Dimensional

The Economics of Climate Change

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This paper summarizes the economics of climate change. We first review the basics of climate science and the historical evolution of greenhouse gas emissions. We then discuss the relation between climate change and economics and assess the economic costs, direct and indirect, of climate change. These costs are uncertain and sensitive to the choice of discount rate, but overall, the expected costs are economically significant, and early mitigation efforts may be more cost-effective than later actions. We discuss the tradeoffs associated with different potential actions, such as carbon taxation and cap-and-trade programs. Finally, we examine the implications of climate change for asset pricing and investment choices.

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1. Introduction

Economic growth was virtually nonexistent before 1800 (Hansen and Prescott, 2002; Galor and Weil, 1999, 2000). By contrast, between 1870 and 2016, living standards in the US doubled every 40 years.[1] This unprecedented growth was sparked by innovations that replaced human and animal toil with mechanical work. Fossil fuels powered several of these technological breakthroughs, such as the steam engine, power plants, and the internal combustion engine. The use of fossil fuels, however, emits carbon dioxide (CO_2) and other greenhouse gases (GHG) into the atmosphere. As a result, fossil fuels have had a huge effect not only on the economy but also on the environment. Indeed, Hsiang and Kopp (2018) report that atmospheric CO_2 concentrations rose from a preindustrial baseline of 278 parts per million to 409 parts per million in 2018. They also report that, consistent with the increased accumulation of GHG in the atmosphere, the global mean surface temperature (GMST) rose by approximately 1.0°C (1.8°F). The United Nations Intergovernmental Panel on Climate Change Fifth Assessment Report (IPCC, 2014) predicts further warming in the 21st century, with negative effects for both humanity and nature.

Unprecedented growth was sparked by innovations that replaced human and animal toil with mechanical work. Fossil fuels powered several of these technological breakthroughs, such as the steam engine, power plants, and the internal combustion engine.

From an economic standpoint, GHG emissions represent a negative externality because economic agents do not pay for the full present and future costs of their GHG emissions. A useful measure of this externality is the social cost of carbon (SCC), a dollar figure that quantifies the damages from an additional metric ton of CO_2 emissions (Nordhaus, 2019). In principle, governments could levy a tax equal to the SCC to get market participants to internalize the full costs of their actions. Such a tax would incentivize firms and individuals to lower their emissions. A similar result could be achieved via a cap-and-trade scheme. Under this setup, the government issues permits for a fixed amount of emissions (cap) per time period, which are then publicly traded. The firms most willing to pay for emissions, likely firms that can produce more valuable output for given emissions, set the price of the permits. As a result, GHG-emitting activities become more expensive, motivating companies to reduce emissions.

Although both of these solutions are theoretically appealing, they present formidable challenges in practice. To begin, quantifying the social cost of carbon requires estimating costs that will occur far in the future, as most of the impacts of climate change will be borne by future generations. These costs must then be discounted to a present dollar value. Arrow et al. (2013) and Pindyck (2013) emphasize that given the long horizons involved, the estimated social cost of carbon is extremely sensitive to the choice of a discount rate, as well as other parameters needed to make intertemporal and intergenerational comparisons. There is also uncertainty about the impact of warming on the economy, in part because the economy's future adaptation potential depends on technological progress. Finally, while climate science has shown that GHG emissions cause warming, the exact magnitude of the relation is still unknown. According to the IPCC Fifth Assessment Report (Box 12.2 in Collins et al., 2013; IPCC, 2014), doubling

CO_2 concentrations in the atmosphere would likely increase global temperatures by 1.5°C to 4.5°C in the long run.[2] In more recent work, Sherwood et al. (2020) find a tighter range of 2.3–4.5°C. For both intervals, warming is significant, but warming at the upper end of the range (or above) would be considerably more disruptive, implying a higher SCC today.

Another source of complexity that plagues many proposed solutions stems from the global nature of the issue. First, climate is a global public good: all countries benefit from a favorable climate, even if they do not help sustain it. Countries therefore have an incentive to profit from the emission reductions of others without lowering their own. Second, nations at different stages of development face drastically different incentives. For least-developed countries, large additional emissions might be a cost worth incurring for additional economic growth. This is especially true when considering the dramatic effects growth can have on health and longevity. Ravallion (2011) finds that, between 1981 and 2005, life expectancy in China rose by seven years and infant mortality decreased by more than half; India and Brazil showed similar improvements. Finally, different regions face different potential costs from climate change. Potential costs vary because individual countries are exposed to different levels of physical risks (sea level rise, warming) but also because countries differ in their capacity to mitigate the effects of climate change.

Climate change poses many questions. We summarize the economic thinking on the tradeoffs and choices related to climate change.

In short, climate change poses many questions. Which options should be picked to address climate change when there is uncertainty about the costs and benefits of each alternative? How should we think about investments over horizons that span multiple generations? What are the most effective mechanisms available to consumers, producers, governments, and investors to address climate change? In this essay, we summarize the economic thinking on the tradeoffs and choices related to climate change. We begin by discussing the latest scientific understanding on climate change (Section 2). We then examine the literature on the social cost of carbon (Section 3) and explore the tradeoffs and choices faced by governments, consumers, and producers in curbing emissions (Section 4). Finally, we address the tradeoffs and choices faced by investors (Section 5). Section 6 concludes.

2. Greenhouse Gases and Climate Change

2.1. GREENHOUSE GASES AND TEMPERATURE

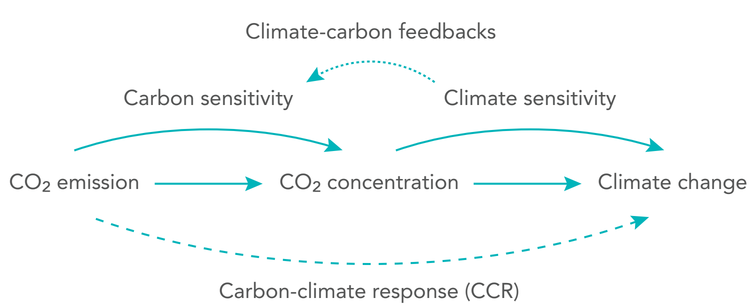
Hsiang and Kopp (2018) state that, in the absence of greenhouse gases, Earth's global mean surface temperature would be –18°C, or about 0°F. Essentially, at this temperature, the incoming energy from the Sun would equal the energy emitted by Earth through infrared radiation, whose intensity increases with temperature. The key property of greenhouse gases is that they block part of the outgoing infrared radiation but not incoming sunlight. When greenhouse gases are introduced, Earth's temperature rises until the infrared radiation that escapes the atmosphere once again equals incoming energy. Equilibrium is, therefore, reestablished at a higher temperature. This is the greenhouse effect.

The link between GHG concentrations and global warming has been known since the 19th century.

The link between GHG concentrations and global warming has been known for a long time. Uppenbrink (1996) gives a brief overview of early research efforts. In particular, chemistry Nobel laureate Svante Arrhenius attempted to quantify the greenhouse effect as early as 1896. He estimated that doubling CO_2 concentrations would increase temperatures by 5–6°C, a range at the upper end of recent estimates.

Hsiang and Kopp (2018) emphasize that multiple factors mediate the relation between GHG concentrations and global temperature: vegetation, oceans, clouds, and ice formations all play a role. Even more importantly, these variables are involved in feedback loops, making Earth's climate a complex system with many nonlinear relations. Rising temperatures increase the atmosphere's humidity, causing additional warming because water vapor reflects infrared radiation. Similarly, permafrost (ground that has been frozen for at least two years) can thaw as a result of warming, releasing methane and carbon dioxide that contribute to further temperature rises (Biskaborn et al., 2019). To make matters even more complex, some phenomena that occur jointly have a conflicting effect on warming. For example, burning coal emits not only GHG but also aerosols (small, solid particles that float in the air). Aerosols reflect sunlight, exerting a cooling effect; their net effect on warming is still the subject of active research (e.g., Rosenfeld et al., 2019).

Exhibit 1: The Carbon-Climate Response



Source: Matthews et al. (2009).

Exhibit 1, taken from Matthews et al. (2009), unties this Gordian knot by decomposing the effect of GHG emissions on temperature, the carbon-climate response, into smaller components. First, GHG emissions lead to higher GHG concentrations in the atmosphere, but the link is not one-to-one. Carbon sensitivity refers to the strength of that relation. The concept accounts for carbon sinks, such as oceans and forests, which absorb emissions that would otherwise end up in the atmosphere. Second, climate sensitivity relates atmospheric GHG concentrations to temperature changes. Some of the aforementioned feedback loops affect climate sensitivity. For instance, Hsiang and Kopp (2018) state that a doubling in CO_2 concentrations would lead to a temperature increase of 1.2°C in the absence of feedback loops. When additional mechanisms, such as increased atmospheric humidity, are accounted for, Hsiang and Kopp (2018) report that the increase is between 2.0°C and 4.5°C instead, consistent with Sherwood et al. (2020). The effect is higher and, crucially, more uncertain than suggested by simple energy balance calculations. Finally, the dotted arrow accounts for the impact of climate change on carbon sinks, such as the permafrost or vegetation.

