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The ultimate cost of carbon

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Abstract
We estimate the potential ultimate cost of fossil-fuel carbon to a long-lived human population over a one million–year time scale. We assume that this hypothetical population is technologically stationary and agriculturally based, and estimate climate impacts as fractional decreases in economic activity, potentially amplified by a human population response to a diminished human carrying capacity. Monetary costs are converted to units of present-day dollars by multiplying the future damage fractions by the present-day global world production, and integrated through time with no loss due from time-preference discounting. Ultimate costs of C range from $10k to $750k per ton for various assumptions about the magnitude and longevity of economic impacts, with a best-estimate value of about $100k per ton of C. Most of the uncertainty arises from the economic parameters of the model and, among the geophysical parameters, from the climate sensitivity. We argue that the ultimate cost of carbon is a first approximation of our potential culpability to future generations for our fossil energy use, expressed in units that are relevant to us.

Keywords Climate impact · Carbon cycle · Deep future · Cost of carbon

1 Introduction

The social cost of carbon (SCC) is a concept that was formulated to account for climate change in cost-benefit analysis (Nordhaus 1982, Pearce 2003, Stern 2006, Greenstone et al. 2013, National Academies of Sciences 2017. Costs from climate change are imposed on models of

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the human economy, assessed relative to a control case without climate change. The present-day value of future costs is obtained by discounting (Ramsey 1928). For emissions in 2010 and discount rates of 2–5%, the SCC is estimated to be about \$20–50 per ton of CO_2 (\$70–180 per ton of C) although higher values have been proposed (Ackerman and Stanton 2012, Kopp and Mignone 2012, Greenstone et al. 2013, Moyer et al. 2014, Moore and Diaz 2015, Nordhaus 2017).

Because future damages are discounted to calculate their present-day values, costs that accrue more than a few centuries into the future become negligible to the present. However, the time scales of the carbon cycle, sea level change, and soil responses to present emissions are much longer than this and are mostly missed by the SCC (National Academies of Sciences 2017). This paper formulates and estimates an ultimate cost of carbon (UCC), integrated over the entire geophysical response to the human climate perturbation. The formulations of the UCC and the SCC are contrasted in Table 1. The two metrics are based on irreconcilably different assumptions, and apply over different time frames, and are therefore not simply or directly comparable.

2 Methods

2.1 Model formulation

It is impossible to predict the deep future of humanity, so our formulation leaves out any consideration of human technological development. The UCC is based on climate impacts to a hypothetical human population that is technologically stationary, agrarian, and in steady state with the carrying capacity of the planet. This unrealistic formulation is not a prediction, but a necessary idealization that makes the problem tractable to address, and the result easy to visualize.

Table 1 Comparison of the social and ultimate costs of carbon

	Social cost of carbon (SCC)	Ultimate cost of carbon (UCC)
Goal	Present-day net value of present and future costs, which are discounted due to assumed future growth and preference for present-day welfare	Equivalent value of cumulative future costs, in present-day units, based on extrusion of our present-day world into the indefinite future. With no growth, the discount rate = 0%.
Characteristic time scale	30 years, set by discount rate	10 to 200 kyr, set by landscape processes or the geological carbon cycle
Economic model	Extrapolated labor and predicted capital are combined using a specified or predicted productivity coefficient	Human activity, population, and economy are equal to present day, scaled by decreases in the planetary carrying capacity
Climate costs	Fractional decrease in economic production relative to a no-warming control	same
Utility function	Average (per capita), taken as the log of consumption (GWP/cap). Near-future population changes are usually specified or strongly influenced by inertia of the present day.	Total utility (GWP). Costs accrue linearly, in units of present-day dollars, rather than logarithmically. Human population in the distant future is determined by steady-state carrying capacity.
Cost basis	Marginal cost of emitting one additional ton of C, given what has already been emitted	Average cost of all carbon ever emitted (total cost/cumulative emission)
Value, \$/ton C	Typically < \$100	\$10,000–\$600,000

2.2 Economic formulation

Climate damages in the model are cast in the form of a fractional decrease of economic activity between a warming case and a no-warming control. The control case is assumed to have a steady, persistent economic productivity equal to the present-day gross world production (GWP) of $100 trillion/year. Future fractional changes in human activity are multiplied by the present-day GWP to tabulate costs in units of present-day dollars.

If in an alternate scenario the GWP were to grow before plateauing at, for example, a higher steady GWP than we have today, the actual dollar cost from climate damages would be higher than we calculate. A UCC defined in actual dollars, including growth, would be impossible to constrain, because the long-term economic and technological future of humanity is impossible to reliably predict, and it is beyond the scope of this paper to try. In our formulation, scaling future damage fractions by present-day GWP, we are valuing the fractional climate damages to future generations as though they applied to our own world: valuing the existence of future generations, rich or poor, as much as we value ours. Normalizing to present-day GWP puts the result in units of present-day dollars, making it easy to visualize.

