jobs are concentrated in just a few states (Hanson 2023). While a large literature in macroeconomics evaluates the consequences of frictional labor reallocation in the face of spatial, industrial or occupational shocks (Caliendo et al. 2019; Acemoglu and Restrepo 2022), this structural literature is less developed when it comes to the energy transition.[9]

In the presence of reallocation costs such as unemployment or lost human capital, the labor market may struggle to reallocate workers from shrinking carbon-intensive industries to expanding carbon-free industries. For instance, Shapiro and Metcalf (2023) evaluate the general equilibrium impacts of a carbon tax in a framework with frictional unemployment. They find that long-run effects depend on green technology adoption, without which the adjustment is costlier.

**Capital.** Energy technologies are capital-intensive, and, like labor, capital will reallocate toward carbon-free industries under mitigation policies. Energy physical capital tends to be long-lived and technology-specific (generators, machines, equipment, vehicles), making them vulnerable to being stranded. Motivated by these observations, a rapidly ex-

[9]Empirically, Walker (2011) and Walker (2013) estimates the displacement effects of plant-level contractions on workers due to the enforcement of the Clean Air Act. He finds worker-level impacts consistent with conventional estimates of displacement effects, but that these costs are small compared to the benefits from regulation.

panding literature assesses how green capital investment shapes the energy transition. Bistline et al. (2023) propose an organizing framework to assess the role of subsidies on green capital investment.

The losses associated with stranded assets and the speed of the energy transition depend on how tightly capital is tied to a particular type of energy. This idea corresponds to the classic concept of vintage capital, which can explain the observed low short-term, but high long-term, energy price elasticities (Atkeson and Kehoe 1999). Building on this idea and on the literature that studies the reallocation of capital across firms with or without financial frictions (Khan and Thomas 2008; Winberry 2021), Capelle et al. (2023) document vast heterogeneity in emissions-intensity across firms and develop a firm dynamics framework with capital vintages to analyze its implications for mitigation policy. They find that policies that incentivize firms to upgrade their capital vintages can lead to long-lasting economic and emissions gains.[10]

Technologies with intermediate carbon-intensity can lead to more nuanced implications. Abuin (2024) builds a model of capital investment in shale gas production and exports to analyze the expansion of liquefied gas export infrastructure in the United States. Similarly to directed technical change, an increase in United States shale gas export capacity can lock the world economy away from renewables in the long run.

Like the literature on labor reallocation following mitigation policies, the literature on the economics of capital reallocation is in its infancy.

# 4 Adaptation

With nearly 1.5°C of warming already sunk in past emissions and modest progress in mitigation to date, societies will need to adapt to climate change. The need for adaptation is not uniform across the globe. Countries vary not only in their exposure to climate change, but also in their economic and institutional capacity to adapt. This adaptation can be reactive or proactive.

Macroeconomists have started studying climate change adaptation only recently. Technological improvements, changes in individual behavior, the ability of trade to insure against climate risk, movements of labor away from exposed areas, reallocation of capital, and climate-related insurance, all constitute forms of adaptation. While there is a larger microeconomic literature on adaptation, macroeconomic estimates of adaptation

[10]Central banks and governments are developing related quantitative models with green and carbon-intensive capital and a rich nesting structure to evaluate institutional climate targets (Varga et al. 2022; Coenen et al. 2024).

costs representative of all sectors of the economy are still scarce (Crimmins et al. 2023). Burke et al. (2024), Carleton et al. (2024), Lemoine et al. (2025), and Grover and Kahn (2025) survey the related literature.

In this section, we first discuss the conditions under which adaptation to climate impacts is relevant. Next, we discuss how shifting exposure of goods, labor, and capital represent adaptation, and how changes in policy can promote it.

