Pricing climate change as a mortal threat

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Abstract

Mitigation of global warming and aggregate consumption are chosen to maximize the product of expected lifetime and population. Constant relative risk aversion (CRRA) utility is parameterized using a panel of annual NASA and World Bank data covering 185 countries from 1990 to 2018. Optimal CO_2 taxes are proportional to consumption per capita and, therefore, vary tremendously from poor to rich countries. Assuming equilibrium climate sensitivity of 2.5°C, base case worldwide average social costs start at \$10/tCO_2 in 2020 (when the anomaly in GMST is about 1°C) and rise to \$125/tCO_2 in 2100 in a "2° world", and to \$162/tCO_2 in 2100 in a "3° world". The latter rises to \$291/tCO_2 under high risk aversion, and falls to \$136/tCO_2 under low risk aversion, all in 2020USD. Under weak assumptions, though, applying such averages as policy globally lowers social welfare, as measured; only progressive climate policy increases social welfare, implying that emissions should be taxed or regulated where they occur, not at the "source" if the price there is determined globally.

Keywords: climate; CO_2; tax; mortal

JEL codes: Q54; J17

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1 Introduction

Stakeholders across the spectrum[1] recommend a tax as a mechanism to optimize emissions of greenhouse gases. Broadly, the optimal tax rate is derived in two stages: 1) estimating the sensitivity of climate to emissions; and 2) monetizing changes in climate. The first stage is climate science, and largely beyond the scope of this paper. The second stage is economics, in which we often find optima where society's incremental rate of substitution of money for a good (or bad) equals its incremental monetary cost. The instant study is an estimate of society's incremental rate of substitution of consumption of goods for reductions in global mean surface temperature (GMST), as a function of the latter; that is, the social demand curve for reductions, a.k.a. "mitigation", in GMST.

Estimation of demand should capture the supply of "adaptation", like the dykes around Amsterdam, a substitute for mitigation, but interact with the supply of mitigation, scalable backstop technologies for which may obviate the upper reaches of the demand price. These are in rapid developmental flux, but some favorites include solar energy stored as chemical energy (e.g., flow batteries, or sunlight heating ammonia, splitting it into N_2 and H_2, and then combining those molecules into ammonia to release the chemical energy) or as potential energy (e.g., raising mass to store energy and lowering mass to release that energy).[2]

This is hardly the first such study, but the approach here is to equate the incremental effects on the number of human life-years of consumption and reductions in GMST. Previous such studies often rely on aggregation of, say, wage-premia attached to marginal mortal risk in dangerous occupations into the value of a "statistical life", when the probabilities of death add to unity. This approach to valuing mortality was formalized by Mishan (1969). For example, Hsiang et al. (2017) write

> To value mortality, we follow the US Environmental Protection Agency (EPA) in applying the value of a statistical life (VSL) of $7.9 million (in 2011$) as a benchmark estimate of Americans' "willingness-to-pay" to reduce mortality risk. This includes both market and non-market costs. (p. 52)

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[1] Both members of the Biden Administration (Waldman (2021)) and the International Gas Union (DiSavino (2021)) have expressed support.

[2] "Gravity Energy Storage" is featured in Lazard's Levelized Cost of Storage 6.0 (p. 11).

But Hammitt and Treich (2007) write

> Economists have … been cautious to make clear that the standard valuation approach – purposely labeled the "value-per-statistical-life" (VSL) approach – applies only when changes in risk are small and similar among the affected population. (p. 46)

And Tol (2005) writes, with regard to climate change,

> Differences in vulnerability will not only be observed between regions, but also within them. Some individuals, sectors, and systems will be less affected, or may even benefit, while other individuals, sectors, and systems may suffer significant losses. (p. 2067)

That is, neither of the crucial conditions for application of the standard VSL approach, a type of willingness to accept or pay valuation, are met in the case of climate change. Part of the contribution of this article is to move away from the VSL approach in monetizing climate change.

Weitzman (2010; p. 65) also asks "What is the total willingness to pay as a fraction of current consumption … that the representative agent would accept to eliminate the temperature [anomaly] $T > 0$ at time $t > 0$ by reducing it to $T = 0$?"

Weitzman uses both the terms "accept" and "pay". Broome (1978) posits that a person might not *accept* any finite amount of money [such as $7.9 million] to go from a situation like $T > 0$ to $T = 0$ if she knew that she would die as a result. Therefore, it would not be just to use what people who do not know they are going to die are willing to accept to increase the probability of dying as the value of the life of someone who will die with certainty, even if those increases add to unity. Thus, a willingness to *accept* criterion, including VSL, is problematic for valuing mortality when it is known with certainty that *someone* will die, even if the identity of the decedent is unknown.

I think a willingness to *pay* criterion is also problematic. If compensation of losers is required, in order to make the willingness to pay criterion Paretian, non-existence of willingness to accept money on the part of someone who is certain to die re-emerges as an obstacle; it may be impossible to compensate losers if the loss is life, itself. Also, if I am destitute, and you point a gun at me and ask what I am willing to *pay* you to spare my life, I will honestly say "zero", and then I will die; even if I regard my life as precious, a willingness to *pay* criterion assigns it zero social value if I have no money. Similarly, the willingness to *pay* of a representative global agent may undercount the human cost of climate change (or the value of consumption of economic goods) in poor countries. This is sometimes referred to as the “climate justice” issue. Tol (2005) also writes

> Developing countries are more vulnerable to climate change than developed countries because their economies rely more heavily on climate-sensitive activities, many already operate close to environmental and climatic tolerance levels, and the lack of technical, economic and institutional resources may prevent successful adaptation. (p. 2067)

Broome concludes that mortality should not be monetized. While I agree that Mishan’s approach is problematic, I note that Broome himself writes

> But if a death counts as an infinite cost, measured in money, then it seems that a cost-benefit analysis will automatically reject any project which causes anybody’s death (***except possibly one which also saves lives***). (p. 92; emphasis added)

Both consumption and climate affect mortality. That economic growth extends human lifetimes is widely understood[3]: Better diet, housing, sanitation, and medical care are all components of growing aggregate consumption, and these goods extend the duration of human life. Climate and weather, on the other hand, are chaotic dynamic processes: Small changes in initial conditions lead to large variation in state variables, which may be random, but may also be deterministic. At a higher GMST, molecules move more rapidly[4], accelerating the chaotic process, some realizations of which are disastrous in their effects on the stock of manufactured and natural capital. Because the process is accelerated at a higher GMST, these disasters occur more frequently, which reduces human lifetimes. According to the U.S. Environmental Protection Agency (EPA), “Many extreme temperature conditions are becoming more common… Heat waves are occurring three times more often than they did in the 1960s… In recent years, a

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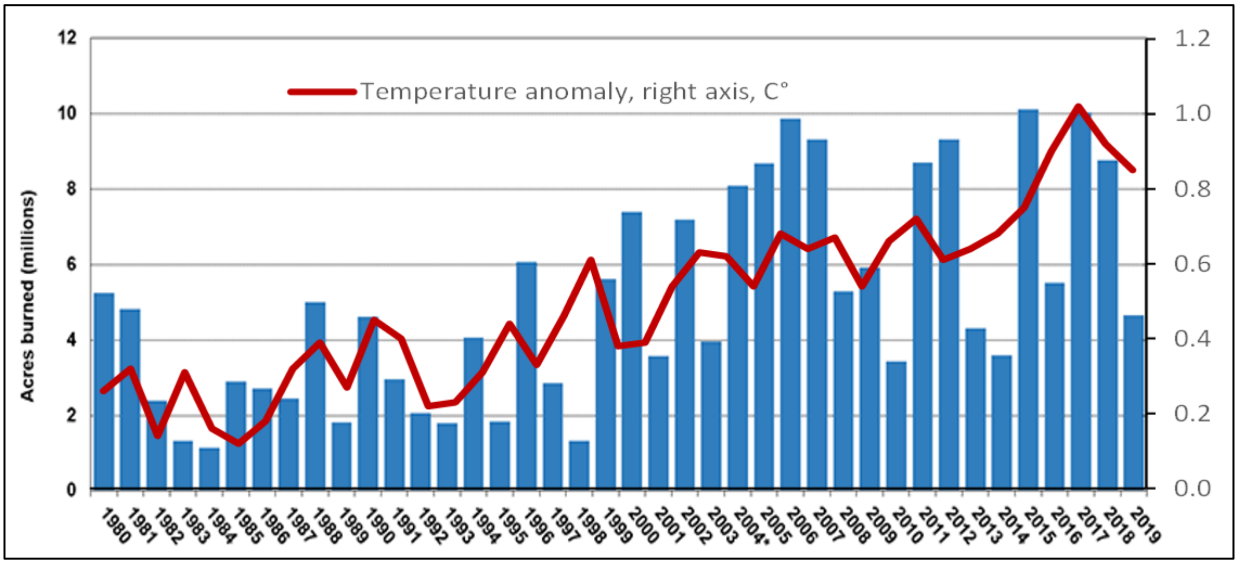
[3] See, for example, Pettinger (2019).