If emissions stayed constant at their current level, it would take about 40 years to emit as much CO_2 as has been emitted since 1750.

2.2. HISTORICAL CLIMATE EVOLUTION

Exhibit 2 presents a few important estimates about GHG emissions and temperatures. These numbers are helpful for understanding the orders of magnitude involved in climate change discussions. If emissions stayed constant at their current level, it would take about 40 years to emit as much CO_2 as has been emitted since 1750. Doubling atmospheric CO_2 concentrations would likely increase temperatures by 1.5°C or more, while the Paris Agreement[3] targets require limiting additional warming to 0.5–1.0°C (Tollefson and Weiss, 2015). Immediate and substantial emission cuts would be necessary to achieve the Paris Agreement objectives.

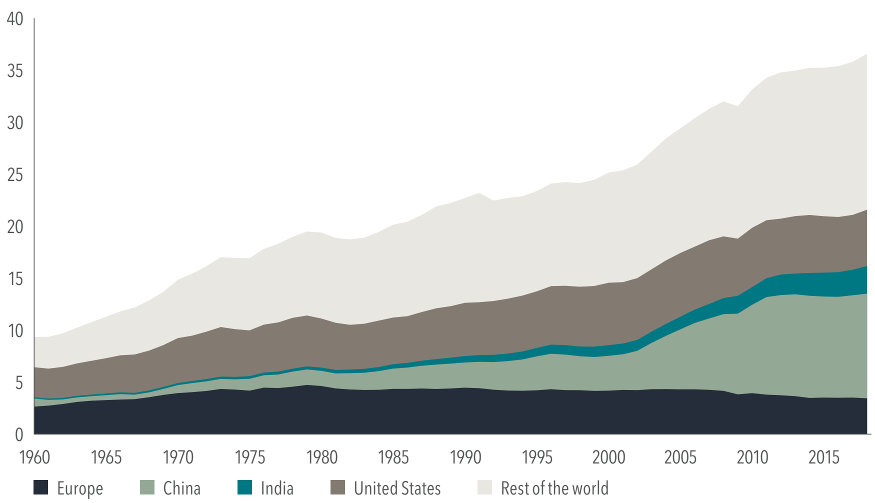
Exhibit 2: Key Figures about CO_2 Emissions and Temperatures

Quantity	Value	Source
Annual CO_2 emissions (World, 2018)	36.6 Gt	Global Carbon Atlas 2018[4]
Cumulative CO_2 emissions (World, 1750-2014)	1474.4 Gt	Boden et al. (2017)
CO_2 atmospheric concentrations, pre-industrial baseline	278ppm	Hsiang and Kopp (2018)
CO_2 atmospheric concentrations (2018)	409ppm	Hsiang and Kopp (2018)
Global mean surface temperature increase since industrialization	Approx. 1.0°C	IPCC (2014)
Paris Agreement targets, with respect to pre-industrial baseline	1.5–2.0°C	Tollefson and Weiss (2015)
Paris Agreement targets, with respect to current temperatures	0.5–1.0°C	Tollefson and Weiss (2015)
Expected temperature increase when CO_2 concentrations double (IPCC Fifth Assessment Report)	1.5–4.5°C	Collins et al. (2013)
Expected temperature increase when CO_2 concentrations double (Recent results, interval incorporates robustness checks)	2.3–4.5°C	Sherwood et al. (2020)

Gt = gigaton (one billion metric tons); ppm = part per million. "ppm" here refers to mole fraction, a unit-free measure of concentration. A 1.0°C (Celsius) increase corresponds to a 1.8°F (Fahrenheit) change. Pre-industrial levels for emissions and temperatures correspond to the 1850–1900 average (Hsiang and Kopp, 2018).

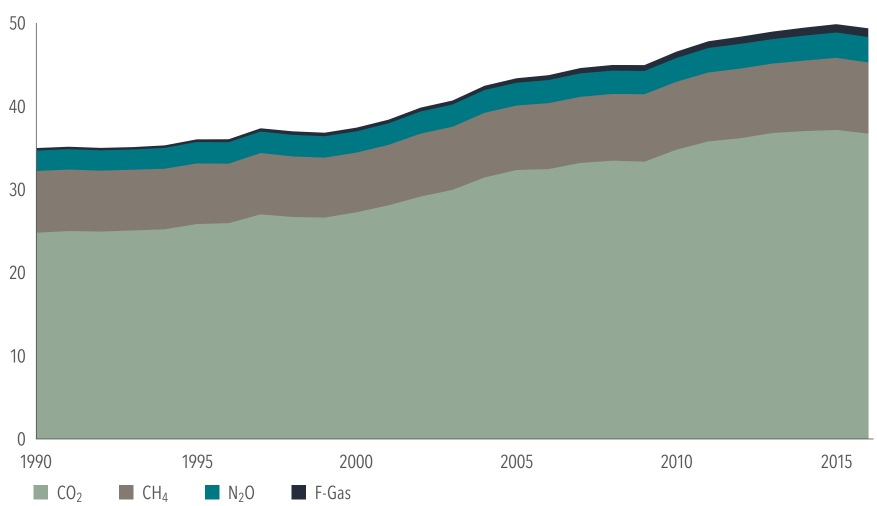
The numbers in Exhibit 2 can also be compared to more familiar reference points. The US Environmental Protection Agency (2018) estimates that, based on average yearly mileage (11,500 miles), the typical passenger vehicle in the US emits 4.6 tons of CO_2 per year. Yearly global emissions (36.6 Gt) are equivalent to every single human (7.8 billion) driving a car for 11,500 miles each year..

Exhibit 3: Global Evolution of CO_2 Emissions (Gt), *1960–2018*



Source: Global Carbon Atlas 2018[4]

Exhibit 4: GHG Emissions per Type of Gas (Gt of CO_2 equivalent)



Source: World Resources Institute CAIT Climate Data Explorer.[5]

As can be seen from **Exhibit 3**, aggregate emissions numbers mask considerable differences across countries. Combined CO_2 emissions for the US and Europe peaked around 2005, at 10.4 billion metric tons (Gt), and declined to 8.9Gt in 2018. Over the same period, real output grew by 25% in the US (US Bureau of Economic Analysis, 2020) and 18% in Europe (Eurostat, 2020), which shows that economic growth need not depend on increasing GHG emissions. China's emissions have been relatively stable since 2012 and stood at 10Gt in 2018. India's emissions are growing, albeit from a lower baseline: emissions were 2.7Gt in 2018.

So far, we have focused on CO_2 emissions, but other gases contribute to the greenhouse effect as well. They all originate mainly from fossil fuel production and usage. **Exhibit 4** shows that CO_2 emissions make up a high and stable percentage of global GHG emissions, with methane (CH_4) being a distant second. Other gases, such as nitrous oxide (N_2O) and fluorinated gases, play lesser roles. Box 3.2 in IPCC (2014) reports that, for a fixed amount of emissions, these other gases have a stronger warming effect than CO_2, especially at short horizons. CO_2 still has an outsized role because it is emitted in high quantities and its effect on warming is long-lasting. This is why we focus on CO_2, but the analysis in this paper applies to all GHG emissions.

Forecasting future temperatures requires modeling the climate and the economy, since emissions crucially depend on economic activity. Forecasting either of these quantities is a monumental task

2.3. CLIMATE MODELS AND FORECASTING

Forecasting future temperatures requires modeling the climate and the economy, since emissions crucially depend on economic activity. Forecasting either of these quantities is a monumental task. For example, even if emissions are known in advance, their impact on future temperatures is uncertain because of imperfect climate models. As noted by Hsiang and Kopp (2018), climate models can produce projections that conflict with observed historical patterns, requiring the use of bias correction techniques before the output can be used. Hansen and Brock (2018), taking an example from Kirtman et al. (2013), note that observed warming in the 2000s falls at the very low end of backtested predictions from models used by the IPCC. Fyfe et al. (2016) and Medhaug et al. (2017) provide a more in-depth treatment of the issue and argue that it has been successfully resolved. The key challenge for decision making is that the forecasts themselves are a moving target as models evolve to reflect the progress of climate science.

Those limitations do not negate the usefulness of climate projections, nor does it overturn their main finding: continued GHG emissions will cause substantial warming. However, they do limit the precision that can be expected from modeling exercises. These difficulties are magnified by the need to predict future emissions, which depend on the level of economic activity, its carbon intensity (CO_2 emissions per unit of output), and future economic and environmental policies. As we shall see in Section 3, the social cost of carbon crucially depends on how these sources of uncertainty are quantified.

As part of its Fifth Assessment Report (IPCC, 2014), the IPCC published a set of widely used projections, the Representative Concentration Pathways (RCPs). Each pathway corresponds to different assumptions about GHG emissions and the economy. These assumptions are inputs for dozens of different models, whose results are then aggregated to obtain a range of outcomes under a given scenario. Scenarios are indexed by a radiative forcing number, with a higher number corresponding to a larger amount of warming due to higher GHG concentrations. **Exhibit 5** summarizes. For reference, the atmospheric CO_2 concentration was 409 parts per million in 2018. The likely ranges highlight the uncertainty around projected warming.