## 4.1 When Does Adaptation Matter? Weather v. Climate Revisited

A common criticism of the canonical damage approach is that it uses short-run weather surprises to identify the impact of long-run, slow-moving anticipated changes in the climate. These impacts may differ for two reasons. First, they may reflect fundamentally different changes in the climatic system: the first half of the "weather v. climate" debate that we discussed in Section 2.2. Second, society may adapt differently to small temporary v. large permanent changes in the climate: the second half of the "weather v. climate" that we now discuss.

Deryugina and Hsiang (2017) formalize this aspect of the "weather v. climate" debate. Using a simple envelope argument, they show that adaptation is irrelevant for welfare—and thus for the cost of carbon—to first order. To the extent that households or firms are already smoothly balancing marginal costs and benefits of adaptation to current weather realizations, the additional valuation of adaptation is zero in response to a change in the climate. Under these conditions, estimates that do not account for adaptation in fact coincide with the cost of climate change inclusive of adaptation.

Of course, there are important caveats to this result (Lemoine 2018). It relies on small changes in the climate. By contrast, multiple degrees Celsius of warming represent uncharted waters. The result also relies on individuals already taking optimal adaptation decisions prior to the change in the climate. By contrast, many adaptation measures may require large, fixed cost investments that have not been made so far. For instance, levies or storm surge barriers will deliver inframarginal welfare gains only once they are built.

## 4.2 Direct Estimates of Adaptation

Direct estimates of adaptation leverage heterogeneity in the response of economic outcomes to weather shocks. For instance, heat waves may have smaller economic impact in Houston, Texas, which is high-income and used to heat, than in Astana, Kazakhstan, which is lower-income and less used to heat. By comparing the response between locations, we might infer that one location has adapted more to heat than the other because of income or baseline climate. More generally, comparing the response of economic activity across locations or times in which income or baseline climate differ may be informative about adaptation.

We group approaches that are based on this idea into three categories. We call the first category the 'cross-sectional heterogeneity' approach. It exploits differences in responsiveness to weather shocks across treatment units, e.g. countries or locations. For instance, Kahn (2005) shows that mortality in richer countries is less responsive to natural disasters than in poorer countries. Barreca et al. (2016) find that locations that have adopted air conditioning display fewer deaths from extreme heat, accounting for most of the decline in the heat-mortality gradient in the United States over time. Carleton et al. (2022) find that richer countries display smaller heat-mortality sensitivities, implying that over a century of warming economic growth leads to a threefold reduction in the mortality impacts of climate change.

Of course, even though adaptation may mute climate impacts, it also comes at a cost. Accounting for these costs is necessary in any cost-benefit analysis. While the structural approaches that we discuss in the next sections incorporate these costs by design (but with more assumptions), it is less clear how to account for adaptation costs when one only observes heterogeneous impacts. Carleton et al. (2022) solve this conundrum by showing that adaptation costs can be recovered by leveraging optimality that equalizes marginal benefits and marginal costs of adaptation, and next integrating marginal benefits across units with heterogeneous treatment effects. Applying this procedure to mortality, they find that adaptation costs represent less than 10% of its benefits.

The second category is the 'time gradient' approach. It uses the idea that the overall sensitivity of economic outcomes to weather shocks declines over time if the economy adapts. The 'time gradient' approach simply estimates this sensitivity across time periods. Burke et al. (2024) use this 'time gradient' approach to evaluate adaptation across a broad range of outcomes. They find limited evidence of adaptation across multiple outcomes (output, mortality, conflict).

The 'cross-sectional heterogeneity' approach relies on stronger identification conditions than direct damage estimates. The 'cross-sectional heterogeneity' approach attributes all differences in elasticities across units to particular variables (e.g. baseline income, baseline climate). However, these variables are likely to be correlated with others in the cross-section of units (e.g. institutions), which may lead to omitted variable bias. The cross-sectional heterogeneity in elasticities—and therefore the evidence of adaptation—is associational rather than causal.