[4] “The average speed c of molecules of mass m at a temperature T is $c = (8kT/\pi m)^{1/2}$, and so the average speed increases with the square root of the temperature.” k is Boltzmann's constant, a fundamental constant of nature. Chemistry Explained; http://www.chemistryexplained.com/St-Te/Temperature.html#:~:text=At%20a%20molecular%20level%2C%20the%20temperature%20of%20a,of%20molecules%20in%20a%20state%20of%20high%20energy, accessed June 1, 2021.

higher percentage of precipitation in the United States has come in the form of intense single-day events."[5]

The EPA writes "...climate change threatens to increase the frequency, extent, and severity of fires through increased temperatures and drought", though their "data do not show an obvious trend" in the frequency of wildfires between 1980 and 2020.[6] An increased extent of wildfires, however, is another possible result of higher GMST. This is shown in Figure 1.

Figure 1: Annual number of acres burned in wildland fires in the United States; 1980-2019



Sources: National Interagency Fire Center via Insurance Information Institute; https://www.iii.org/fact-statistic/facts-statistics-wildfires, accessed March 20, 2021; National Aeronautic and Space Administration

Proof that the trends shown in Figure 1 are **causally connected** is beyond the scope of this paper. Other reasons for the increase in acreage burned may include incursion of human habitat on wildlands, transformation of agricultural land to forest as farmland has become more productive, and changes in forest management practices, like clearcutting giving way to selective logging.

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[5] EPA; https://www.epa.gov/climate-indicators/weather-climate, accessed May 25, 2021.
[6] EPA; https://www.epa.gov/climate-indicators/climate-change-indicators-wildfires, accessed May 25, 2021.

> Every year, thousands of acres of forest burn down. Clearcutting provides a barrier that can be thought of as a fire line. Without fuel to burn, the fire can't advance, which makes containment much easier. In addition, in the process of clearcutting, debris is usually piled up and purposely burned, removing yet more fuel. This is done mainly to make replanting easier, however it does also aid with controlling the spread of wildfire.[7]

Figure 2 shows that the states where burn has increased the most are also the top lumber-producing states, and clearcutting went into decline when acreage burned increased.

> The Forest Service began to back away from this controversial harvesting method, when Chief Dale Robertson proposed new policies in 1988 and 1992. The 1992 policy, with seven criteria, called for eliminating clearcutting by as much as 70 percent from the 1988 levels....
>
> Clearcutting remains the silvicultural timber harvest method of choice, especially in the private sector, but resource conditions and restrictions by various forest and ecosystem plans have made clearcutting on the national forests mostly a memory.[8]

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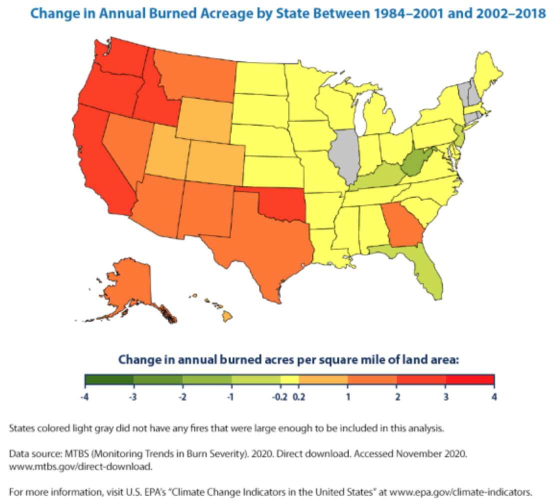
[7] Source: Act for Libraries; http://www.actforlibraries.org/reasons-to-clear-cut-forests/, accessed May 13, 2021

[8] Source: Forest History Society; https://foresthistory.org/research-explore/us-forest-service-history/policy-and-law/forest-management/controversy-over-clearcutting/controversy-over-clearcutting-timeline/recent-changes-in-the-clearcutting-policy-in-the-forest-service/#:~:text=The%20problems%20with%20clearcutting%20have%20persisted.%20The%20Forest,much%20as%2070%20percent%20from%20the%201988%20levels., accessed May 13, 2021

Figure 2: Increased acreage burned in wildfires and lumber production by state



Source: U.S. Environmental Protection Agency; https://www.epa.gov/climate-indicators/climate-change-indicators-wildfires, accessed May 13, 2021

Source: York Saw and Knife Company, Inc.; https://www.yorksaw.com/guide-to-sawmills/sawmills-in-the-usa/, accessed May 13, 2021

Proof that the trends in Figure 1 are **not causally connected** is also beyond the scope of this paper. It is not hard to imagine that both higher GMST and reduced clearcutting are contributing factors to the increased extent of wildfires, but I do not attempt to quantify their contributions. Inasmuch as there is a link between GMST and the extent of wildfires, a return to clearcutting on federal lands could be part of a policy of adaptation.

Raffin and Seegmuller (2014) model a dynamic system that includes economic growth, pollution, and longevity. In keeping, I use such relationships, rather than willingness to accept or pay, to monetize changes in climate. The optimum, again, occurs where the effect on human lifetimes of an incremental increase in aggregate consumption equals that of an incremental decrease in GMST. I am not claiming that the value of human life is infinite ("death is not the worst of evils"), only that it is the same whether attenuated by poverty or natural disaster.

I describe human lifetimes as a measure of social utility in Section 2. In Section 3, I derive symbolic expressions for optimal relationships between aggregate consumption and mitigation of climate change. I estimate the parameters of the utility function in Section 4, and examine variation in estimated optima by risk aversion and GMST in Section 5. In Section 6, I derive cardinal values for optimal CO_2 taxes by quintile of global aggregate consumption under different assumptions about risk aversion and GMST, and discuss policy implications qualitatively. I discuss further research in Section 7, and derive some properties of the utility function and optima in the appendix.

2 Human lifetimes as a measure of social utility

I assume that social utility in each nation is monotonically related to the product of population and expected lifetime, denoted by $U(C,T)$, where C is aggregate consumption, and T is the anomaly in GMST.

$$U(C,T) = -C^{1-\sigma} + \beta_0 - \beta C^{1-\sigma} T^{1+\gamma} \tag{1}$$

I estimate β_0 and β empirically in Section 4, where β_0 is the intercept term, and $\hat{\beta} > 0$ with high statistical significance. Using empirical work by Hall (1988), I assume $\sigma > 1$; I also assume $\gamma > 0$, so utility increases in consumption and decreases in the anomaly in GMST.

(1) is interpersonally comparable: If one person lives a year longer while another dies a year sooner, social utility is unchanged. The death of a young person, though, will carry a greater social cost than that of an old person, because many more life-years are lost when a young person dies.

(1) also exhibits constant relative risk aversion (CRRA). A coefficient of relative risk aversion is the negative of the second derivative of a utility function with respect to an argument divided by the first derivative with respect to the same argument, all times the argument. σ is the coefficient of relative risk aversion over consumption, and γ is the coefficient of relative risk aversion over temperature anomaly. In the analysis, I look at different assumptions about risk aversion, but I assume that people have similar preferences regarding risk to consumption and risk to temperature anomaly. More precisely, I set γ relative to σ so that the proportional distance of the certainty equivalent from an inferior outcome, in an even bet between that inferior outcome and a superior outcome, is the same for both consumption and temperature anomaly. The relationship is

$$\gamma = \frac{\ln\left(\frac{1}{2}\right)}{\ln\left(2 - \left(\frac{1 + 2^{1-\sigma}}{2}\right)^{\frac{1}{1-\sigma}}\right)} \tag{2}$$

I derive Equation (2) in the appendix. I support this assumption only by intuitive appeal, anecdotal evidence, and an empirical look at robustness in Section 5. Intuitively, people will have a tendency to be either prudent or courageous in different areas of their lives. Anecdotally, people who favor strict climate policy, which would follow from a high value of γ, also tend to favor either a drop in present consumption to avoid risk of infection from COVID-19, or borrowing from the future for the same reason[9], as well as more egalitarian social welfare policies, and the latter three preferences would follow from a high value of σ. Casually observing such correlated variation in preferences across the American political divide indicates that we should not put too much weight on the point estimates of the monetary value of mitigation made assuming homogeneous preferences, but it also helps to affirm narrowness of the range for that value estimated using Equation (2); preferences may vary from person-to-person, but preferences regarding risk do seem to correlate positively across the different economic goods, private or public, that each person consumes.

Hall (1988) estimates the range of values for risk aversion over consumption to be $\sigma \in [2,4]$. Accordingly, and applying (2), I examine the three cases shown in Table 1.