Uncertainty in future growth undermines the use of the UCC in any calculation of optimality. Comparing it with the SCC or costs of mitigation also requires relating costs through deep time, which remains a question for economics, futurology, and moral philosophy, and is also beyond the scope of this paper. The UCC is cast in units of present-day dollars, but it cannot be taken to the bank, exactly. It is a scale bar for climate damages, presented in modern-day terms.

It seems likely that the dominant impact of our fossil fuel use on the world and human activity 100,000 years from now will be through persistent changes in climate, rather than by our fossil-fuel-based construction of some long-lived economic infrastructure or persistent wealth. If this is the case, the UCC can be seen as a first approximation of our potential culpability to future generations, expressed in units that are meaningful to us.

The costs are accrued linearly, even though the welfare benefit of consumption is typically treated as logarithmic (for example, Golosov et al. 2014), for clarity and because the economies of the hypothetical worlds differ by order tens of percent, a relative range over which the log function is approximately linear. The scaled costs from all future years are accumulated through time, with no loss due to discounting, analogously to how one would time-integrate a CO_2 source to get cumulative emissions that drive climate change. In the exponentially growing world of economics and finance, relating value across time requires consideration of how future values should be discounted. The discount rate, r, used to calculate the present-day value of a future cost (Ramsey 1928), is calculated as

$$r = \delta + \eta g$$

where δ is a pure rate of time preference (concern for the future vs. eating dessert first), g is the growth rate of per capita income, and η is the elasticity of the marginal utility of consumption (expressing the different impacts of giving an extra dollar to a rich versus a poor person). The pure time preference may be larger than 0% to reflect a selfish interest in the present day, but to express a particular ethical position, or if we assume that the representative individuals in the scenario live forever, δ might be set to 0% (Stern 2006).

The growth term ($\eta\, g$) expresses the idea that a cost, fixed in dollars, would be relatively smaller in a wealthier future. In the formulation for the UCC, the assumption of steady state

requires that the growth rate $g = 0\%$ under conditions of constant planetary habitability. Under these idealized conditions, values are combined through time using a discount rate r equal to 0%.

In addition to direct climate impacts on the economy due to impacts on worker productivity, storm damage, etc. (Weitzman 2009, Howard and Sterner 2017, Hsiang et al. 2017, National Academies of Sciences 2017, Burke et al. 2018), in the long-term steady state, there is a potential population feedback that could impact the scale of the human enterprise. In economic models of climate change, GDP does not respond strongly to changes in agricultural land (Nordhaus 2017). On the longer time scales of the UCC, a steady-state population declines by definition in response to a decrease in Earth's carrying capacity or agricultural potential, just as wildlife populations are declining now, in response to decreasing undisturbed range. This might not affect the well-being of individuals (GWP per capita), but its impact on the total utility (GWP) counts as a cost in the UCC. From the perspective of people living in the no-warming control case, the loss of some fraction of their world would seem costly, as it would to us if we were to sacrifice some fraction of our world today. Decreasing the scale of a future human population would increase their risk of extinction and decrease their scope for creativity (Parfit 2017).

2.3 Biophysical formulation

The analysis in this paper is based on a simple numerical model, coded in python, of temperature, sea level, and economic response to global warming (see supplemental materials). In order to capture the entire climate perturbation until the eventual natural uptake of the fossil fuel carbon, the model is run one million years into the future (Walker and Kasting 1992, Archer et al. 1997, Archer 2005, Archer and Brovkin 2008, Archer et al. 2009, Eby et al. 2009, Clark et al. 2016).

2.3.1 Evolution of atmospheric CO_2

The scenario begins with the instantaneous release of 1000–5000 Gton C to the atmosphere. The high end of this range is commonly taken as complete fossil fuel utilization (Sundquist 1985; Archer et al. 1997; Caldeira and Wickett 2005). Most of the available fossil carbon is in the form of coal, the extractable inventory of which has at least a factor of three uncertainties (Rogner 1997; Rutledge 2011; Ritchie and Dowlatabadi 2017). Business as usual projections, without mitigation, result in the release of about 1300 Gton C by the year 2100, with an additional few centuries required to emit the full 5000 Gton C. The model does not attempt to resolve the dynamics of the CO_2 release and equilibration with the ocean, on time scales of decades to centuries, because the costs accruing on these time scales are negligible compared with those accruing over millions of years. The first parameter in the model is the amount of CO_2 release (Table 2).