Exhibit 5: Representative Concentration Pathways (RCPs)

Scenario	CO_2 Concentrations (ppm)	Warming Relative to 1986–2005	Likely Range
RCP 2.6	421	1.0°C	0.3–1.7°C
RCP 4.5	538	1.8°C	1.1–2.6°C
RCP 6.0	670	2.2°C	1.4–3.1°C
RCP 8.5	936	3.7°C	2.6–4.8°C

All numbers are projected for 2080-2100. RCPs are described in depth in IPCC (2014). CO_2 equivalent concentrations taken from Table 4 in Meinshausen et al. (2011).

The most optimistic scenario, RCP 2.6, is based on immediate cuts to emissions, which decline by two-thirds before 2050 and become net negative in 2080 (Box 2.2, IPCC, 2014). This is why CO_2 concentrations are barely higher than today in 2100, as net emissions must be zero to stabilize concentrations and negative to reduce them. The IPCC classifies RCP 4.5 and RCP 6.0 as intermediate scenarios and RCP 8.5 as a high-emission scenario. In the absence of additional mitigation efforts ("business-as-usual"), future emissions and warming are expected to be between RCP 6.0 and RCP 8.5 (Box 2.2, IPCC, 2014). Under RCP 6.0, CO_2 emissions peak and decrease late in the century, while they reach a plateau (but do not decrease) under RCP 8.5.

3. Assessing the Economic Costs of Climate Change

The social cost of carbon (SCC) quantifies the damages from an additional metric ton of CO_2 emissions.

Climate economics models typically assume that each additional dollar of consumption yields diminishing benefits and increasing environmental costs.

Nordhaus (2019) defines the social cost of carbon (SCC) as a dollar value that quantifies the damages from an additional metric ton of CO_2 emissions or, equivalently, the benefits from a one-ton emissions reduction. The SCC is useful for quantifying the costs and benefits of environmental policies, including carbon taxation (Greenstone et al., 2013). It is defined relative to a small change in emissions because most environmental projects involve small emissions reductions compared to the global total. For example, based on Exhibit 3, a policy that immediately reduced US emissions by 10% would cut global CO_2 emissions by less than 1.5%. Also, even ambitious climate policies involve gradual changes over time rather than a single, one-time cut.

How do economists estimate the social cost of carbon? Consider the following framework, inspired by Daniel et al. (2019), in which an agent chooses the fraction of resources allocated to climate mitigation efforts to maximize the welfare of current and future generations, $V(y_t)$:

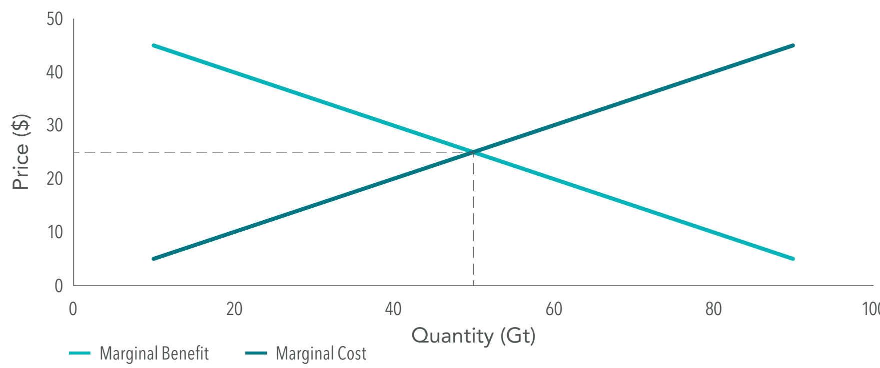
$$V(y_t) = \max_{m_t}[u[\omega(1-y_t)(1-m_t)] + \beta V(y_{t+1})]$$
$$y_{t+1} = g(m_t, y_t)$$

Each period t corresponds to a generation. Every generation receives the same amount of consumption good ω. A fraction y_t is lost due to climate damages, leaving $(1-y_t)$ available for consumption and investment in mitigation efforts m_t. Tomorrow's climate depends on today's climate and today's mitigation efforts through $g(m_t, y_t)$. $u(\cdot)$ measures the benefit each generation derives from consumption. The main tradeoff is that higher mitigation efforts lower future climate damages y_{t+1}, at the price of lower consumption in the current period.

The problem is recursive: the current generation cares about the welfare of the next, which cares about the next generation, and so on. Each generation has the same preferences, which are represented by $u(\cdot)$. The discount factor β measures how the welfare of future generations affects today's decisions. Importantly, each generation accounts for the impact of its actions on all future generations when picking the optimal mitigation effort m_t^*.

Climate economics models typically assume that each additional dollar of consumption yields diminishing benefits and increasing environmental costs. **Exhibit 6** illustrates these assumptions. The light blue curve is a marginal benefit curve. For each emission level, it shows the benefit of a small emissions increase, which comes from the additional consumption unlocked by lower mitigation efforts. For example, when total emissions are 20Gt, emitting an additional ton of CO_2 yields social benefits worth \$40. The marginal benefit curve is downward sloping because benefits from consumption (and hence emissions) decline with each additional unit of consumption. This is how economists reflect the fact that the first bite of the cake tastes much better than the last. The dark blue curve is a marginal cost curve. It is upward sloping because larger emissions impose larger additional costs on future generations, as the induced warming becomes increasingly hard to mitigate.

Exhibit 6: Social Cost of Carbon and Optimal Emissions



When these assumptions about the marginal cost and benefit of emissions hold, the intuition behind the optimal solution m_t^* is clear: the agent should pick the level of mitigation that equates the marginal cost and benefit of emissions. The marginal cost of emissions at the equilibrium is the social cost of carbon.

Therefore, to estimate the social cost of carbon, climate economics models need to specify the agent's preferences $u(\cdot)$, the climate system $g(\cdot)$, and the discount factor β. Some models also incorporate production and capital accumulation functions. Different assumptions across models lead to different estimates of the SCC. Accordingly, we first review the inputs and assumptions that enter these models and their impact on the SCC estimation. We then survey the dollar estimates of SCC reported in the literature.

We note in passing that the social cost of carbon can have a term structure; for example, in the Dynamic Integrated Climate-Economy (DICE) model, the SCC rises at the rate of interest[6] (Nordhaus, 2007; Becker et al., 2010), while it is expected to decrease in the EZ-Climate model (Daniel et al., 2019). Also, some authors define the SCC for allocations that are suboptimal, such as an emissions level that is more stringent than the social optimum. In this case, defining the SCC as the marginal benefit or cost of emissions no longer yields equivalent results. One approach in this case (e.g., Nordhaus, 2017) is to define the SCC as the marginal benefit of emissions. By construction, imposing a tax equal to this SCC induces the current generation to emit at the more stringent level. We abstract from these technicalities to simplify the presentation. In what follows, "the" SCC is defined relative to the optimal policy, given today's climate and today's economy.

Warming since the pre-industrial era has been approximately 1.0°C.

3.1. PHYSICAL EFFECTS OF CLIMATE CHANGE

Discussions of climate change often focus on global mean surface temperature (GMST), a variable that is both important and well defined. However, this summary statistic has a significant drawback: it masks temperature variation across regions and within a given year, even though economic damages crucially depend on that variation. First, GMST combines land and ocean temperatures, and surface temperatures are expected to rise faster on land because oceans absorb heat. Collins et al. (2013) show that 1.0°C of global warming implies a 1.25°C–1.75°C rise over many densely populated regions. Second, a small rise in average temperatures can drastically increase the probability of extreme heat episodes. In fact, Diffenbaugh et al. (2017) show that past warming likely increased the frequency of such events already. For example, they find that in tropical areas the temperatures during the hottest month on record were at least four times as likely to occur under the current climate than under a baseline climate without warming.

As mentioned above, warming since the pre-industrial era has been approximately 1.0°C. Even under RCP 4.5, a moderate-emissions scenario, the global mean surface temperature is expected to increase by another 1.8°C by 2100. Based on the aforementioned research, this would imply significant temperature increases in populated regions and more frequent extreme temperatures, which are the relevant metrics for several types of damages. If temperatures in Chicago rise by an average of 2.0°C, this would likely cause little disruption in the middle of winter but could result in more frequent heat waves in the summer. For health effects such as heat strokes, the extreme heat prevalence matters far more than gradual shifts in average temperatures.

Temperature changes also have important indirect effects. Warmer oceans are associated with sea level rises, increased humidity, more frequent flooding, and more frequent tropical storms (Hsiang and Kopp, 2018). Droughts could become more likely, especially in dry regions. Warming can also have negative effects on natural habitats. One well-known example is the bleaching of coral reefs caused by warmer and more acidic oceans (due to increased CO_2 concentrations—carbon dioxide is acidic). Overall, GHG emissions can alter the physical environment through multiple channels.

Through its impact on the physical environment, climate change can damage existing investments and lead to higher costs of capital.