The 'time gradient' approach requires weaker identification conditions than the 'cross-sectional heterogeneity' approach because it does not attempt to assign adaptation to a particular variable. The advantage is that it captures in principle all relevant margins through which society may adapt. The disadvantage is that it can only be used to evaluate past adaptation, not assess future adaptation.

These two approaches rely on a third, important identifying assumption: that individuals and society adapt similarly to high-frequency weather and to long-run climate. This assumption allows backing out adaptation from heterogeneity in marginal responses. But if society adapts only to long-run climate, heterogeneity in marginal responses is uninformative about adaptation.

The third category partly addresses these limitations. We call it the 'long difference' approach. It estimates a similar panel regression to the impact estimates, but replaces short-run changes in weather with long-run changes in weather that approximate the climate—for instance 10-year averages of local temperature. By comparing the effect of a short-run weather shock to the effect of a long-run change in weather, one can infer whether the local economy adapts to long-run changes. In principle, the 'long difference' approach, together with the traditional panel weather approach, estimates exactly the object of interest: impacts and adaptation.

Burke and Emerick (2016) use the 'long difference' approach to infer adaptation in agricultural productivity in the United States. They use a panel approach across locations. They find similar impacts in response to long-run changes in average temperature and to short-run weather fluctuations, and conclude that long-run adaptation to extreme heat is likely weak in agriculture. Burke and Tanutama (2019) and Kalkuhl and Wenz (2020) apply this approach to subnational output data in multiple countries. Burke and Tanutama (2019) find that, if anything, long difference estimates exceed short-run weather estimates. These results suggest that adaptation may be weak.

In practice, the 'long difference' approach also faces challenges. Long-run changes in weather are likely correlated with long-run (unrelated) shocks to the outcome of interest across locations, if only by chance. Therefore, it can be challenging to argue convincingly in favor of identification. In addition, the 'long difference' approach requires one to enumerate and measure the universe of weather outcomes that might affect economic activity, just as for the traditional panel impact estimates. Unlike for short-run fluctuations, using global temperature in long differences is of course infeasible or faces an even steeper uphill identification battle.

Our view is that none of these three approaches is perfect. However, we note that the 'long-difference' approach appears to most directly estimate the object of interest: impacts inclusive of adaptation. It is also the approach that has received the least attention in the literature. Therefore, we hope that future work will use it for a broad range of outcomes and assess whether credible identification can be achieved.

Given the challenges involved in estimating adaptation directly, a natural complement is to estimate it indirectly. In that case, one combines a structural model that specifies which actions individuals or society can take to adapt, with empirical estimates of the responsiveness of those action. The model then converts these estimates into benefits and costs of adaptation. We now turn to this approach, structured around three main actions: reallocating production, labor and capital.

## 4.3 Reallocation of Production

In areas exposed to climate change, a natural way to adapt in place is to shift activity to sectors that suffer less from climate change. This shift can occur with or without trade.

**Changes in sectoral specialization.** Shifting economic activity away from agriculture is a particularly relevant example. Costinot et al. (2016) develop a high-resolution model of crop switching, and find that agricultural losses from climate change are three times larger if farmers cannot adapt by switching crops. These results contrast with those from Burke and Emerick (2016) who find limited evidence of adaptation, although in the United States only. Reconciling these conclusions is an important topic for future work.

Changes in agricultural productivity can further hamper the reallocation of labor to other sectors. Combining a structural model and global firm-level data, Nath (2024) shows that non-homothetic food demand limits the reallocation of workers away from agriculture in the face of climate stress: relative demand for food rises as the economy shrinks due to climate change, leading to more, rather than less, specialization in agriculture.

**Trade.** Given the specialization of locations in particular sectors, changes in sectoral comparative advantage across space imply that trade acts as a potential adaptation mechanism. Building on an earlier literature (Reilly and Hohmann 1993; Rosenzweig and Parry 1994), Costinot et al. (2016) find that trade in agricultural products is less important than crop switching.