Natural carbon-cycle feedbacks may amplify or ameliorate the anthropogenic carbon release. The land surface biosphere has been taking up anthropogenic CO_2 (Tans 2009), for reasons that are not well known but might be a response to a longer growing season, or fertilization due to the rise in atmospheric CO_2 or nitrate deposition. However, a dominant response looking forward is a release of carbon from the decomposition of thawing permafrost soils, which contain thousands of gigatons of C (Lawrence and Slater 2005, Zimov et al.

Table 2 Parameters to the geophysical component of the model

Parameter name	Description	Value note
CReleaseGton	Gigatons of anthropogenic carbon	The buffer chemistry in the model is intended for the range 1000–5000 Gton C
CFeedbackFactor	Fraction by which the natural carbon cycle amplifies the human source	Presumably < 1.5, or else the natural carbon cycle would be observably tippier (Archer and Buffett 2005)
oceanAcidTime	Time scale for pH recovery of the ocean, years	Probably a few thousand years (Broecker and Peng 1987) (Archer et al. 1997)
thermostatTime	Time scale for atmospheric CO_2 recovery, years	About 200 kyr from models (Berner 2006), probably longer than the 100-kyr glacial interglacial cycles
warmingTime	Time scale for temperature equilibration	Governed by ocean circulation, in reality a range of time scales up to about 1000 years (Bala et al. 2005).
iceMeltingTime	Time scale for collapsing ice sheets, years	Models find time scales of a few thousand years (Clark et al. 2016), but could be centuries (Hansen et al. 2016)
dt2X	The equilibrium climate sensitivity, degrees C per doubling of CO_2	Range from IPCC Fifth Assessment Report is 1.5–4.5 °C (IPCC 2014)

2009). The lack of runaway carbon greenhouses in the paleoclimate record suggests the magnitude of this feedback is probably less than 1.5 (Archer and Buffett 2005).

The CO_2 perturbation relaxes back to zero on two time scales, representing different stages of the response. First, on a shorter time scale, acidification of the ocean drives an imbalance in the weathering and burial of $CaCO_3$, which ultimately restores the pH of the ocean (Broecker and Peng 1987; Archer et al. 1997; Caldeira and Wickett 2005), replenishing its buffer capacity to absorb CO_2. Second, a longer time scale, the excess CO_2 from the surface "fast" carbon cycle (atmosphere, ocean, land surface) is removed by enhanced weathering of calcium-bearing igneous rocks (Berner 2006), which carry CO_2 back to the deep Earth as $CaCO_3$. This process is known as the rock weathering "thermostat." Each exponential decay is parameterized by an initial "airborne" component of the released CO_2 (residing in the atmosphere), and a time scale, as

$$C_{\mathrm{Atm}} = C_{\mathrm{AtmInit}} + C_{\mathrm{Release}}\left(A_{\mathrm{OcnEquil}}\, e^{-\lambda_{\mathrm{Acid}} t} + A_{\mathrm{Neut}}\, e^{-\lambda_{\mathrm{Thermostat}} t}\right)$$

where C denotes a mass of carbon in gigatons as CO_2, A an initial airborne fraction, and λ a time scale in years. The airborne fractions, A_{OcnEquil} and A_{Neut}, are taken from the carbon cycle model results from the "long tail" model intercomparison project (Archer et al. 2009) (Fig. 1). The airborne fraction values from the models at 1000 years are taken to be representative of the stage in which the ocean is acidified, after CO_2 invasion but mostly before $CaCO_3$ dissolution neutralizes the acidity of the fossil CO_2. The airborne fractions at 10,000 years are taken to represent neutralized ocean conditions, which will subside on the rock weathering "thermostat" time scale. The simulations show higher airborne fractions for 5000-Gton C release experiments than for 1000 Gton C, due to exhaustion of the buffer chemistry of the ocean before its restoration by $CaCO_3$ compensation. For release between 1000 and 5000 (for marginal cost estimation), the airborne fraction values are interpolated.

The time scale for ocean pH neutralization has been estimated to range between 1000 and 10,000 years (Broecker and Peng 1987; Archer et al. 1997; Archer et al. 1998; Caldeira and Wickett 2005). The decrease in the ocean concentration of carbonate ion (CO_3^{2-}) causes a