3.2. MAPPING PHYSICAL EFFECTS TO ECONOMIC COSTS

Through its impact on the physical environment, climate change can damage existing investments and lead to higher costs of capital. Potential mechanisms include more frequent forest fires (Abatzoglou and Williams, 2016) and flooding (e.g., Hinkel et al., 2014 and Hallegatte et al., 2013). In addition, climate change can make investors more reluctant to invest in damage-prone areas, depressing the values of existing property and raising the cost of capital for issuers tied to those areas. Moreover, rising water levels might force firms and families to relocate. Costs related to damages to existing physical capital as well as potential future damages are one channel through which climate change can affect the economy.

Another channel is damages to productivity. Schlenker and Roberts (2009) find that US maize crop yields increase with temperatures up to 29°C (84°F) and decrease sharply above this threshold. Indeed, a single day of extreme heat can have significant effects. Substituting a single 29°C day with a 40°C day (104°F) is expected to decrease yields for the entire season by 7%. This example is important for two reasons. First, it shows how the frequency of extreme heat episodes matters, not just average warming. Second, mitigation measures are less obvious in the case of agricultural damages than in the case of property damages.

Climate change can increase mortality and morbidity, and the effect is not limited to extreme heat.

Societal effects constitute another source of potential economic costs. Carleton and Hsiang (2016) provide a rich overview of the varied effects of climate change on both individuals and societies. Health effects are one important category. Climate change can increase mortality and morbidity, and the effect is not limited to extreme heat. For example, Barreca and Shimshack (2016) find that influenza mortality in the US increases with absolute humidity. The climate can have more subtle societal impacts as well. Studies have linked warming and its impact on resources to increased crime and conflict (Hsiang et al., 2013), lower fertility rates (Barreca et al., 2016), and higher suicide rates (Burke et al., 2018).

This section provides an overview of the various economic costs of climate change, which must be correctly modeled to find the SCC. In addition, estimating those costs further in the future requires projecting the evolution of mitigation technologies and their prices. Once all externality costs have been estimated over a reasonably long horizon, the next step in the calculation of the SCC is the selection of proper discount rates. This is what we discuss next.

3.3. HOW SHOULD FUTURE COSTS BE DISCOUNTED?

How should we discount future damages due to climate change? If we approach the question from an ethical perspective, it is unclear whether we should discount at all. Indeed, the intrinsic worth of humans born in 2100 is no lower than ours. Why, then, should we adjust the costs that they will face downwards? This question is not new to economics. It also applies to other investments with long-term payoffs, such as investments in infrastructure and research and development, and it can be addressed using Ramsey's (1928) rule.

The rule starts from two premises: the well-being of each generation is equally valuable, and improvements in living standards yield positive but decreasing gains in well-being. In a framework with economic growth, Ramsey's rule states that the discount rate should increase with the growth rate. The intuition is simple. With economic growth, tomorrow's generation is wealthier than today's. Therefore, under the framework's assumptions, an additional dollar of consumption tomorrow has a smaller impact on the well-being of tomorrow's generation, and projects that reduce consumption by $1 today should only be undertaken if they result in more than $1 of benefits tomorrow. The discount rate succinctly measures how high future benefits should be for the investment today to cover its costs.

But what should the discount rate be? Sources of uncertainty abound. The impact of GHG emissions on future warming depends on parameters that are not precisely estimated at present. For instance, Daniel et al. (2016) point out that the 1.5°C–4.5°C range for equilibrium sensitivity obtained by IPCC (2014) is the same interval found by Charney et al. (1979) more than three decades ago, underlining how slow the resolution of scientific uncertainty can be. Some recent studies (e.g., Sherwood et al., 2020), however, find tighter intervals. On the technological front, we do not know if low-cost, scalable carbon-capture technologies will be available when expected, sooner, or later. Although economic growth has been continuous since the late 19th century, there are no guarantees that it will continue at the same rate (Christensen et al., 2018). Gollier (2010, 2019) and Heal (2017) argue that the lost benefits from a healthy ecosystem may not be easily replaceable. All these considerations can affect the value of the discount rate for the SCC.

Becker et al. (2010) take a different approach. They argue that the relevant discount rate is the opportunity cost of capital, which can be inferred from market prices, and illustrate the point with the following example. Suppose that the discount rate based on ethical arguments is 3%, while the market cost of capital is 6%. The 3% discount rate implies that a climate mitigation investment of $1 that reduces damages by $20 after 100 years should be undertaken. Since a dollar invested at 3% is worth $19.21 after 100 years, the opportunity cost of the investment ($19.21) is lower than its benefit ($20) at the end of the period. Suppose instead that climate change is ignored and that the capital is invested at 6% over the next century. The investment is worth $339.30 at the end of the period, more than enough to cover the $20 damages due to the foregone mitigation project. Hence, it could be more efficient to undertake an alternative project today, as it will enable more spending on mitigation (as well as more spending overall) in the future.

This approach to estimating discount rates, however, ignores the possibility of irreversible damages to our planet (disappearance of animals, plants, and natural habitats while capital is invested in non-mitigation projects). Becker et al. (2010) recognize this fact and suggest that mitigation projects can be evaluated at lower rates than those implied by market prices because mitigation projects could provide insurance against catastrophic outcomes—including irreversible environmental damages.

The discount rate is arguably the variable with the largest impact on the estimated social cost of carbon.

A wide range of discount rates have been used in applied work. The Stern Review uses 1.4% (Nordhaus, 2007). At the other end of the spectrum, Becker et al. (2010) suggest using long-term returns on bonds and equities as a starting point; for reference, the average real return between 1926 and 2020 on US equities is around 8.5%. Even with downward adjustments to reflect the potential insurance value of mitigation projects, starting from capital market returns would likely lead to relatively high discount rates. Nordhaus (2016) uses a discount rate of approximately 4.25%, roughly in the middle of those two bounds.

While these differences in discount rates might appear small, they can actually lead to large differences in the SCC. For instance, the 2020 SCC is $236 under a 2% discount rate but only $49 under a 4% rate (Table 2 in Nordhaus, 2019). The discount rate is arguably the variable with the largest impact on the estimated SCC, whose value we now discuss.

3.4. DOLLAR VALUE OF THE SOCIAL COST OF CARBON

Given the huge uncertainty around how to model the future costs of climate change and how to discount them, it is not surprising that the academic estimates of the SCC vary widely. Nordhaus (2016) finds a value of $31 per ton of CO_2 for the 2015 SCC measured in 2010 dollars, although the estimate comes with wide uncertainty: the 10th and 90th percentiles of possible values are $7 and $77, respectively. Even within a given model, parameter uncertainty makes the SCC hard to estimate. Turning to other contributions, the *Stern Review's* (Stern, 2006) recommendations imply a tax of approximately $300 (see Nordhaus, 2007). Daniel et al. (2019) find a declining SCC path that starts at $125 per ton in their base calibration, while Cai and Lontzek (2019) find a range of $60–$100 for the SCC.

Assuming unchanged emissions after the introduction of a tax, a $20 and $100 carbon tax would correspond, respectively, to 0.85% and 4.25% of global economic output.

These differences are economically significant. In 2018, global emissions stood at 36.6Gt while global GDP was $85.9 trillion.[7] Assuming unchanged emissions after the introduction of a tax, a $20 and $100 carbon tax would correspond, respectively, to 0.85% and 4.25% of global economic output. Since *all* current taxes represent 15% of global GDP,[8] the resulting tax increase would range between 5% and 28%.

In spite of these varied results, we find two areas of consensus in the literature. First, delaying mitigation is costly. Models recommend different levels of mitigation today, but most models imply that starting today is less painful than starting tomorrow. Indeed, Daniel et al. (2019) find that delaying mitigation for a decade would generate damages equal to a permanent, recurring 20% decrease in annual GDP. Nordhaus (2018a) mentions that the SCC has risen with time because mitigation has been delayed. In the original paper introducing the DICE model (Nordhaus, 1992) the initial carbon tax compatible with the optimal path was a mere $5 per ton (approximately $10 after adjusting for inflation), compared to a starting point of around $35 today.

A second area of consensus is the insurance value of mitigation efforts, especially against the possibility of catastrophic damages. Daniel et al. (2019) take a broad view of risk and emphasize that, given our incomplete knowledge, damages from climate change could be much worse than expected. Not only do we not know the probabilities of catastrophic damages, but we also do not know the threshold above which the climate "tips over" to a catastrophic outcome. Tipping points are thresholds above which sudden and irreversible changes to the climate occur. For example, once the Greenland ice sheet completely melts, the resulting sea level rise would be virtually impossible to reverse. Several models include tipping points: recent contributions include Cai and Lontzek (2019), Daniel et al. (2019), Lontzek et al. (2015) and Lemoine and Traeger (2014).

The possibility of irreversible changes increases the value of mitigation efforts and hence the value of the social cost of carbon.

Kopp et al. (2016) report that two-thirds of the SCC in the DICE model is due to catastrophic damages. The possibility of irreversible changes increases the value of mitigation efforts and hence the value of the SCC.

In summary, the estimated value of the SCC is sensitive to model assumptions, especially those that pertain to discounting. Most of the literature suggests that mitigation is less costly if undertaken early and more valuable when uncertainty is large. Although the conventional view (Nordhaus, 2019) is that the SCC should start at a moderate level and gradually increase, risk management could dictate a higher SCC instead. Vigorous mitigation today has insurance value and might spur innovation that makes green technologies less costly (Acemoglu et al., 2012). These facts have implications for policy making, which we explore next.