Table 1: Cases of risk aversion

	σ	γ
High risk aversion	4	1.92
Base case	3	1.25
Low risk aversion	2	0.71

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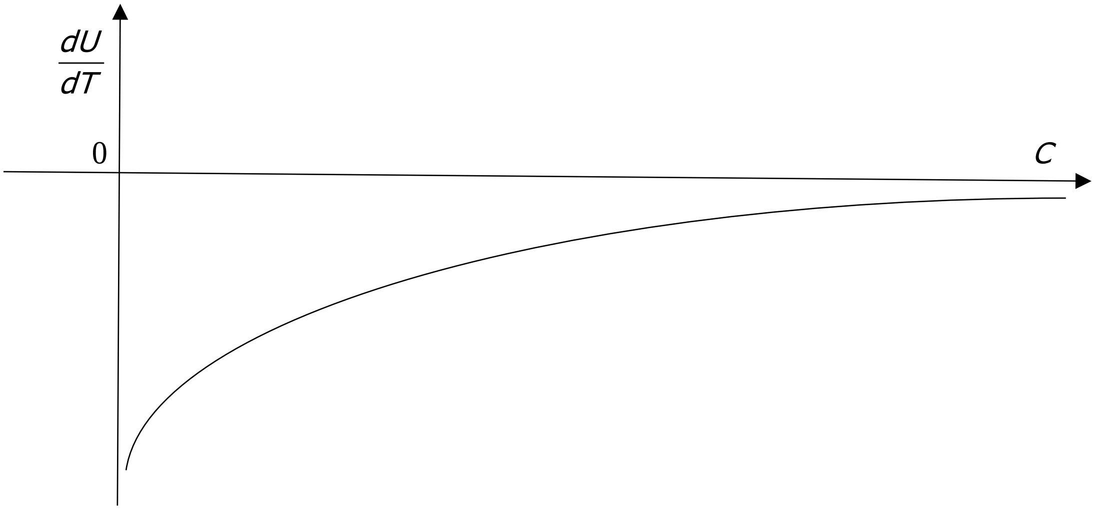
[9] In a Ramsey (1928) model with CRRA, the social discount rate is $\rho + \sigma b$, where ρ is the pure rate of time preference, and b is the rate of growth in consumption per capita.

Weitzman (2010) assumes $\gamma = 1$.

Some **properties of the utility function** are as follows:

1) $\frac{d}{dC}\frac{dU}{dT} = -\beta\left(1+\gamma\right)\left(1-\sigma\right)C^{-\sigma}T^{\gamma} > 0$; the marginal benefit of mitigation is decreasing in consumption; (1) exhibits a "climate justice" property, described in the second quote from Tol (2005) in the introduction, and depicted in Figure 3;

Figure 3: "Climate justice"; the marginal benefit of mitigation diminishes in consumption



2) $\frac{d}{dC}\frac{dU}{dC} = \sigma\left(1-\sigma\right)C^{-1-\sigma}\left(1+T^{1+\gamma}\right) < 0$; the marginal benefit of consumption is also decreasing in consumption, as in most commonly used utility functions, and this may more than "offset" the effect of Property 1), climate justice, on the optimal CO_2 tax in a poor country;

3) If consumption and temperature grow over time, then the annual discount rate that equalizes the present value of utility in all years is $r = 1 - \frac{(1+g)^{1-\sigma}\left(1+\beta(1+\Delta)^{\frac{1+\gamma}{2100-2020}}\right) - \beta_0}{1+\beta-\beta_0}$, derived in the appendix, where g is the annual rate of growth in consumption, and $1+\Delta$ is the temperature anomaly in 2100. The temperature anomaly is approximately unity in 2020. r increases in g and decreases in Δ.

3 Optimizing consumption and emissions

Setting the total differential of (1) equal to zero equates the incremental effects of consumption and temperature on utility (i.e., human life-years).

$$\begin{aligned} U(C,T) &= -C^{1-\sigma} + \beta_0 - \beta C^{1-\sigma}T^{1+\gamma} \\ dU &= \\ \left(-(1-\sigma)C^{-\sigma} - (1-\sigma)\beta C^{-\sigma}T^{1+\gamma}\right)dC - (1+\gamma)\beta C^{1-\sigma}T^{\gamma}dT &= 0 \\ -\left(1+\beta T^{1+\gamma}\right)(1-\sigma)C^{-\sigma}dC &= \beta(1+\gamma)C^{1-\sigma}T^{\gamma}dT \end{aligned} \tag{3}$$

The absolute change in consumption needed to “offset” the effect on human life-years of a one degree rise in GMST is, therefore,

$$\frac{dC}{dT} = -\frac{\beta(1+\gamma)CT^{\gamma}}{\left(1+\beta T^{1+\gamma}\right)(1-\sigma)} \tag{4}$$

Dividing by consumption gives the fractional change in consumption needed to “offset” the effect on human life-years of a one degree rise in GMST.

$$\frac{dC}{dT}\frac{1}{C} = -\frac{\beta(1+\gamma)T^{\gamma}}{\left(1+\beta T^{1+\gamma}\right)(1-\sigma)} \tag{5}$$

Note that a one-degree change in GMST is large; the kind of change that the value of a statistical life approach does not deal with well. (4) and (5) are two forms of the "damage function", empirical estimates of which quantify the second stage of emissions pricing mentioned at the outset of this study, and are its main results. Assuming that $\sigma > 1$, which is generally believed, (5) is positive so long as β is positive. Conveniently, (5) is independent of consumption, C. In the empirical estimation in Section 4, if I added the term $\beta_T T^{1+\gamma}$ to (1), which would have brought C into the RHS of (5), it would be found to be statistically insignificant and, therefore, the term is omitted.

If (4) and (5) are estimated well, then any deviation therefrom (up or down; CRRA utility is quasi-concave) would sacrifice human life "on net", possibly in favor of some other objective. Whether such a thing exists is a philosophical question. I think, for example, that if a person who would wipe out the world's population of dolphins were never conceived to begin with, Saint Jerome's strict and mystical view of birth control notwithstanding[10], that would be a good thing, so my welfare criterion is not perfect. As a practical matter, though, I adopt an objective function that he might not object to because data are available and, I would say, (4) and (5) are a reasonable expression of the overall optimum in the trade-off between mitigation of climate change and consumption: *A priori*, there is little reason to believe that the rate of substitution would be different if the objective were the quality, rather than the extent, of human life independent of measured consumption of goods, or some form of animal life, and I do not think one could justify any earthly objective besides those two that could possibly supersede human life itself. Tol (2005) also writes "…'physical' metrics may be suited to measure the impact on natural systems, but they are inadequately linked to human welfare, ***the ultimate indicator of concern***." (emphasis added)

Moreover, this unweighted utilitarian social welfare function is an improvement on the standard VSL approach applied to climate change, given the heterogeneity of climate risks described by Tol (2005). Hammitt and Treich (2007)

> ...investigate how the results of benefit-cost analysis (BCA) depend on information about heterogeneity of individual risks and risk changes in the conventional static VSL model. We compare these results with maximization of social welfare, defined as the mean of

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[10] http://www.religioustolerance.org/abo_hist.htm, accessed May 21, 2021.

> individuals' expected utilities (Harsanyi 1953, 1955). This measure of social welfare is independent of information about risk heterogeneity when, as in our analysis, people are otherwise identical.
>
> ...In the usual case in which one aggregates individuals' willingness to pay (WTP) for a project that reduces risk, information about heterogeneity of the risk change decreases the value of the project. (p. 47)

Here, the "project" is either substitution of mitigation of the anomaly in GMST for consumption, or vice-versa, and the heterogeneity of risk implies that either one could be undervalued using WTP in VSL, assuming that maximizing the product of expected lifetime and population, as a CRRA function of GMST and consumption, is a valid objective.

Some **properties of the utilitarian optimum**, derived in the appendix, include:

1) $\frac{d}{dT}\left(\frac{dC}{dT}\frac{1}{C}\right) \gtrless 0$ if and only if $\gamma \lessgtr \beta T^{1+\gamma}$; with $\gamma > 0$, as I attempt to justify, and $\beta \in \left[0, 0.5\right]$, as I estimate, the damage function is convex for all temperatures above a certain level; there is no precipitous drop in incremental damage at high GMSTs;
2) $\frac{d}{dC}\frac{dC}{dT} = -\frac{\beta\left(1+\gamma\right)T^{\gamma}}{\left(1+\beta T^{1+\gamma}\right)\left(1-\sigma\right)} > 0$; as consumption rises across space or time, the monetary value of mitigation also rises.

4 Estimation

I estimate β using annual data on 185 countries from 1990 to 2018. These include population (series SP.POP.TOTL), expected lifetime (series SP.DYN.LE00.IN), and gross domestic product (series NY.GDP.MKTP.PP.KD) in dollars converted using purchasing power parity[11], and national savings rates (series NY.GNS.ICTR.ZS) from the World Bank's world development

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[11] According to the OECD (2006; p. 6), "When measuring income (e.g., GDP), using purchasing power parities (PPP) is more appropriate for looking at long-term issues in developing countries than is income measured using market exchange rates (MER)." This is because markets for non-traded goods, which are often crucial to human well-being, have little effect on market exchange rates.

indicators. I apply capital depreciation of 15% for the United States, based on data from the Bureau of Economic Analysis (series A191RC and A027RC), to all countries. I use data on the global mean surface temperature anomaly, relative to 1951-80, from the U.S. National Aeronautic and Space Administration (NASA). According to *The Climate Lab Book*, "2015 was likely the first time in recorded history that global temperatures were more than 1°C above pre-industrial levels", so the NASA data used here, defined relative to a 1951-80 baseline, and where $T = 1.02^{\circ}$ in 2016, coincide with the climate record used to establish the Paris Accord goal of a 2° temperature anomaly in 2100, relative to "pre-industrial levels". GDP is in 2017$. Data are summarized in Table 2.