Of course, trade and sectoral specialization may matter beyond crop choice. Conte et al. (2022) and Cruz (2024) develop multisector models of economic activity that incorporate the adaptation benefits from sectoral switching and trade for the broader economy. Without sectoral comparative advantage, Cruz and Rossi-Hansberg (2024) find only a moderate role for trade as an adaptation mechanism. By contrast, Conte et al. (2022) find a larger role for trade when incorporating changing comparative advantage across a broader range of sectors than agriculture.

Trade itself further interacts with the economy in the presence of climate change. Trade leads to emissions due to national and international transportation. Cristea et al. (2013) document that emissions related to trade are non-trivial. However, Shapiro (2016) finds that the gains from trade outweigh climate damages associated with trade-related emissions.

## 4.4 Reallocation of Labor and Migration

When adaptation in place to climate change and extreme weather through sectoral switching or trade is too costly, out-migration is another option to adapt. Of course, whether households in exposed areas can migrate out depends on available resources to do so as well as migratory barriers.

Whether migration responds to climate change remains an unsettled question. Empirically, there is some evidence that migration responds to climate shocks within developed countries (Leduc and Wilson 2023; Bilal and Rossi-Hansberg 2025).

Across countries however, the evidence is mixed, with some finding positive but weak migratory responses (Cattaneo and Peri 2016) and others finding larger responses (Missirian and Schlenker 2017). More recent work highlights that these conflicting results can be rationalized based on heterogeneous responses across different demographic groups (Benveniste et al. 2022; Benveniste et al. 2024). Some groups even exhibit negative migratory responses, perhaps because climate change depletes the resources it takes to migrate. Determining whether and under what conditions migration responds to climate change is of first-order policy relevance.

Perhaps to fill this relative paucity of data, the literature has taken a more structural approach that models migration within and across countries as responding to migration costs and idiosyncratic preferences, as well as to income and amenities that can be influenced by climate change (Cruz and Rossi-Hansberg 2024; Bilal and Rossi-Hansberg 2025). Collectively, these papers find meaningful adaptation benefits from migration, that can offset up to 40% of the direct impact of climate change.

## 4.5 Reallocation of Capital

Climate change affects the comparative advantage of locations not only for labor, but also for capital—structures, equipment, housing. Therefore, assets can become stranded in exposed locations. Conversely, changing investment behavior across locations is a potentially powerful adaptation mechanism.

Does capital reallocate in response to climate change? There is some, though little, direct evidence on how structures and equipment are reallocated following climate change. Perhaps for this reason, the literature is scarce and largely structural. Bilal and Rossi-Hansberg (2025) model and estimate local capital investment responses to heat and storm shocks with rich spatial heterogeneity at the county level. They find that investment and capital ultimately reallocate away from the South-East Atlantic coast of the United States which is exposed to more frequent coastal storms. Fried (2022) develops an incomplete market model with storm risk to assess the impact of climate change and federal insurance policies on capital accumulation and adaptation with a small number of locations. She finds that the negative moral hazard effects of federal disaster aid offset the positive effects of adaptation investment aid.[11]

There is comparatively more work evaluating whether housing prices respond to climate change. Much of the literature has focused on reduced-form estimates of the impact of flood risk. This strand of work has progressively moved from cross-sectional hedonic regressions (Bernstein et al. 2019), to panel analyses (Hino and Burke 2021), and to large-scale randomized experiments on online platforms (Fairweather et al. 2024). Collectively, these papers find that housing prices do respond to information about flood risk, but that important gaps between information and actual risk remain. With a few exceptions focusing on flood risk or hurricanes (Ostriker and Russo 2024; Aron-Dine 2025), the broad effects of climate change on housing development in at-risk areas remain to be determined. It is our hope that the comparatively large literature on housing and the allocation of capital in macroeconomics (Piazzesi et al. 2007; Kaplan et al. 2020) will be fruitfully brought to shed light on the reallocation of private capital and housing in response to climate change.