4. Economic Mechanisms for Curbing Emissions

In most countries, companies compete with one another to produce goods and services that consumers want under laws and regulations established by governments. Therefore, both the public and private sectors have important roles to play in curbing carbon emissions. We first consider different policy-making choices, including carbon pricing initiatives, regulatory policies, and research and development. We then look at progress made in the private sector.

4.1. CARBON PRICING

A key function of prices in competitive markets is to process information and guide the efficient allocation of resources. Therefore, carbon pricing can send information to market participants about the environmental impact of carbon-intensive goods and services through higher prices. Producers can react to that information by substituting toward less carbon-intensive inputs or production technologies (e.g., replacing coal-based energy with nuclear or renewable energy). The same logic applies to consumers. Carbon pricing can also send entrepreneurs a signal to innovate and develop more efficient, less carbon-intensive methods of production or to develop technologies that mitigate the impact of carbon emissions, such as carbon-removal and carbon-capture technologies.

Some argue that a similar outcome could be obtained through direct intervention—for example, by banning carbon-intensive goods and services. The key difference is that carbon pricing lets agents decide how to adjust their behavior to the higher cost of carbon emissions. In well-functioning markets, this adjustment process leads to a more efficient outcome than direct intervention, which is why carbon pricing has a prominent place in current policy debates.

There are two major carbon pricing mechanisms: carbon taxes and cap-and-trade systems.

There are two major carbon pricing mechanisms: carbon taxes and cap-and-trade systems. According to the World Bank (World Bank, 2020), as of early 2020, there were 61 planned or implemented carbon pricing initiatives worldwide, covering about 22% of global GHG emissions. Of those, 30 were carbon tax schemes and 31 were cap-and-trade systems.

As mentioned earlier, carbon emissions related to climate change represent a negative externality. The standard theoretical solution to a problem of negative externalities is to impose a tax that equates the private marginal cost of the externality to its social marginal cost (this is known as a Pigouvian tax). Therefore, in the case of climate policy, the tax should be set to equal the SCC. While this is theoretically straightforward, practical difficulties in calculating the SCC may explain why real-world carbon taxes vary widely and tend to be below SCC estimates. For instance, in the 30 carbon tax initiatives identified by the World Bank, taxes range from less than $1 to $119 per ton. Only six countries impose a carbon tax greater than $35 per ton, the SCC estimated by Nordhaus (2019).

The difficulty in calculating the SCC might have also led to policy proposals that are more focused on temperature targets rather than explicit carbon prices. Notably, the Paris Agreement seeks to keep the increase in global mean surface temperature to under 2°C above pre-industrial levels. The carbon tax required to meet such a target would be so high that the abatement costs would likely exceed the benefits of those carbon abatement measures (see **Exhibit 7**). Nordhaus's work suggests that the optimal policy path leads to a temperature increase of 3°C by 2100 (Nordhaus, 2019), which implies that measures seeking to limit climate change to less than 3°C do not, *as of today*, pass the cost-benefit analysis test.

Exhibit 7: Carbon Taxes in 2010 Dollars per Ton of CO_2 Emissions

	2015	2020	2025	2030	2050
Optimal Tax Based on Nordhaus's Estimate of SCC	29.5	35.3	49.1	64.0	153.5
Optimal Tax Necessary to Limit Climate Change to Less than 2.5°C	184.1	229.0	284.0	351.0	1008.4

Source: The Royal Swedish Academy of Sciences (2018) "Scientific Background on the Sveriges Riksbank Prize in Economic Sciences in Memory of Alfred Nobel 2018: Economic Growth, Technological Change, and Climate Change."

The amount of the carbon tax is not the only key consideration when it comes to analyzing the costs and benefits of a carbon pricing approach to curbing emissions.

The amount of the carbon tax, however, is not the only key consideration when it comes to analyzing the costs and benefits of a carbon pricing approach to curbing emissions. A second important consideration related to carbon taxing is to what goods and services it should be applied. The consensus among economists is that it should be applied uniformly across all goods and services, based on their carbon content, and applied at the point emissions enter the economy (energy production, transportation, etc.). This design prevents so-called carbon leakage, which can occur when a policy impacts only some sectors of the economy or some jurisdictions. Similarly, economic analysis suggests that rebates should be given for activities that result in permanent carbon capture or reutilization.

A third important consideration is over which jurisdiction the tax should be instituted. Local taxation could merely induce firms to relocate production to jurisdictions with more lenient regulation, an example of carbon leakage. Indeed, if the taxing jurisdiction is one in which economic activity is already relatively green, shifting some of that activity to polluting jurisdictions because of taxes could lead to more pollution for the same amount of economic activity.

Two recent carbon tax proposals seek to address some of those issues. In early 2019, the Climate Leadership Council released a plan for the US endorsed by a group of over 3,500 economists, including most living Nobel laureates in economics, former chairs of the President's Council of Economic Advisers, and many other prominent economists. The proposal would impose an initial economy-wide tax of $40 (in 2017 dollars) per ton on CO_2 emissions in 2021. The tax would then increase every year by at least 5% above inflation to achieve a goal of cutting US emissions by half by 2035 relative to 2005, a more ambitious schedule than the one set in the Paris Agreement (in which emissions are cut by 26–28% by 2035).

The plan has three additional points. First, the tax would be revenue neutral and would replace various carbon-related regulations that do not rely on price signals. The authors of the plan contend this would have a positive impact on US economic growth by substituting costly and cumbersome regulations with simpler and more transparent carbon taxes. Second, the revenue from the tax would be redistributed to US citizens through equal lump-sum rebates, which addresses questions about the incidence and fairness of the tax. And, third, to promote and protect US competitiveness and to encourage other countries to adopt similar policies, the tax would include a border carbon adjustment to be applied on both exports and imports. Exports to countries without a comparable system would receive rebates for the carbon taxes paid, and imports of carbon-intensive goods from such countries would face fees (tariffs) on the carbon content of those goods. This border adjustment means that the tax would, for all practical purposes, be international in nature, as it would apply to domestic activities and foreign economic activity associated with exports to the US.

The second proposal, which relies more on international cooperation, is the establishment of international climate clubs. Because limiting climate change is a global public good that all countries enjoy regardless of how much they contribute to the production of that good by reducing their emissions, countries have a perverse incentive to rely on the efforts of other countries to achieve the desired reductions in carbon emissions. To eliminate that incentive, Nordhaus (2015) proposes the establishment of an international climate club among different nations. Club members would agree to establish mechanisms to curb emissions—say, for instance, a uniform carbon tax of $50 per metric ton—and would impose penalties to nonmembers in the forms of tariffs on goods exported from nonmember countries to member countries—say, for instance, a uniform tariff of 3%.

From an economic perspective, the international climate club proposal of Nordhaus and the US carbon tax proposal of the US Carbon Leadership Council share two key features of using carbon pricing as a mechanism to curb emissions.

From an economic perspective, the international climate club proposal of Nordhaus and the US carbon tax proposal of the US Carbon Leadership Council share the two key features of using carbon pricing as a mechanism to curb emissions: first, a carbon tax to incentivize those inside the taxed jurisdiction(s), and, second, a trade tax (border adjustment tax or a tariff) to incentivize those outside the taxed jurisdiction(s). Note that, under both schemes, corporations cannot avoid the tax by relocating their operations.

Cap-and-trade systems are another mechanism to implement carbon pricing. The largest cap-and-trade system in the world is the European Union's Emission Trading Program, started at the beginning of 2005, which applies to more than 11,000 power and heat-generation plants, energy-intensive industrial sectors, and airlines across all the member countries of the European Union plus Iceland, Liechtenstein, and Norway.[9] The goal of the system is to reduce emissions from the sectors covered by the program relative to their 2005 levels by 21% in 2020 and 43% in 2030.

The intuition behind a cap-and-trade system comes from the work of Nobel laureate economist Ronald Coase.

The intuition behind a cap-and-trade system comes from the work of Nobel laureate economist Ronald Coase. Coase's suggestion to deal with externalities was to internalize them by creating property rights related to the externality—in the case of climate change, carbon emissions—and allowing economic agents to freely trade those rights as they saw fit (Coase, 1960). In this way, those economic agents that value those rights the most would be the ones that end up owning them.

Many of the same considerations that apply to a carbon tax apply to a cap-and-trade system. In fact, if the carbon emission permits in a cap-and-trade system are auctioned off rather than given away by regulators, the systems are very similar (Mankiw, 2009). In the case of carbon taxes, the key is to get the level of the tax roughly equivalent to the SCC; in the case of a cap-and-trade system, getting the correct number of emission permits is one of the keys for this approach to be effective in curbing overall emissions. Too many permits would lead to more emissions than socially optimal; too few would unduly reduce current standards of living.

In the case of carbon taxes, the key is to get the level of the tax roughly equivalent to the social cost of carbon. In the case of a cap-and-trade system, getting the correct number of emission permits is one of the keys for this approach to be effective in curbing overall emissions.