Table 2: Summary of sample data

Variable	Observations	Mean	Standard deviation	Coefficient of variation	Minimum	Maximum
Human life-years (hundreds of millions)	5,830	22	87	3.94	0.010	1,068.280
Consumption (tens of billions of 2017$, PPP)	5,406	43	151	3.51	0.002	2,122.936
Temperature anomaly (C° - 14)	29	0.580	0.198	0.34	0.220	1.020

Table 3 shows results of the base case regression. The regression is done in first differences to guard against spurious inference associated with non-stationarity of variables. Three lags of the dependent variable are included to minimize first order autocorrelation in the residuals, which is estimated to be only 0.0135 as a result, suggesting that the equation is well specified. The change in sign from the first to the second lag suggests that a global business cycle needed to be modeled, even though the sum of the coefficients of the lags is small. Statistics describing the explanatory power of the model are interior: About a fourth of the total variation is explained by the regressor, and 29% of the unspecified variation is explained by country effects. Though the correlation of the country effects with the regressor is modest (0.1680), it is enough for a random effects model to fail a Hausman test for bias, so fixed effects are used.

All of the coefficients are highly significant, leaving little doubt that consumption extends human life, and global warming attenuates it, though the *p*-value on $T^{1+\gamma}$, were it included as a regressor, would be 0.62, so it is not. The coefficient would be 0.7769, indicating a positive effect on the extent of human life, but with far too little confidence to retain in the model. We believe that someone, somewhere benefits from climate change, but there is too little of this to appreciably “offset” its global costs. While I have specified the model to minimize autocorrelation in the residuals, the estimator, devised by Baltagi and Wu (1999), is robust to that form of error, and other specifications produce similar estimates of β.

Table 3: Base case regression; σ = 3 and γ = 1.25

FE (within) regression with AR(1) disturbances		Number of obs.	=	4248
Group variable: ID		Number of groups	=	185
		Obs. per group		
R-sq: within =	0.2535	Minimum	=	1
between =	0.9265	Average	=	23
overall =	0.2519	Maximum	=	24
		F(4,4059)	=	344.56
Correlation of country effects with regressor(s) =	0.1680	Probability > F	=	0

$D(U+C^{1-\sigma})$	Coefficient	Standard Error	z	Probability > z	[99% Conf.	Interval]
$D(C^{1-\sigma}T^{1+\gamma})$	-0.1567	0.0071	-22.15	0	-0.1749	-0.1384
$L(D(U+C^{1-\sigma}))$	-0.2256	0.0151	-14.97	0	-0.2645	-0.1868
$L(L(D(U+C^{1-\sigma})))$	0.2543	0.0147	17.32	0	0.2164	0.2921
$L(L(L(D(U+C^{1-\sigma}))))$	0.0508	0.0137	3.71	0	0.0155	0.0862
Constant	-0.4466	0.1685	-2.65	0.008	-0.8809	-0.0123

0.0135	first order autocorrelation of residuals
7.0095	standard deviation of country effects
10.9618	standard deviation of residuals
0.2902	fraction of variance due to country effects

L is the lag operator, and D is the difference operator.

With σ = 3 and γ = 1.25, $\hat{\beta} = \underset{0.0099}{0.1702}$, with a 99% confidence interval of [0.1446, 0.1958]. This long run effect is calculated by collapsing the lag structure in the econometric model and taking the geometric sum of effects over time:

$$\begin{aligned} U_{it} + C_{it}^{1-\sigma} &= \beta_0 + \beta_i + \beta_X\left(C^{1-\sigma}T^{1-\gamma}\right) + \beta_1\left(U_{it-1} + C_{it-1}^{1-\sigma}\right) \\ &\quad + \beta_2\left(U_{it-2} + C_{it-2}^{1-\sigma}\right) + \beta_3\left(U_{it-3} + C_{it-3}^{1-\sigma}\right) + \varepsilon_{it} \end{aligned} \qquad (6)$$

$$\hat{\beta} = \frac{\hat{\beta}_X}{1 - \hat{\beta}_1 - \hat{\beta}_2 - \hat{\beta}_2} \tag{7}$$

where the hat denotes estimates.

5 Cases

Estimates of $\hat{\beta}$ for the cases of risk aversion shown in Table 1, along with a case in which consumption is converted using market exchange rates, rather than purchasing power parities, are shown in Table 4.

Table 4: Estimates of β by case

Case	$\hat{\beta}$	Standard error	z	Probability > z	[99% Conf. interval]	
High risk aversion	0.334	0.015	22.740	0.000	0.296	0.371
Base case	0.170	0.010	17.150	0.000	0.145	0.196
Low risk aversion	0.141	0.016	8.660	0.000	0.099	0.183
Market exchange rates	0.162	0.011	14.590	0.000	0.134	0.191

Also substituting (7) into (5) gives the point estimates and confidence intervals for the percentage change in consumption needed to save the same number of life-years lost to a one degree rise in GMST for the various cases, and by temperature anomaly $T = (1,\ldots,6)$. This is shown in Table 5. Except at two- and three-degree anomalies under high risk aversion, the monetized human cost of a one degree increase in GMST generally varies between sixteen and twenty five percent of aggregate consumption. At a 2.5% annual rate of growth in consumption, each degree of temperature anomaly sets the economy back six to nine years in its effect on human lifetimes. These relationships are also depicted in Figure 4. Results are robust to the use of purchasing power parity instead of market exchange rates. Base case results, with moderate risk aversion, mainly show the same or lower monetized value for mitigation than under either high or low risk aversion. At these moderate values, the benefits of consumption better “offset” the costs of climate change. If more extreme risk-aversion, high or low, is less likely, then damage costs of global warming are likely lower.

Table 5 also shows the implicit discount rate that would equalize the present value of social utility across years, from Property 3) of the utility function, assuming annual real growth in global consumption of 2.47%. As in other studies (e.g., Nordhaus 2017; Figure 3, p. 1520), higher values for mitigation generally accompany lower discount rates, though risk aversion, itself, has a strong influence on the discount rate, independent of its effect on the value of mitigation.

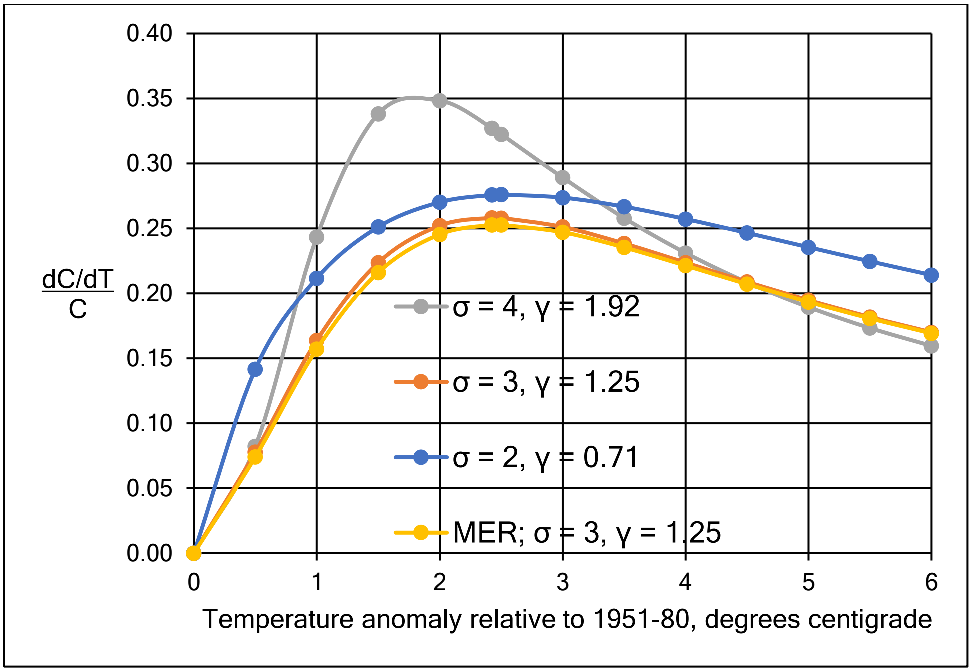
Coefficients of relative risk-aversion, like σ and γ, also measure aversion to inequality in utilitarian optima, wherein the sum of individual utilities is maximized. The higher the values of these parameters, the greater the difference in marginal utility between different values of the argument, so the greater the gain in social utility from reallocating units of the argument from haves to have nots. Inequality may be observed, and reallocation may occur, across either space or time. Across space, a social planner with a high aversion to inequality would choose a high value for σ (and, by (2), γ), and reallocate from rich to poor. When the discount rate is used as an input, it is typically a positive function of σ, as in a Ramsey (1928) model with CRRA, where the discount rate is $\rho + \sigma b$, where ρ is the pure rate of time preference, and b is the rate of growth in consumption per capita; this economic growth implies that the marginal utility of consumption will be lower in the future, so a social planner with a high aversion to inequality will choose a high discount rate by choosing a high value for σ, and reallocate from future to present. A philanthropist with altruistic preferences regarding both today’s poor and future generations may, then, feel conflicted when attempting to ascertain the correct value for σ. With the discount rate as an output, as in Table 5, rather than an input, a high value of σ implies a high value of β, given the sample data, which, in turn, raises the marginal utility of future consumption relative to that of present consumption, so the discounting needed to keep the present value of utility constant from year-to-year is lower than with a low value of σ. With the combination of theoretical and empirical models used here, the philanthropist need not feel conflicted.