## 4.6 Policy-Driven Adaptation

Public policy is a key margin of adaptation (Analytical Perspectives—Office of Management and Budget 2022, Council of Economic Advisers 2023), with the same economic rationale as for any local public good. We group policies into two broad categories. The first involves direct public investment. The second consists of government transfers.

[11] Conte et al. (2021) and Desmet et al. (2021) emphasize a different type of capital accumulation. They develop dynamic spatial structural frameworks to study the reallocation of knowledge capital across locations under climate stress due to heat or sea level rise. They find that knowledge capital tracks changing comparative advantage and concentrates in favorable locations.

Direct public investment, in particular infrastructure investment, is one of the most salient margins that governments can leverage to adapt to climate change. Because large infrastructure projects are rare, it is challenging to evaluate their costs and benefits purely empirically. Thus, the literature is mostly structural and relatively scarce. Balboni (2025) uses a quantitative spatial framework to study public infrastructure investment in flood-prone coastal areas, and finds that they can have substantial costs by keeping economic activity exposed to floods. Hsiao (2023) develops and estimates a spatial model of Jakarta and shows that time-inconsistency problems can lead governments to respond inefficiently with defensive investments such as a sea wall.

One exception to the structural approach is Benetton et al. (2025), who evaluate the effect of Venice's sea wall activation on property prices by leveraging differential exposure of properties to flood protection depending on elevation. Although their identification strategy is complicated by the contemporaneous pandemic shock, they find that sea wall costs just balance benefits at conventional discount rates. This result suggests that the envelope argument of Deryugina and Hsiang (2017) may also apply approximately to large infrastructure projects.

Governmental post-disaster transfers can complement protective investments, and are likely to rise in magnitude with climate change. Deryugina (2017b) shows that automatic stabilizers such as unemployment insurance and medical insurance pay out larger sums than direct disaster aid after hurricanes. Henkel et al. (2022) document that post-hurricane transfers are more generous in election years.

Transfers related to trade policy may also react to climate shocks. Hsiao et al. (2024) collect measures of trade policy around the world and show empirically that they respond to climate shocks. Governments protect domestic consumers and producers of agricultural goods. These interventions may distort domestic and international prices, and limit private incentives to reallocate production to less exposed sectors.

# 5 Conclusion

It is useful to return to the four questions that frame macroeconomics of climate change posed in the introduction. As we have discussed, some areas have seen tremendous progress and have mature literatures, while other literatures are nascent and their subjects are quite incompletely understood.

Concerning the first question—quantifying the loss and damage from climate change—a tremendous amount of progress has been made on the empirical estimation of damage functions and improvements of integrated assessment models. While there are important econometric issues that need resolution, the preponderance of the estimates suggests that the global damages from climate change, as measured by the SCC, are large, in the range of $150 to $1,200 per ton CO2—in everyday units, ranging from $1.35 to $10.70 per gallon of gasoline. Those damages will increase as atmospheric concentrations rise. Those damages are well in excess of the marginal abatement cost of many effective climate policies (Gillingham and Stock 2018), and exceed the magnitude of nearly all carbon taxes observed in practice.

One area where there is a lack of agreement in the SCC is discounting, however that disagreement stems from deeper problems in asset pricing including the lack of an accepted resolution to the equity premium puzzle. Barring a breakthrough in asset pricing theory, climate economists must learn to live with this lack of agreement.

Another area with a lack of clarity is the treatment of deep uncertainty, which is especially relevant as temperatures rise into a range, and at a rate, not experienced over human civilization. This deep uncertainty encompasses the vexing challenge that economists must project damages into this new future environment based on historical data. Although various ways to structure this uncertainty are available, moving to compelling quantitative implications from a realistic model so far has been elusive.