One important difference between carbon taxes and a cap-and-trade system is that, while the former fixes the price of emitting carbon and lets the quantity of carbon vary, the latter fixes the quantity and lets the price vary. As a result, prices under quantity-based systems tend to be more volatile than under price-based systems (Weitzman, 1974; Nordhaus, 2007). Because price stability is an important and desirable feature of the system, a carbon tax may be preferable to a cap-and-trade system unless the latter allows for the storage of emission permits so that permits can be used when it is most cost-effective to do so, which could help dampen price volatility.

4.2 REGULATION-BASED POLICIES

In addition to pricing mechanisms, governments can enact regulations that directly target carbon-intensive activities. Since most economic activity involves GHG emissions, regulations can target a wide range of sectors: energy, transportation, and construction are obvious examples. Rather than provide a comprehensive overview, we emphasize two major points.

First, carbon pricing may be a more effective approach than regulation. Carbon pricing dictates the goal (reduce emissions) and gives flexibility to firms and consumers on how to reach it. By contrast, regulations are more prescriptive and may lead to an inefficient outcome. For instance, regulations could prescribe fuel efficiency standards for gasoline cars. Conforming to these new standards is costly and may require additional R&D spending by carmakers or changes to production processes. The key point is that these same resources could potentially have been used to achieve a greater reduction in GHG emissions at the same cost. Indeed, the most cost-efficient way to reduce emissions may be to improve electric cars or encourage carpooling, rather than to spend resources to upgrade gasoline cars. Carbon pricing avoids this pitfall by encouraging firms and consumers to reduce their emissions at the lowest possible cost. Regulations can also have unintended effects: if more efficient cars make driving cheaper by requiring less fuel, consumers may offset efficiency gains by driving more.

Since most human activity has environmental effects, regulations need to take a holistic approach to be fully effective.

Second, since most human activity has environmental effects, regulations need to take a holistic approach to be fully effective. For example, a carbon tax could induce employees to move closer to work to reduce their fuel consumption. However, if zoning laws result in high rents in urban areas, people may be reluctant to move—housing and environmental policies are effectively offsetting each other. By contrast, if moving is cheap, a small carbon tax may be enough to induce people to move and reduce their emissions significantly. One corollary is that regulations can be used to remove barriers to adaptation and mitigation. In this example, zoning rules that facilitate new housing construction could help reduce emissions.

4.3 RESEARCH AND DEVELOPMENT POLICIES

The economic case for government support of research and development to address climate change is very similar to the case for pricing carbon emissions. Long-term economic growth depends on innovation and technological progress, a fact first established by Solow (1956; 1957). Innovation produces positive externalities (North, 1981; Romer, 1990) because new ideas are both *nonrival* (many people can use them simultaneously) and *nonexcludable* (those who own the innovation cannot easily prevent others from benefiting). Therefore, just as the divergence between the private and social costs of pollution leads to excessive GHG emissions, the divergence between the private and social benefits of R&D can lead to an insufficient research effort in developing new climate-related technologies.

With well-defined property rights and proper incentives, which depend on the legal and regulatory framework established by governments, competitive markets tend to do a good job of allocating resources efficiently.

In theory, governments can address this suboptimal outcome in at least a few ways. First, they can incentivize the production of new ideas by granting patents that confer monopoly rights to their owners for a limited amount of time. Second, they can grant tax credits or subsidies for R&D and directed technological change toward clean energy or, more broadly, toward climate change mitigation technologies (Acemoglu et al., 2012). Although governments have historically had a mixed record in this area (Gillingham and Stock, 2018; Stock, 2020), tax credits and subsidies can promote technologies that mitigate carbon emissions and climate change. Finally, governments can also fund basic scientific research related to climate change. Because some of this general scientific research has the properties of a public good and may not have direct and immediate commercial applications, the private sector may underinvest in this type of research, leaving a role for the government (McAfee, 2019).

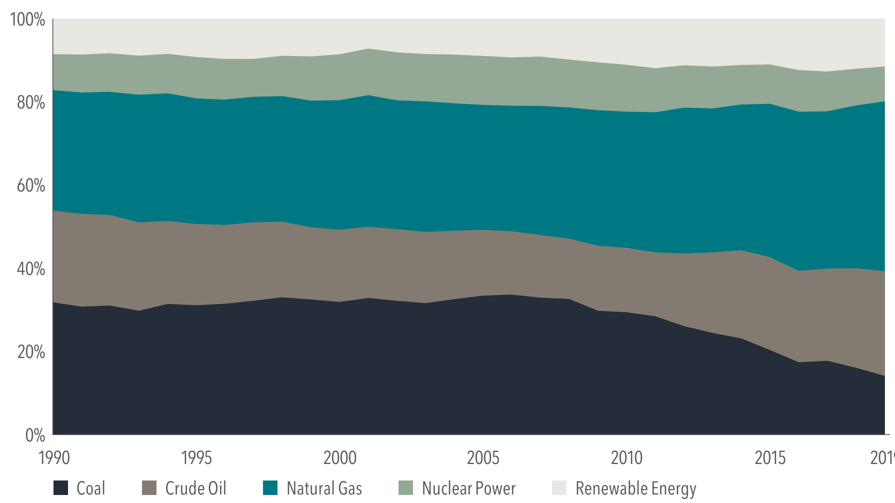
4.4 PRIVATE SECTOR SOLUTIONS

With well-defined property rights and proper incentives, which depend on the legal and regulatory framework established by governments, competitive markets tend to do a good job of allocating resources efficiently. Profit-maximizing firms have an incentive to economize on the use of resources, limit waste, and increase efficiencies through innovation and technological change. There is ample evidence that this has happened in many sectors of the economy, with a positive impact on the environment and carbon emissions.

One example is the US energy sector. Over the last 30 years, there has been a shift toward cleaner sources of energy thanks to innovations in fossil fuel extraction methods and the greater commercialization of renewable sources of energy. **Exhibit 8** shows the evolution of US primary energy production from 1990 to 2019. Coal-based energy, which emits over 200 pounds of CO_2 per million British thermal units (Btu),[10] decreased from 32% of all energy produced in the US in 1990 to 14% in 2019. In contrast, energy from natural gas, which emits 117 pounds of CO_2 per million Btu, increased from 29% in 1990 to 41% in 2019. The decline of coal usage has likely been driven in part by market forces, as generating energy from coal is expensive relative to other energy sources on a new-build basis.[11]

Energy from renewable sources, such as wind, solar, hydroelectric, and biomass, also increased between 1990 and 2019, from 9% to 12%. Wind and solar energy, which barely existed in 1990, accounted for 3% and 1%, respectively, of all primary energy produced in the US in 2019. If the cost of generating wind and solar energy continues to decline and the technology for storing electricity from renewables continues to improve, these renewable sources of energy will most likely continue to gain market share in the coming years, especially if the social cost of carbon is internalized through a carbon pricing system.

Exhibit 8: US Primary Energy Production by Source, *1990–2019*



Source: US Energy Information Administration (2020).[12]

In agriculture, innovations in farming have led to a decrease in the total amount of land used for agriculture and a significant increase in the total factor productivity of the US agricultural sector. The US Department of Agriculture estimates that land and energy used for agriculture decreased by 7% and 35%, respectively, between 1990 and 2017, the last year for which data are available.[13] During that time, total factor productivity increased by 38% and total agricultural output increased by 43%. The efficiency gains in agriculture mean that fewer resources, including land, are needed to feed a growing population and that some land previously used for agriculture can be repurposed for biological carbon sequestration.

The Environmental Protection Agency estimates that in 2018 the net carbon emissions removed from the atmosphere due to land use, land-use change, and forestry (LULUCF) activities were equivalent to about 12% of all US carbon emissions.[14] Gillingham and Stock (2018) point out that reforestation and other biological carbon sequestration approaches are among the lowest cost approaches to reducing GHG emissions.

Because what matters for climate change is not so much annual GHG emissions as the concentration of GHGs in the atmosphere, taking a ton of GHG out of the atmosphere permanently should generally be just as efficient in preventing climate change as not emitting one additional ton of GHG, all other things being equal. In recent years, we have seen the emergence of an industry engaged in alternative carbon capture and sequestration (CCS) and carbon capture and utilization (CCU) methods. The emergence of this industry is likely related to changing consumer demand. As consumer tastes and preferences have changed toward less-carbon-intensive goods and services, entrepreneurs are figuring out ways to turn waste, CO_2 emissions released into the atmosphere, into a valuable input in the creation of goods and services (CCU) or permanently bury that CO_2 underground (CCS).

As incomes per capita have risen and consumers have become more aware of climate change and its potential for severe consequences, they have begun to demand fewer carbon emissions. That demand for cleaner air is reflected in the goods and services companies produce and their carbon footprint.

There are additional examples of how we have been able to adapt and improve the efficiency of producing, transporting, and delivering goods and services. Examples range from more energy-efficient homes to smart phones to aluminum cans for beverages, which now weigh only 15% of what they used to. MIT scientist Andrew McAfee (2019) refers to this process as "dematerialization" and attributes it to four complementary causes: competitive markets, technological innovations, public awareness, and responsive government. As incomes per capita have risen and consumers have become more aware of climate change and its potential for severe consequences, they have begun to demand fewer carbon emissions. That demand for cleaner air is reflected in the goods and services companies produce and their carbon footprint.