Table 5: Estimated percent change in consumption “offsetting” a one degree rise in GMST by risk-aversion and temperature anomaly

T	$\frac{dC}{dT}\frac{1}{C}$	Standard Error	Z	Probability > z	[99% Conf. Interval]		Implicit real discount rate
<u>High risk aversion</u>							
1	0.2434	0.0080	30.33	0.0000	0.2227	0.2641	0.16%
2	0.3483	0.0043	80.10	0.0000	0.3371	0.3595	0.15%
3	0.2892	0.0014	210.04	0.0000	0.2856	0.2927	0.14%
4	0.2311	0.0005	456.39	0.0000	0.2298	0.2324	0.14%
5	0.1894	0.0002	854.42	0.0000	0.1888	0.1899	0.14%
6	0.1596	0.0001	1438.65	0.0000	0.1593	0.1599	0.13%
<u>Base case</u>							
1	0.1638	0.0082	20.07	0.0000	0.1427	0.1848	3.36%
2	0.2521	0.0081	31.06	0.0000	0.2312	0.2730	3.17%
3	0.2511	0.0048	51.81	0.0000	0.2386	0.2636	3.06%
4	0.2236	0.0027	83.40	0.0000	0.2167	0.2305	2.97%
5	0.1947	0.0015	126.65	0.0000	0.1908	0.1987	2.91%
6	0.1700	0.0009	182.26	0.0000	0.1676	0.1724	2.86%
<u>Low risk aversion</u>							
1	0.2117	0.0214	9.89	0.0000	0.1565	0.2668	3.58%
2	0.2702	0.0213	12.66	0.0000	0.2152	0.3251	3.31%
3	0.2737	0.0164	16.67	0.0000	0.2314	0.3160	3.15%
4	0.2572	0.0118	21.75	0.0000	0.2267	0.2877	3.04%
5	0.2355	0.0085	27.83	0.0000	0.2137	0.2573	2.95%
6	0.2141	0.0061	34.84	0.0000	0.1983	0.2299	2.88%
<u>Market exchange rates</u>							
1	0.1571	0.0093	16.96	0.0000	0.1333	0.1810	1.77%
2	0.2454	0.0095	25.86	0.0000	0.2210	0.2699	1.67%
3	0.2471	0.0058	42.69	0.0000	0.2321	0.2620	1.61%
4	0.2214	0.0032	68.30	0.0000	0.2130	0.2297	1.57%
5	0.1934	0.0019	103.37	0.0000	0.1886	0.1983	1.54%
6	0.1692	0.0011	148.44	0.0000	0.1663	0.1722	1.51%

For temperature anomalies of $T = 1, 2, \text{or } 3$, if I relax the mapping from aversion to risk to consumption, σ, to risk to climate change, γ, shown in Equation (2), by combining the extreme values of one parameter from Table 1 with middling values of the other, I lower the minimum fractional change in consumption needed to "offset" a 1° rise in GMST in Table 5 from 0.1638, if $\sigma = 3$, $\gamma = 1.2522$, and $T = 1$, to 0.0906, if $\sigma = 3$, $\gamma = 0.7095$, and $T = 1$. I raise the maximum from 0.3483, if $\sigma = 4$, $\gamma = 1.9183$, and $T = 2$, to 0.4512, if $\sigma = 3$, $\gamma = 1.9183$, and $T = 2$. That is, relaxing Equation (2) widens the range of estimated social costs of emissions, at both of its extremes. This is why the casual observation of variation in Americans' policy preferences discussed in Section 2, while diminishing the usefulness of the point estimates in Table 5, affirms the narrowness of the confidence intervals.

Figure 4: Estimated percent change in consumption "offsetting" a one degree rise in GMST by case and temperature anomaly



6 Policy implications

I stated at the outset of this article that derivation of an optimal tax on CO_2, for the purpose of mitigating climate change, involves two steps, the first $\left(dT/dG\right)$ being climate science, and the second $\left(dC/dT\right)$ economics, where G is atmospheric CO_2, and C is aggregate consumption. "Equilibrium climate sensitivity" (ECS) is the *eventual* rise in GMST resulting from a doubling of atmospheric CO_2:

$$ECS \equiv \frac{dT}{dG}\frac{2-1}{1.5}G \tag{8}$$

The worldwide average social demand price for a metric ton of CO_2 is

$$\begin{aligned} P_{CO_2} &= \frac{dC}{dG} \\ &= \frac{dC}{dT}\frac{dT}{dG} \\ &= \frac{dC}{dT}\frac{1}{C}\frac{dT}{dG}C \\ &= \frac{dC}{dT}\frac{1}{C}\frac{ECS\times 1.5}{G}C \end{aligned} \tag{9}$$

where C is worldwide consumption. Therefore,

$$P_{CO_2} = \left(-\frac{\beta\left(1+\gamma\right)T^{\gamma}}{\left(1+\beta T^{1+\gamma}\right)\left(1-\sigma\right)}ECS\times 1.5\right)\frac{C}{G} \tag{10}$$

where the terms preceding "ECS" are from (5). I use 2.5°C for ECS. Lewis and Curry (2018) estimate a 95% confidence interval of $ECS \in \left[1.2, 3.1\right]$, but Sherwood et al. (2020), **who draw heavily on Lewis and Curry**, write that an estimate under 2.0°C "is difficult to reconcile with any of the three lines of evidence". As a consumer, not producer, of climate science, I find the apparent contradiction problematic. The reader may choose a different relationship between emissions and temperature to include in Equation (10). I use $G = 3{,}181{,}794{,}000{,}000$ metric tons and $C = 53{,}057{,}319{,}677{,}180$ USD in 2020.

Consumption increases life-years nationally, though, while mitigation increases life-years globally. Equation (4) says that the absolute change in consumption needed to save the number of life-years lost to a given increase in GMST is proportional to consumption. Therefore, a proportional change in consumption worldwide will save that number of life-years, but a non-proportional change in consumption in the same aggregate amount will save fewer life-years. Ideally, the absolute change in consumption for each person, then, would be proportional to that person's consumption. Practically, that (5) is independent of consumption means that the optimal (utility-maximizing) CO_2 tax is a kind of "flat income tax", with the tax rate on CO_2 proportional to consumption per capita in the jurisdiction applying the tax.

I can write $C = \sum_{j=1}^{N} C_j$, where C_j refers to consumption in one of N percentiles of global consumption. C_j affects life-years in Percentile j, while T affects life-years worldwide. The social demand price in Percentile j that equates the incremental effects of consumption on life-years in Percentile j to the incremental effects of mitigation of T on life-years in Percentile j is, therefore,

$$P_{CO_2}^{j} = \left(-\frac{\beta\left(1+\gamma\right)T^{\gamma}}{\left(1+\beta T^{1+\gamma}\right)\left(1-\sigma\right)} ECS \times 1.5 \right) NC_j \qquad (11)$$

where, again, N is the number percentiles of consumption. Applying (11) in every Percentile j equates the incremental effects of consumption on life-years, worldwide, to the incremental effects of mitigation of T, worldwide. Because the distribution of income is very unequal globally, I have done this in Table 6. Data are again from the World Bank; Series NY.GDP.MKTP.PP.KD. The Lorenz curve is shown in Figure 5. The Gini Index is 0.862, far from zero, and close to unity. To derive the social demand prices in Table 6, I use estimates for β from Table 4, for σ and γ from Table 1, and values for T as indicated.

When CO_2-emitting fossil fuels, and other goods, are used in poor countries, they may extend human lifetimes in ways that marginal uses in rich countries do not, and the estimates in Table 6 would incent relative increases in consumption of all goods, including fossil fuels, in poor countries, with relative decreases in rich countries.

(10) is the average of (11):

$$\frac{1}{N}\sum_j^N P_{CO_2}^j = P_{CO_2} \qquad (12)$$

For example, using base case risk-aversion, the social demand price for mitigation is \$10.24/tCO$_2$ at a 1°C anomaly, \$125.49/tCO$_2$ at 2°, and \$162.16/tCO$_2$ at 3°. Using 2016 emissions and the 2020 base case tax rates, the CO$_2$ tax bill per capita would have been \$4.45 in a poor country, \$29.67 in a middle-income country, and \$176.05 in a rich country.