Regarding the second question—the macroeconomics of the energy transition and mitigation policy—a great deal is known about carbon pricing and its implications: it is effective when there are low-carbon substitutes available, and not especially costly macroeconomically in terms of output, inflation, or employment if implemented predictably. Much less is known, however, about the aggregate implications of the large labor and capital market shifts that will come with the energy transition. And while directionally the importance and early timing of innovation policy is clear, the magnitude and shape of that policy, its role in subsidizing learning-by-doing, and generally the role of green industrial policy are all areas in which more knowledge is needed to guide active real-world policy.

A striking feature of the literature on the macroeconomics of climate policy is its focus on policies that are first-best in standard, relatively simple dynamic models, in particular carbon pricing and innovation policy, to the exclusion of many policies and frameworks that appear in public discourse. We have mentioned the relative paucity of work on climate targets and carbon budgets, for example. On the policy side, there are exceedingly few papers on the macroeconomics of solar radiation management, carbon dioxide removal, carbon removal obligations, green industrial policy, and degrowth—all issues that could have profound macroeconomic implications and on which macroeconomists could say much, but have not. As conventional climate policies, especially carbon pricing, founders, we would hope for much more work on these alternative policies.

The literature on the third question—the macroeconomics of adaptation—is in its infancy. We have sketched out what we know, but it is clear that many questions, including a high-level framing of the topic—remain unanswered. The extent to which societies will adapt to climate change impacts remains unclear. Adaptation involves a host of individual and institutional decisions at various levels of aggregation: households and firms; local, state and federal governments; and groups of countries. We hope that the macroeconomics of climate adaptation takes a prominent place within the field of macroeconomics.

The final question—the implications for monetary and fiscal policy—is the topic of a separate review (Bilal and Stock 2025). Work in this area is growing but here, too, much remains unknown, including the macroeconomic ramifications of geopolitical changes stemming from the energy transition, the effect of transition shocks (the manifestation of a "disorderly transition"), the ways (if any) in which climate and energy-transition shocks differ from conventional supply and demand shocks, and which short-term transition risks should be the most relevant to policymakers.

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# A The DICE Model

## A.1 Economic Module

The economic module of the DICE model resembles the neoclassical growth model. The main differences are the inclusion of climate damages (similar to productivity shocks) and of abatement costs. Gross output at time t is $Y_t = A_t K_t^\alpha L_t^\alpha$, where $A_t$ denotes total factor productivity, $K_t$ is the capital stock and $L_t$ is the stock of labor. $\alpha \in [0,1]$ is the capital share in production. The paths of $A_t, L_t$ are exogenously given.

Output net of climate damages and abatement costs then writes: $Y_t^{\text{net}} = (1 - \Omega(T_t))Y_t - \Lambda(\mu_t)Y_t$. $\Omega(T_t)$ is the damage function that depends on temperature. $\Lambda(\mu_t)$ is the abatement cost function expressed as a share of output, and depends on the fraction of emissions abated $\mu_t$, with $\Lambda(0) = 0$.

Capital accumulates according to $K_{t+1} = (1 - \delta_K)K_t + I_t$, where $I_t$ denotes investment and $\delta_K$ is the capital depreciation rate. Aggregate consumption is then $C_t = Y_t^{\text{net}} - I_t$. Households have standard time-separable preferences with flow utility function $U$ and discount factor $\beta$.

## A.2 The Climate Module

Emissions are given by $E_t = \sigma_t(1-\mu_t)Y_t + E_t^{\text{land}}$, where land emissions $E_t^{\text{land}}$ are exogenously given. The first component $\sigma_t\,(1-\mu_t)\,Y_t$ represents emissions from economic activity and is proportional to gross output $Y_t$, the fraction of unabated emissions $(1-\mu_t)$, and the exogenous emissions intensity of production $\sigma_t$. A secular decline in $\sigma_t$ can capture technological progress in low-emission energy sources.