The transition toward cleaner sources of energy and more efficient methods of production is reflected in US emissions over time. From 1990 to 2019, GDP per capita in 2010 dollars increased from $36,000 to $56,000, a 47% increase. To support this economic growth, primary energy production increased from 71 quadrillion Btu in 1990 to 101 quadrillion Btu in 2019, an increase of 43%. And yet, GHG emissions in the US only increased by 4% between 1990 and 2018, the last year for which the EPA has available data, from 6,437 million metric tons of CO_2 equivalents to 6,677 million metric tons. If we follow the Paris Agreement protocol and take 2005 as our base year, US emissions declined by about 10%, from 7,392 Mt of CO_2 in 2005 to 6,677 Mt of CO_2 in 2018. If we consider CO_2 removal from the atmosphere by carbon sinks, net carbon emissions from 2005 to 2018 also declined by about 10%, from 6,577 Mt of CO_2 to 5,903 Mt of CO_2.

According to the World Bank, CO_2 emissions per unit of GDP declined by 45% between 1990 and 2016 in the US.

This is also reflected in the carbon intensity of US economic activity. According to the World Bank, CO_2 emissions in kilograms per dollar of US GDP (in 2010 USD) decreased from 0.536 in 1990 to 0.295 in 2016, the latest year for which data are available, a decline of 45%. Many other countries around the world have experienced similar decreases in their carbon intensity.

The main inferences from all that evidence are twofold. First, it is possible to decouple economic growth from pollution, carbon emissions, and environmental degradation. Second, the combination of efficient public policy, market incentives, technological innovation, and changes in public attitudes toward climate change can lead to significant reductions in carbon emissions and concentrations.

5. Implications for Investors

Our review of the scientific literature suggests that, among environmental issues, climate change stands out because of its scope and importance. Given its economic importance and global impact, climate change is likely to affect asset prices. Indeed, growing evidence shows that prices in a variety of asset markets incorporate information about climate risk. We discuss this literature in Section 5.1. We then examine the implications for investors from three different angles. Section 5.2 discusses the potential impact of climate risk on buy and sell decisions. Section 5.3 considers the use of climate risk information to maximize the value of existing holdings through investment stewardship. Section 5.4 examines the implications of the scientific evidence on climate change for investors pursuing sustainability goals.

5.1. CLIMATE CHANGE AND ASSET PRICES

The valuation equation provides a useful framework to think about the impact of climate change on asset pricing. It expresses asset prices as the present value of expected future cash flows:

$$p_t = \sum_{k=1}^{\infty} \frac{E[CF_{t+k}]}{(1+r)^k}$$

The valuation equation tells us that climate change can affect asset values through two channels: by changing expectations around future cash flows or by changing discount rates.

The equation tells us that climate change can affect asset values through two channels: by changing expectations around future cash flows or by changing discount rates. Discount rates, or, equivalently, expected rates of returns, could change because of changes in risk or changes in tastes and preferences.

Asset pricing theory (e.g., Merton, 1973) provides guidance about the link between expected returns and risk. In the Intertemporal Capital Asset Pricing Model (ICAPM), differences in expected returns are driven by differences in systematic, undiversifiable risk. Investors require higher expected returns to hold assets that expose them to adverse systematic changes in investment, consumption, and employment opportunities.

Our earlier discussion suggests that climate change has important effects on the economy. Climate change may alter weather patterns and the habitability of certain areas of the planet. These changes, in turn, may directly impact the operations of many companies and thus the real economy. This impact is often referred to as the physical risk of climate change.

Governmental and consumer responses to climate change are another source of uncertainty. For example, governments might force publicly traded companies to estimate and disclose their exposure to physical risks from climate change and how such risks are being managed and monitored. New taxes on greenhouse gas emissions are also possible. Both disclosures and taxes can lead to additional costs. Consumers may also demand goods and services to be produced in less carbon-intensive ways. All of these sources of uncertainty are referred to as the transitional risk of climate change.

Companies are likely to vary in their exposure to the potential physical effects of climate change (the physical risk of climate change). Similarly, companies are likely to vary in their exposure to the indirect effects of climate change, such as shifts in government regulation and taxation, as well as shifts in consumer demand (the transitional risk of climate change). Asset pricing theory implies that these cross-sectional differences in climate risk exposure are likely to lead to differences in expected returns.

Investors' tastes and preferences can also affect discount rates. Large demand for a specific set of assets could push up their prices and lower their expected returns. Fama and French (2007) explore the general impact of tastes and preferences on asset prices, while two recent studies (Baker et al., 2018; Pastor et al., 2020) focus specifically on tastes and preferences related to green assets. In both models, investors prefer green assets, which leads them to accept a lower expected return. In addition, the model of Pastor et al. (2020) implies that green assets have lower expected returns because they hedge climate risk.

In the valuation equation, information about climate risk is likely to affect not only discount rates but also future cash flows. For example, consider the possible introduction of a carbon tax. Such a tax would plausibly lower the expected cash flows of emission-intensive firms. At the same time, if the timing and magnitude of the tax are unknown, uncertainty could increase discount rates for firms vulnerable to the impact of the tax. Both effects could lead to lower asset prices for emission-intensive firms.

Overall, the evidence from academic research supports the predictions of valuation theory and shows that market prices reflect information about climate risk.

Because of the uncertainty around each step in the path from climate change to security prices, there is an ongoing debate among consumers, investors, and policy makers about whether climate change risks are priced correctly. We believe that, while not perfect, the market does a good job of incorporating publicly available information into prices. This includes information about variables investors disagree on and variables that are hard to forecast, such as inflation, unemployment, economic growth, and changes in regulation. Indeed, the performance data of money managers provide compelling evidence that professional investors have been unable to systematically outguess market prices.[15] We know of no compelling evidence that this observation does not hold for ESG-related risks, including risks related to climate change.

Overall, the evidence from academic research supports the predictions of valuation theory and shows that market prices reflect information about climate risk. For example, Schlenker and Taylor (2019) look at climate futures traded on the Chicago Mercantile Exchange between 2002 and 2019. Daily temperatures in a given month and location pin down the payoff of the contracts. The authors leverage the fact that short-term weather forecasts become unreliable after 10 days. Therefore, the price of the July contract on June 15 reflects investors' beliefs about the climate (average temperature in July) rather than short-term weather variation. The key finding of the study is that, from 2002 and 2019, warming trends predicted from climate models, inferred from market prices, and measured from observed temperatures all coincide. The study thus shows that investors transacting in the climate futures market have expectations in line with the scientific consensus. The unique setting of the study, in which asset payoffs depend on temperatures and nothing else, suggests that changes in prices are mostly driven by changes in expected cash flows. The setting also allows the authors to confirm that expectations are rational—investors do not systematically underestimate or overestimate future payoffs. This kind of judgment is essentially impossible with instruments such as stocks and bonds, whose cash flows can span long horizons and be influenced by confounding factors.

Another paper that examines whether investors react to climate information is Griffin et al. (2015). This paper finds that the stock prices of the 63 largest US oil and gas energy firms fell by 1.5% to 2% after the publication of a landmark paper in *Nature* (Meinshausen et al., 2009). The latter paper argues that most fossil fuel reserves could not be emitted if warming is to be kept under 2°C by 2050. Therefore, most reserves would become worthless under aggressive mitigation policies. Interestingly, markets reacted in the three days following the publication of the article in 2009, although the article was only publicized by the press a few years later. This finding suggests that markets react to new climate information quickly.

Academic research also suggests that companies (Chava, 2014; Delis et al., 2019) and municipalities (Goldsmith-Pinkham et al., 2019; Painter, 2020) with higher exposure to climate risk face a higher cost of capital. Painter (2020) notes that municipal bonds are an illuminating particular case because municipalities, unlike corporations, cannot relocate to avoid the physical effects of climate change. In a similar vein, buildings are essentially impossible to relocate. Hence, the real estate market represents another setting in which exposure to climate risk can more easily be measured. Two studies on the real estate market (Ortega and Taşpinar, 2018; Bernstein et al., 2019) focus on flooding risk and find that it is priced by investors. Bernstein et al. (2019) contend that, when beliefs about climate risk are heterogenous, "believers" could potentially sell to "non-believers" at a price that does not fully reflect climate risk. They find instead that flooding risk has a substantial impact on coastal property prices: houses exposed to sea level rise trade at a 7% discount to properties with similar characteristics. Interestingly, most of the discount is driven by houses that are not at risk of being flooded for another 50 years. The study thus suggests that investors consider the long-term implications of climate change and that prices can reflect climate risk even in decentralized, less liquid markets, such as real estate.

Measures of climate risk might be useful for the pursuit of higher expected returns only if they contain reliable information about the cross-section of expected returns beyond the information contained in current prices and profitability.