The optimal tax on emissions varies greatly between poor and rich countries, suggesting that a uniform global tax on CO$_2$ would be profoundly regressive. Suppose there are two countries, $i = 1,2$. From (1), the marginal utility of consumption in Country i is

$$\frac{\partial U_i}{\partial C_i} = -\left(1+\beta T^{1+\gamma}\right)\left(1-\sigma\right)C_i^{-\sigma} > 0 \qquad (13)$$

Averaging (4) across countries, the uniform tax paid by both countries to purchase one unit of mitigation would change consumption by

$$\Delta C_i = \frac{\beta\left(1+\gamma\right)T^{\gamma}}{\left(1+\beta T^{1+\gamma}\right)\left(1-\sigma\right)}\bar{C} < 0 \qquad (14)$$

where $\bar{C} \equiv \left(C_1 + C_2\right)/2$, $C_2 > C_1$, without loss of generality, and I normalize $\bar{C} \equiv 1$. Combining (13) and (14), the change in utility in Country i from paying the tax is

$$\Delta U_i = \frac{\partial U_i}{\partial C_i}\Delta C_i = -\beta\left(1+\gamma\right)T^{\gamma}\bar{C}C_i^{-\sigma} < 0 \qquad (15)$$

Under an equally weighted utilitarian social welfare function, the change in social welfare caused by payment of the uniform tax is

$$\frac{\Delta U_1 + \Delta U_2}{\Delta C} = -\beta\left(1+\gamma\right)T^{\gamma}\bar{C}\left(C_1^{-\sigma} + C_2^{-\sigma}\right) < 0 \tag{16}$$

From (1), the marginal utility in Country *i* of a unit of warming (negative mitigation) is

$$\frac{\partial U_i}{\partial T} = -\beta\left(1+\gamma\right)T^{\gamma}C_i^{1-\sigma} < 0 \tag{17}$$

Under the unweighted utilitarian social welfare function, the change in social welfare from a unit of mitigation is

$$\frac{\Delta U_1 + \Delta U_2}{-\Delta T} = \beta\left(1+\gamma\right)T^{\gamma}\left(C_1^{1-\sigma} + C_2^{1-\sigma}\right) > 0 \tag{18}$$

Adding (16) and (18) gives the total change in social welfare caused by imposition of the uniform tax.

$$\begin{aligned} \frac{dU_1 + dU_2}{-dT} &= \beta\left(1+\gamma\right)T^{\gamma}\left(C_1^{1-\sigma} + C_2^{1-\sigma} - C_1^{-\sigma} - C_2^{-\sigma}\right) \\ &\propto C_1^{-\sigma}\left(C_1 - 1\right) + C_2^{-\sigma}\left(C_2 - 1\right) < 0 \end{aligned} \tag{19}$$

because $\bar{C} \equiv 1$ and

$$\begin{aligned} C_1^{-\sigma}\left(C_1 - 1\right) &< C_2^{-\sigma}\left(1 - C_2\right) \\ \left(\frac{C_2}{C_1}\right)^{\sigma} &> \frac{1 - C_2}{C_1 - 1} = 1 \end{aligned} \tag{20}$$

so long as people are risk (and inequality)-averse $\left(\sigma, \gamma > 0\right)$ and given the econometric results, including $\hat{\beta} > 0$. This result does not depend on Equation (2), wherein people are similarly averse to risk to both consumption and climate change, or on $\sigma \in \left[2, 4\right]$, from Hall (1988).

Equally weighted utilitarian social welfare, total human life-years, as I have measured it empirically, *declines* with imposition of the uniform carbon tax, despite Property 1 of the utility function; "climate justice" (Figure 3). "Denial" of anthropogenic climate change would be better than imposing this uniform tax, as far as Jeremy Bentham and John Stuart Mill might be concerned, and I would agree.[12] [13]

Climate change is deadly, but climate policy must be sufficiently progressive, or it will be more deadly.

In particular, emissions or emitting fuels should be taxed or regulated at or near the point of consumption, rather than at or near the "source", inasmuch as the markets for those fuels are

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[12] Nicholas Kaldor and Sir John Hicks, on the other hand, might prefer to impose the uniform tax, as it would maximize their willingness to pay criterion. From (14), the bill to Country *i* for a unit of mitigation under a uniform tax would be

$$\begin{aligned}\Delta C_i &= -\frac{\beta\left(1+\gamma\right)T^{\gamma}}{\left(1+\beta T^{1+\gamma}\right)\left(1-\sigma\right)}\bar{C} \\ &= -\frac{\beta\left(1+\gamma\right)T^{\gamma}}{\left(1+\beta T^{1+\gamma}\right)\left(1-\sigma\right)}\frac{C_1+C_2}{2}\end{aligned}$$

Combining this with (4), the global bill equals global willingness to pay for a unit of mitigation

$$\Delta C_1 + \Delta C_2 = \frac{dC_1 + dC_2}{dT} = -\frac{\beta\left(1+\gamma\right)C_1T^{\gamma}}{\left(1+\beta T^{1+\gamma}\right)\left(1-\sigma\right)} - \frac{\beta\left(1+\gamma\right)C_2T^{\gamma}}{\left(1+\beta T^{1+\gamma}\right)\left(1-\sigma\right)}$$

which is the same as in the utilitarian optimum, but allocated more to Country 1 under a uniform tax. This reallocation is what would lower social utility relative to a tax of zero. The utilitarian optimum is Pareto efficient, else the sum of utilities could be raised, and a Pareto efficient allocation maximizes willingness to pay, since a compensated reallocation would be a Pareto improvement, but all Pareto allocations are not utilitarian optima. (e.g., Imelda gets all the shoes in the world.) Since it may be impossible to compensate losers when their loss is life itself, the "potential Pareto improvement" normally used to justify application of Kaldor-Hicks may be impossible, as well.

[13] According to Böhringer, Carbone, and Rutherford (2018), "The main effect of carbon tariffs is to shift the economic burden of developed-world climate policies to the developing world."

global, and their production should not be restricted, because such policies would raise their prices globally, and be tantamount to a uniform tax. The market for crude oil is basically regarded as global.[14] Markets for natural gas are more localized, but decreasingly so as liquefaction and regasification terminals are installed. Transportation costs represent a large fraction of the delivered price of coal, so, unlike oil and gas, taxing coal at the source or restricting its production might still raise social utility. Unlike the global market for crude oil, a price increase in a local market for coal will create mitigation benefits beyond the market, but the less equal the distribution of consumption within the local market for coal, the lower the optimal increase in the price there, and the local net (utilitarian) benefits, exclusive of the external benefits beyond the local market, will still be negative.

According to the International Energy Agency (2021; p. 21), “There is no need for investment in new fossil fuel supply in our net zero pathway. Beyond projects already committed as of 2021, there are no new oil and gas fields approved for development in our pathway, and no new coal mines or mine extensions are required.” As it regards oil, and possibly, also, natural gas, this stance can be expected to attenuate human life overall, especially in poor countries.

Rather, the demand price of each fuel in each country should exceed a globally determined supply price by the external costs of emissions in each country, from Equation (11). Going forward, Saudi Arabia, Norway, the United States, and other rich producers should produce and, increasingly, export any crude oil, refined products, and liquefied natural gas whose marginal costs come in below their globally determined supply prices, even as those countries’ wealth implies large reductions in consumption of those fuels domestically.[15] Because the “tax wedge” is small in poor countries, and marginal costs of production are low in Persian Gulf countries and at low quantities supplied elsewhere, including in U.S. shale plays, the instant study may imply a qualitatively different path than the IEA’s.

While taxing or regulating emissions locally in poor countries might be administratively difficult, Table 6 shows that emissions there are well below those in middle- and upper-income countries,

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[14] See Adelman, 2004, page 19.

[15] Whether OPEC+ actually will produce where marginal cost equals price is doubtful, but (16) shows that the cost of its exercise of market power can be measured in attenuated human life in poor countries. In the past, there was a perceived benefit of conservation from OPEC’s high prices, but this seems to have been obviated by climate policy, which itself will defer or nullify much consumption and, therefore, extraction of nonrenewable emitting sources of energy.

so there is little to gain in terms of mitigation by administering climate policy in poor countries. Practically speaking, they could be left alone.