The standard climate module posits: $M_t = (\text{Id} + B)M_{t-1} + E_t$, where $M_t = \left[M_t^{\text{AT}}, M_t^{\text{UO}}, M_t^{\text{LO}}\right]$ is the vector of carbon masses in the three main reservoirs (the atmosphere, the upper oceans, and the lower oceans). Here, Id denotes the $3\times 3$ identity matrix, and $B$ is a $3\times 3$ matrix that represents carbon mass transfer between the reservoirs, with $\sum_j B_{ij} = 0$ by mass conservation.

Radiative forcing takes the form $F_t = F_0 \log\left(M_t^{\text{AT}}/\overline{M}\right) + F_t^{\text{EX}}$, where $F_0$ is the climate sensitivity, $\overline{M}$ is the long-run mass of atmospheric carbon absent anthropogenic emissions, and $F_t^{\text{EX}}$ is exogenous forcing.

Temperatures in the atmosphere and the oceans then follow: $T_{t+1}^{\text{AT}} = T_t^{\text{AT}} + c_1\big(F_t - \lambda\, T_t^{\text{AT}} - c_2(T_t^{\text{AT}} - T_t^{\text{OC}})\big)$, and $T_{t+1}^{\text{OC}} = T_t^{\text{OC}} + c_3\big(T_t^{\text{AT}} - T_t^{\text{OC}}\big)$. The coefficients $c_1, c_2, c_3$ capture heat exchange between the atmosphere and the oceans, and $\lambda$ represents radiative feedback.

## A.3 Decision Problem

**Planning problem.** A world planner chooses the optimal path of investment and abatement to solve:

$$\max_{\{\mu_t, C_t\}_t} \sum_{t=0}^{\infty} \beta^t L_t U\left(\frac{C_t}{L_t}\right),$$

$$\text{subject to:} \quad (1) \quad C_t + K_{t+1} = [1-\Omega(T_t) - \Lambda(\mu_t)]A_t K_t^{\alpha} L_t^{1-\alpha} + (1-\delta_K)K_t,$$

$$(2) \quad \text{the climate module,}$$

where $\Omega(T)$ represents climate damages, $\Lambda(\mu)$ represents abatement costs, $A_t$ is productivity, $\delta_K$ is the depreciation rate, and $\beta$ is the discount factor.

**Decentralized equilibrium.** In the decentralized equilibrium, dynasties of households and firms make individual decisions. Firms earn zero profits due to constant returns to scale. Because households are atomistic and do not internalize the benefits of decarbonization, they always set $\mu_t = 0$. Households then choose:

$$\max_{\{C_t\}_t} \sum_{t=0}^{\infty} \beta^t L_t U\left(\frac{C_t}{L_t}\right),$$

$$\begin{aligned}
\text{subject to:} \quad & (1) \quad C_t + K_{t+1} = w_t + r_t K_t + (1 - \delta_K) K_t \\
& (2) \quad \text{given the paths of } w_t, r_t. \\
\text{In addition:} \quad & r_t = \alpha[1 - \Omega(T_t)] K_t^{\alpha-1} L_t^{1-\alpha}, \text{ and } w_t = (1-\alpha)[1 - \Omega(T_t)] K_t^{\alpha} L_t^{-\alpha}, \\
& T_t \text{ is given from the climate module.}
\end{aligned}$$

**Functional forms.** Common functional forms include:

$$U(c) = \frac{c^{1-\gamma} - 1}{1 - \gamma}, \quad \Omega(T) = 1 - \frac{1}{1 - \Omega_1 T - \Omega_2 T^2}, \quad \Lambda(\mu) = \Lambda_0 \sigma_t \mu^2.$$

**Interpretation.** Our discussion of loss and damage in Section 2 corresponds broadly to various specifications and parametrizations of the damage function $\Omega(T)$. Our discussion of mitigation in Section 3 corresponds broadly to various specifications and parametrizations of the abatement cost curve and technological progress $\Lambda(\mu), \sigma_t$. Our discussion of adaptation in Section 4 amounts to adding more choices and margins to the planner or the representative households in the decision problem.