5.2. IMPLICATIONS FOR SECURITY SELECTION

Overall, the literature provides compelling evidence that the impact of climate change risk on asset prices is captured well through the valuation framework. This suggests that investors can use current prices and reliable proxies for expected future cash flows (such as current profitability) to identify and pursue systematic differences in expected returns. Measures of climate risk might be useful for the pursuit of higher expected returns only if they contain reliable information about the cross-section of expected returns beyond the information contained in current prices and profitability.

Research at Dimensional (Dai and Meyer-Brauns, 2020) examines if climate variables, such as GHG emission intensity, levels of emissions, or changes in emissions, provide additional information about future profitability beyond that contained in current profitability. Using a sample from 2010 to 2018, they find that cross-sectional differences in GHG emissions do not predict cross-sectional differences in future profitability once current profitability is controlled for. They also find that different measures of GHG emissions have no reliable effect on returns after controlling for firm size, relative price, and profitability in the case of stocks and forward rates in the case of bonds.

The study's findings suggest that the impact of climate change on the expected returns of high-emissions firms, for example, is well captured by prices and proxies for expected future cash flows. This evidence is consistent with the broader literature, which finds that ESG variables are largely subsumed by known drivers of expected returns (Bebchuk et al., 2013; Polbennikov et al., 2016; Blitz and Fabozzi, 2017).

An effective way to incorporate ESG considerations in investment strategies is through the promotion of good corporate governance practices overseen by strong boards representing shareholder interests.

In summary, ample empirical asset pricing research shows that climate change considerations and their expected effect on a company's business are incorporated into asset prices and do not appear to contain additional information about expected returns. In our view, a systematic and broadly diversified investment approach that focuses on reliable drivers of expected returns (size, value, and profitability in equities and forward rates in fixed income) remains the most reliable way for investors to pursue higher expected returns.

5.3. INVESTMENT STEWARDSHIP

As previously discussed, valuation theory suggests that a company's environmental practices (as well as its social and governance practices) are reflected in the price of its publicly traded securities through their impact on the company's expected future cash flows and discount rates. Therefore, improvements to a company's ESG practices may increase shareholder value through a combination of lower discount rates and higher expected cash flows. An effective way to incorporate ESG considerations in investment strategies is through the promotion of good corporate governance practices overseen by strong boards representing shareholder interests.

Investment stewardship activities, however, are not free: there are costs and benefits associated with company engagement and proxy voting. Similarly, the actions that stewardship activities may advocate for, such as increased disclosure, have costs and benefits. One important implication is that investment stewardship should focus on the issues that have the strongest ramifications for shareholders. Scientific research suggests that, for many firms, climate risk is such an issue. Indeed, few firms are completely insulated from climate change, potential carbon taxation, or shifting consumer tastes toward sustainability-focused products.

Another important implication is that investment stewardship should take a case-by-case approach to shareholder proposals. For example, proposals requiring companies to disclose hard-to-identify and hard-to-measure impacts on the environment might divert company resources from better uses and may even reduce shareholder value. However, if a company publicly recognizes (in its regulatory filings) the materiality of a climate risk issue, yet does not provide adequate information for shareholders to assess the company's current handling of the issue, a proposal that asks for adequate information to assess the handling of material risk might be beneficial. Examples include policies governing the handling of each material risk, a description of management-level roles/groups involved in oversight and mitigation of each material risk, a description of the metrics used to assess the effectiveness of mitigating each risk, the frequency at which performance against these metrics is assessed, and a description of how the board is informed of material risks and the progress against relevant metrics.

Similarly, when a company has demonstrated a lack of response to shareholder concerns related to a serious climate change risk issue, demonstrated a lack of follow-through on prior commitments to report requested information, or experienced recent failings related to the issue at hand, a proposal requiring more information from company management might help protect shareholder value. In summary, investment stewardship should encourage management to have processes to address material climate risks and to provide shareholders with information to assess the efficacy of those processes.

5.4. SUSTAINABILITY-FOCUSED STRATEGIES

Effective sustainability strategies should target measurable sustainability issues that have significant potential impact on the environment now and in the future. Leading environmental scientists have identified climate change as the most important environmental sustainability issue and GHG emissions as the primary contributor to climate change. Therefore, GHG emissions should be a key consideration when designing investment strategies focused on environmental sustainability.

Robust sustainability strategies can target focused and measurable sustainability goals, such as a reduction in GHG emissions exposure, without sacrificing sound investment principles or the pursuit of higher expected returns. They can target well-defined sustainability objectives within a broadly diversified, systematic investment framework. For instance, since firms can be ranked based on their GHG emissions, portfolio weights can be derived by starting from market capitalization weights and then overweighting firms with lower emissions and underweighting firms with higher emissions rather than

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relying only on exclusions of the worst polluters. Depending on the eligible universe, a weighting approach combined with targeted exclusions can be used to construct a broadly diversified portfolio with meaningfully reduced exposure to greenhouse gas emissions. Broad diversification not only allows for the reliable pursuit of higher expected returns and flexible trading, but also provides opportunities to incorporate additional environmental issues, such as land use, water use, toxic spills and releases, and palm oil, with the goal of emphasizing companies with better sustainability profiles.

Focusing on GHG emissions can also results in greater transparency for investors. Berg et al. (2020) document conflicting ESG ratings from different providers, including conflicting environmental ratings. They find that differences arise in part because rating providers use different variables to measure the same concepts, that is, because rating providers do not fully agree on the definition of "sustainability" or "good governance." Emphasizing GHG emissions can help sidestep this issue by providing investors with a well-defined way to evaluate the environmental sustainability characteristics of their portfolio.

6. Conclusion

We make two concluding remarks. First, when analyzing the implications of climate change, economic reasoning offers a powerful unifying framework. Investors, policy makers, and citizens must all grapple with the uncertain effects of climate change and weigh costs and benefits to find the best course of action. Since decision making under uncertainty is a central theme in economics, the connection with climate change is a natural one. Simple, tried-and-true concepts—the value of insurance in the face of uncertainty, the importance of incentives to steer behavior, and the opportunity cost of investment—can all help investors understand the potential ramifications of climate change.

Second, a sound investment philosophy can help investors organize their thinking around climate change. As we have emphasized throughout this paper, climate science, climate economics, and sustainability investing are all active, burgeoning fields. Therefore, investors face voluminous and sometimes contradictory academic evidence. Here, too, simple, tried-and-true investing principles can help: using information in current market prices throughout the investment process, evaluating the costs and benefits of investment stewardship activities, having well-defined investment goals, and maintaining broad diversification are keys to a successful investment experience. In our view, these principles provide a robust framework to help investors navigate the risks and opportunities around climate change.

1. Authors' own calculations based on the Maddison Project Database 2018 (Bolt et al., 2018). Living standards are measured by real GDP per capita.
2. At the time of writing, the Sixth Assessment Report is scheduled for release in 2022. The IPCC Assessment Reports synthesize evidence from many sources and seek to summarize the scientific consensus on climate change.
3. The Paris Agreement is an accord signed in 2016 within the United Nations Framework Convention on Climate Change to keep the long-term increase in global average temperature under 2°C above pre-industrial levels. As of February 2020, 189 nations had become party to it.
4. Global Carbon Atlas, 2018. Data retrieved from *globalcarbonatlas.org/en/CO2-emissions* on March 26, 2020. See Le Quéré et al. (2018) for more information about the underlying data. Europe corresponds to EU 28 in the Global Carbon Atlas.
5. "Climate Watch (CAIT): Country Greenhouse Gas Emissions Data," World Resources Institute; data retrieved from *climatewatchdata.org/ghg-emissions* on July 10, 2020.
6. Strictly speaking, at the net carbon interest rate (Nordhaus, 2007), which accounts for CO_2 reabsorption.
7. "GDP (current US$)," World Bank. *data.worldbank.org/indicator/NY.GDP.MKTP.CD*.
8. "Tax revenue (% of GDP)," World Bank. *data.worldbank.org/indicator/GC.TAX.TOTL.GD.ZS*.
9. "EU Emissions Trading System (EU ETS)," European Commission. *ec.europa.eu/clima/policies/ets_en*.
10. "How Much Carbon Dioxide Is Produced When Different Fuels Are Burned?" US Energy Information Administration. *eia.gov/tools/faqs/faq.php?id=73&t=11*.
11. "Annual Energy Outlook 2020 with Projections to 2050," US Energy Information Administration's Office of Energy Analysis. *eia.gov/outlooks/aeo/pdf/AEO2020%20Full%20Report.pdf*.
12. *https://www.eia.gov/totalenergy/data/annual/index.php*.
13. "Agricultural Productivity in the US," Table 1: Indices of Farm Output, Input, and Total Factor Productivity for the United States, 1948–2017, USDA, Economic Research Service. *ers.usda.gov/data-products/agricultural-productivity-in-the-us/*.
14. "Sources of Greenhouse Gas Emissions: Land Use, Land-Use Change, and Forestry Sector Emissions and Sequestration," US Environmental Protection Agency. *epa.gov/ghgemissions/sources-greenhouse-gas-emissions#land-use-and-forestry.*
15. See, for instance, Dimensional's 2020 Mutual Fund Landscape study or S&P SPIVA reports (*spindices.com/spiva/#/reports*).

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