Table 6: World distribution of consumption and associated taxes on CO_2

		Low income	Lower middle income	Middle income	Upper middle income	High income
Quintiles of consumption per capita in 2020 (USD)		1,481	2,677	3,136	3,777	8,577
Shares		0.075	0.136	0.160	0.192	0.437
Lorenz Curve		0.075	0.212	0.371	0.563	1.000
45° line		0.200	0.400	0.600	0.800	1.000
Area under 45° line	2.500					
Area under Lorenz Curve	0.344	0.008	0.029	0.058	0.093	0.156
Gini index	0.862					
Emissions per capita in 2016 (metric tons)		1.153	2.907	3.631	4.653	7.876
2020 (1° world) social cost of CO_2-Induced climate change ($/t$CO_2$)						
High risk aversion		3.34	6.03	7.06	8.50	19.31
Base case		3.86	6.98	8.17	9.84	22.35
Low risk aversion		5.86	10.59	12.41	14.94	33.94
2100 2° world social cost of CO_2-Induced climate change (2020$/t$CO_2$)						
High risk aversion		64.85	117.17	137.26	165.32	375.47
Base case		47.31	85.48	100.13	120.60	273.91
Low risk aversion		49.30	89.08	104.35	125.68	285.45
2100 3° world social cost of CO_2-Induced climate change (2020$/t$CO_2$)						
High risk aversion		109.79	198.37	232.39	279.88	635.67
Base case		61.14	110.46	129.40	155.85	353.96
Low risk aversion		51.13	92.38	108.22	130.34	296.02

Figure 6 shows a forecast by year for optimal emissions tax rates in the United States and Mexico, together with the worldwide average, where rates of growth in consumption per capita are assumed to average 1.00%, 2.00%, and 1.77% p.a., respectively. The US curve starts at $40.07 in 2020 and rises to $343.87 in a “3° world” in 2100. The MX curve starts at $12.24 in

2020 and rises to $233.86 in 2100 at 3°. “Leakage” of emissions from the United States to Mexico would surely occur, but as part of a process that maximized the extent of human life. In particular, continued exports of pipeline gas from the United States to Mexico is likely socially, as well as privately, economic by my utilitarian criterion. The world curve, which I argue has no specific policy application, but does measure a central tendency of policy-relevant national curves, starts at $10.24 in 2020 and rises to $162.16 in 2100 at 3°, all in 2020 USD. Again, these numbers are based on an equilibrium climate sensitivity of 2.5°C. A different response of temperature to a doubling of CO_2 in the atmosphere would change optimal taxes proportionally.

Figure 5: Global Lorenz curve; 2020

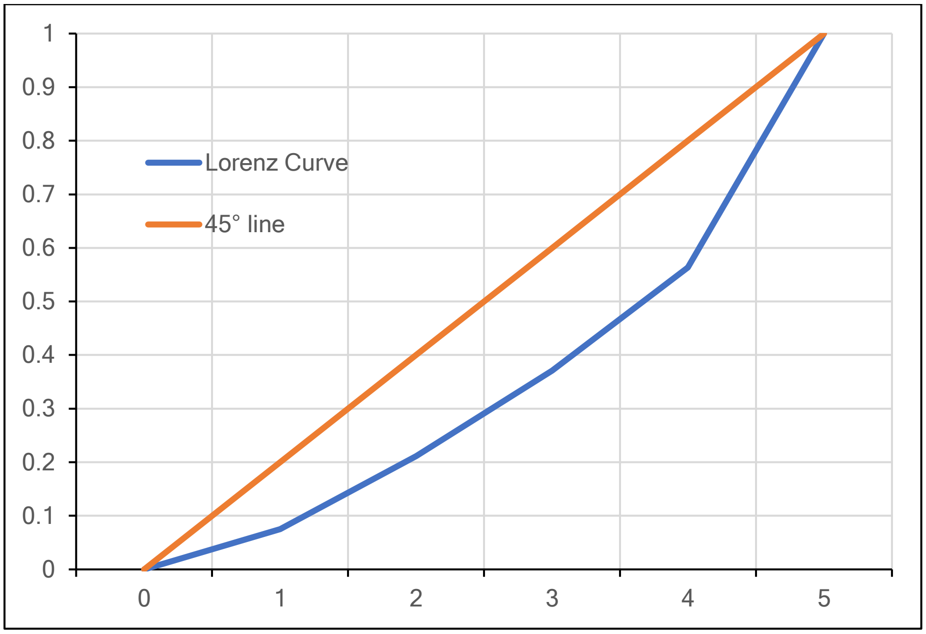
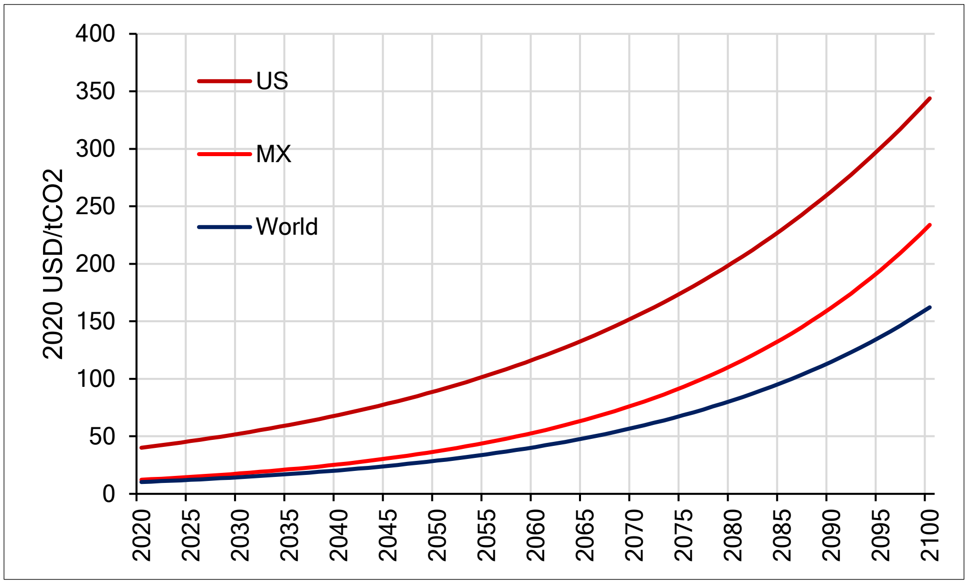


Figure 6: Example optimal CO_2 tax paths for the United States and Mexico, with world average



A well-designed system of lump sum transfers could soften the trade-off between mitigation and utility from consumption of goods, but equating $P^{j}_{CO_2}$ to the marginal cost of mitigation at the observed value of T , whatever that is, should maximize the extent of human life, assuming that it is interpersonally comparable.

Because the tax wedge from Equation (11) is increasing in GMST in all countries, large natural oscillations may also affect the optimal path of mitigation.

I have said nothing here about other greenhouse gases, like CH_4, methane, N_2O, nitrous oxide, and HFCs, hydrofluorocarbons, but even what I have said about CO_2 specifically is only illustrative. The focus is on monetizing temperature, and the illustration can be adapted to any greenhouse gas, once the relationship of concentrations of the gas to GMST is estimated.

7 Further research

Table 6 and Figure 6 do not account for the social costs of ocean acidification due to emissions of CO_2, because those impacts do not work through changes in temperature. Rather, emissions are simply absorbed into ocean water and lower the pH balance. Talberth and Niemi (2018) have done useful work on this, which I estimate adds about \$4.50/tCO$_2$ to the worldwide social demand price for mitigation in 2020. Increased CO$_2$ concentrations may have other effects, good and bad, that do not work through increases in temperature: If CO$_2$ is too low, plants have trouble breathing, and if CO$_2$ is too high, humans do.[16] Currently at 420 ppm, CO$_2$ concentrations are the highest they have been during the 800,000 years for which we have "robust evidence.[17] Hominids have been around for about four million years, so it is not clear how higher concentrations of CO$_2$, apart from their effects through temperature, will affect us.

If I include $CO_2^{1+\gamma}$ in the interaction term in the base case, the term remains highly significant, and, in a 1°, 420 ppm world, as we presently have, the change in consumption needed to "offset" a 1° rise in GMST, holding CO$_2$ constant, increases from 16.38% (from Table 5) to 20.08%, with a 99% confidence band of [0.1764,0.2251], and the change in consumption needed to "offset" a 100 ppm rise in CO$_2$, holding temperature constant, is 4.78%, with a 99% confidence band of [0.0420,0.5359]. A non-interacted $CO_2^{1+\gamma}$ term is not significant, whether included in the interaction term or not.

On the other hand, if new data render a non-interacted temperature term, $T^{1+\gamma}$, significant, its coefficient will likely be positive, lowering the estimated social costs of emissions. At low risk-aversion, the term is already positive and significant at the 95% level, but I omit it from the analysis because the interacted term, which is highly significant, meets the much higher standard. This suggests, though, that preferences regarding risk are a powerful driver of our opinions about climate policy. People with low risk-aversion are more likely to appreciate any prospective benefits from global warming.

Updating the analysis as data become available, especially on temperature anomaly, is also a direction for further research. The existing historical record is informative: A skewness and kurtosis test for normality of the 29 observations of the anomaly in GMST associates a p-value of 0.91 with a null of normality, and, under the assumption of normality, the 99% confidence interval for the coefficient of variation is [0.22,0.48], so the variation in temperature anomaly in this sample is statistically significant. Still, it is much lower than those for the other variables, and the possible future values shown in Table 5 are mainly outside the observed range. It is

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[16] See Allen et al. (2016).

[17] Source: Mulhern (2020).

unknown how such values would affect the chaotic systems that are climate and weather. In Knightian terms (Knight, 1921), this is decision-making under uncertainty, rather than just risk, but decreasingly so as data accumulate.

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Appendix

Restricted risk aversion; derivation of Equation (2)

Certainty equivalent, X_C, to an even bet between C and $2C$.

$$\begin{aligned} E\left(U\left(C\right)\right) &= \frac{1}{2}\left(-C^{1-\sigma} + \beta_0 + \beta C^{1-\sigma} T^{1+\gamma}\right) + \frac{1}{2}\left(-\left(2C\right)^{1-\sigma} + \beta_0 + \beta\left(2C\right)^{1-\sigma} T^{1+\gamma}\right) \\ &= -X_C^{1-\sigma} + \beta_0 + \beta X_C^{1-\sigma} T^{1+\gamma} = U\left(X_C\right) \end{aligned} \tag{21}$$

Let $T = 1$. Cancelling terms,

$$\begin{aligned} -\frac{1}{2}\left(1+\beta\right)\left(C^{1-\sigma} + \left(2C\right)^{1-\sigma}\right) &= -\left(1+\beta\right)X_C^{1-\sigma} \\ -\frac{1}{2}\left(1+\beta\right)\left(1+2^{1-\sigma}\right)C^{1-\sigma} &= -\left(1+\beta\right)X_C^{1-\sigma} \\ \frac{1+2^{1-\sigma}}{2}C^{1-\sigma} &= X_C^{1-\sigma} \\ X_C &= \left(\frac{1+2^{1-\sigma}}{2}\right)^{\frac{1}{1-\sigma}} C \end{aligned} \tag{22}$$

Certainty equivalent, X_T, to an even bet between T and 0.

$$E\left(U\left(T\right)\right)=\frac{1}{2}\left(-C^{1-\sigma}+\beta_0+\beta C^{1-\sigma}T^{1+\gamma}\right)+\frac{1}{2}\left(-\left(2C\right)^{1-\sigma}+\beta_0+\beta\left(2C\right)^{1-\sigma}T^{1+\gamma}\right)$$
$$=-C^{1-\sigma}+\beta_0+\beta C^{1-\sigma}X_T^{1+\gamma}=U\left(X_T\right) \tag{23}$$

Let $C=1$. Cancelling terms,

$$-\frac{1}{2}\beta T^{1+\gamma}=-\beta X_T^{1+\gamma}$$
$$X_T=\left(\frac{1}{2}\right)^{\frac{1}{1+\gamma}}T \tag{24}$$

From $\left(C,T\right)=\left(1,1\right)$, equate the proportional distances to the certainty equivalents.

$$\frac{X_C-1}{2-1}=\frac{X_T-1}{0-1}$$
$$\frac{\left(\frac{1+2^{1-\sigma}}{2}\right)^{\frac{1}{1-\sigma}}-1}{2-1}=\frac{\left(\frac{1}{2}\right)^{\frac{1}{1+\gamma}}-1}{0-1}$$
$$\left(\frac{1+2^{1-\sigma}}{2}\right)^{\frac{1}{1-\sigma}}-1=1-\left(\frac{1}{2}\right)^{\frac{1}{1+\gamma}} \tag{25}$$
$$\left(\frac{1+2^{1-\sigma}}{2}\right)^{\frac{1}{1-\sigma}}=2-\left(\frac{1}{2}\right)^{\frac{1}{1+\gamma}}$$
$$\frac{1}{1+\gamma}\ln\frac{1}{2}=\ln\left(2-\left(\frac{1+2^{1-\sigma}}{2}\right)^{\frac{1}{1-\sigma}}\right)$$

Therefore,

$$\gamma=\frac{\ln\frac{1}{2}}{\ln\left(2-\left(\frac{1+2^{1-\sigma}}{2}\right)^{\frac{1}{1-\sigma}}\right)}-1 \tag{2}$$

Property 1) of the utility function: climate justice

$$
\begin{aligned}
\frac{dU}{dT} &= -\left(1+\gamma\right)\beta C^{1-\sigma}T^{\gamma} < 0 \\
\frac{d}{dC}\frac{dU}{dT} &= -\beta\left(1+\gamma\right)\left(1-\sigma\right)C^{-\sigma}T^{\gamma} > 0
\end{aligned}
\tag{26}
$$

Property 2) of the utility function: diminishing marginal utility of consumption

$$
\begin{aligned}
\frac{dU}{dC} &= -\left(1-\sigma\right)C^{-\sigma} - \beta\left(1-\sigma\right)C^{-\sigma}T^{1+\gamma} > 0 \\
\frac{d}{dC}\frac{dU}{dC} &= \sigma\left(1-\sigma\right)C^{-1-\sigma}\left(1+\beta T^{1+\gamma}\right) < 0
\end{aligned}
\tag{27}
$$

Property 3) of the utility function: positive discounting when consumption grows

Let consumption in Year 1 be C and consumption in Year 2 be $\left(1+g\right)C$, while T is the temperature anomaly in 2020 and $T+\Delta$ is the temperature anomaly in 2100. Optimally, the present value of utility would be the same in both periods. Since utility is negative when given by Equation (1), the discount rate enters with a negative sign:

$$
\begin{aligned}
-C^{1-\sigma} + \beta_0 - \beta C^{1-\sigma}T^{1+\gamma} &= \frac{-\left(\left(1+g\right)C\right)^{1-\sigma} + \beta_0 - \beta\left(\left(1+g\right)C^{1-\sigma}\right)\left(T+\Delta\right)^{\frac{1+\gamma}{2100-2020}}}{1-r} \\
1-r &= \frac{-\left(\left(1+g\right)C\right)^{1-\sigma} + \beta_0 - \beta\left(\left(1+g\right)C^{1-\sigma}\right)\left(T+\Delta\right)^{\frac{1+\gamma}{2100-2020}}}{-C^{1-\sigma} + \beta_0 - \beta C^{1-\sigma}T^{1+\gamma}}
\end{aligned}
\tag{28}
$$

Letting C and T equal unity, where the former is normalization, and the anomaly was actually one in 2020,

$$
\begin{aligned}
1 - r &= \frac{-\left(1+g\right)^{1-\sigma} + \beta_0 - \beta\left(1+g\right)^{1-\sigma}\left(1+\Delta\right)^{\frac{1+\gamma}{2100-2020}}}{-1+\beta_0-\beta} \\
r &= 1 - \frac{\left(1+g\right)^{1-\sigma}\left(1+\beta\left(1+\Delta\right)^{\frac{1+\gamma}{2100-2020}}\right) - \beta_0}{1+\beta-\beta_0}
\end{aligned}
\tag{29}
$$

Property 1) of the optimum: convexity of (4)

$$
\begin{aligned}
\frac{dC}{dT}\frac{1}{C} &= -\frac{\beta\left(1+\gamma\right)T^{\gamma}}{\left(1+\beta T^{1+\gamma}\right)\left(1-\sigma\right)} \\
\frac{dC}{dT}\left(\frac{dC}{dT}\frac{1}{C}\right) &= -\frac{\gamma\beta\left(1+\gamma\right)T^{\gamma-1}\left(1+\beta T^{1+\gamma}\right)\left(1-\sigma\right) - \left(1+\gamma\right)\beta T^{\gamma}\left(1-\sigma\right)\beta\left(1+\gamma\right)T^{\gamma}}{\left(\left(1+\beta T^{1+\gamma}\right)\left(1-\sigma\right)\right)^{2}} \gtrless 0
\end{aligned}
\tag{30}
$$

Cancelling terms,

$$
\begin{aligned}
&\gamma T^{-1}\left(1+\beta T^{1+\gamma}\right) - \left(1+\gamma\right)\beta T^{\gamma} \lessgtr 0 \\
&\gamma\left(1+\beta T^{1+\gamma}\right) \lessgtr \left(1+\gamma\right)\beta T^{1+\gamma} \\
&\gamma + \gamma\beta T^{1+\gamma} \lessgtr \beta T^{1+\gamma} + \gamma\beta T^{1+\gamma} \\
&\gamma \lessgtr \beta T^{1+\gamma}
\end{aligned}
\tag{31}
$$

Property 2) of the optimum: Mitigation is a normal good.

$$\begin{aligned}
\frac{dC}{dT} &= -\frac{\beta\left(1+\gamma\right)CT^{\gamma}}{\left(1+\beta T^{1+\gamma}\right)\left(1-\sigma\right)} > 0 \\
\frac{d}{dC}\frac{dC}{dT} &= -\frac{\beta\left(1+\gamma\right)T^{\gamma}\left(1+\beta T^{1+\gamma}\right)\left(1-\sigma\right)}{\left(\left(1+\beta T^{1+\gamma}\right)\left(1-\sigma\right)\right)^{2}} \\
&= -\frac{\beta\left(1+\gamma\right)T^{\gamma}}{\left(1+\beta T^{1+\gamma}\right)\left(1-\sigma\right)} > 0
\end{aligned} \tag{32}$$