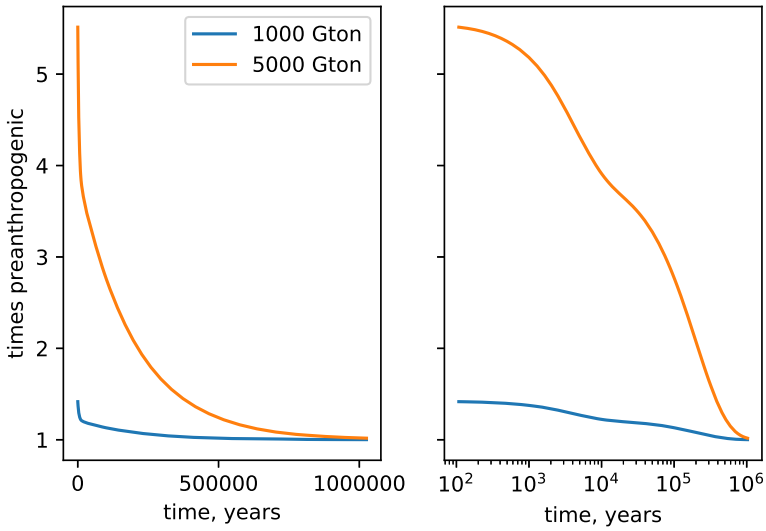

Fig. 1 Atmospheric CO_2 evolution in the model. Results from 1000 and 5000 Gton C anthropogenic CO_2 releases are plotted on a linear time scale on the left, and a log scale on the right

decrease in $CaCO_3$ production (Riebesell et al. 2000), and an increase in sedimentary $CaCO_3$ dissolution (Archer et al. 1998), while the increase in atmospheric CO_2 and the increase in temperature lead to an increase in terrestrial $CaCO_3$ weathering (Liu et al. 2018), all of which contribute to the neutralization response. The ocean pH evolution through the glacial cycles serves as a constraint on this response time, but it is complicated by a significant deglacial increase in shallow-water $CaCO_3$ deposition on flooding continental shelves (Milliman 1993).

The time scale for ultimate CO_2 removal by the weathering thermostat is set by the rates of geochemical weathering reactions, combining a CaO component of igneous rocks with CO_2 to produce $CaCO_3$, the pathway for carbon return to the deep Earth. These reactions, balanced against natural CO_2 degassing from the Earth, comprise a planetary carbon cycle thermostat system (Walker et al. 1981, Berner et al. 1983). The time constant for reaching the equilibrium CO_2 concentration is estimated from the Geocyc model (Archer et al. 2009, http://climatemodels.uchicago.edu/geocyc/, based on Berner et al. 1983) to be about 200 ,000 years.

The weathering thermostat time scale is informed by reconstructions of the past. The Paleocene-Eocene thermal maximum event can be taken as an analog to global warming, with a fast release of isotopically light carbon, a resulting climate warming, and a gradual recovery. The event as recorded in ocean sediments has a smooth exponential recovery with a time scale of ~ 100,000 years (Zachos et al. 2001). The more recent glacial cycles included large swings in atmospheric CO_2, the 100-kyr durations of which set a lower limit to the response time, consistent with our best estimate of a 200-kyr response time.

The anthropogenic impact on climate will take place within the context of natural climate variability, driven through glacial/interglacial cycles resulting, in part, from wobbles in Earth's orbit around the sun. However, Earth's orbit around the sun is currently approaching circularity, as it does every 400 kyr, minimizing variations in sunlight intensity and leading to an expected long interglacial interval like Marine Ice Sheet Stage 11 about 400 kyr ago (Paillard 2001). The rhythm of the ice ages complicates the impact of global warming, but less so than if we had started industrial activity 200 kyr ago when orbital variations in sunlight intensity were

more intense (Archer and Ganapolski 2005). It would no doubt be costly to descend into another ice age, but if this was a motivating factor in fossil energy use, our carbon stock could be deployed more strategically by waiting until the descent into an ice age is imminent (Shaffer 2009).

In summary, the carbon drawdown dynamics are idealized but well understood relative to other parts of this analysis. Atmospheric pCO_2 values are plotted as a function of time in Fig. 1.

2.3.2 Global mean temperature anomaly

The equilibrium temperature for a given atmospheric CO_2 concentration is calculated from the climate sensitivity as

$$T_{\text{equil}} = \Delta T_{2x} \times \frac{\ln\left(\frac{pCO_2}{pCO_{\text{init}}}\right)}{\ln(2)}$$

where ΔT_{2x} is a parameter in the model and is thought to be in the range of 1.5–4.5 °C for doubling CO_2 (IPCC 2014).

The temperature of the Earth relaxes toward T_{equil} on a time scale specified as a model parameter, warmingTime. The initial T_{evolving} is taken to be 80% of the initial T_{equil} value, as an approximation to the present day, and it relaxes toward T_{equil} as

$$\Delta T_{\text{evolving}} = \left(T_{\text{equil}} - T_{\text{evolving}}\right) \times \frac{\Delta t}{\text{warming Time}}$$

After the initial temperature transient, T_{evolving} is taken as equal to T_{equil} as a numerically stable approximation. The evolution of temperature for the two values of CO_2 releases is shown in Fig. 2.

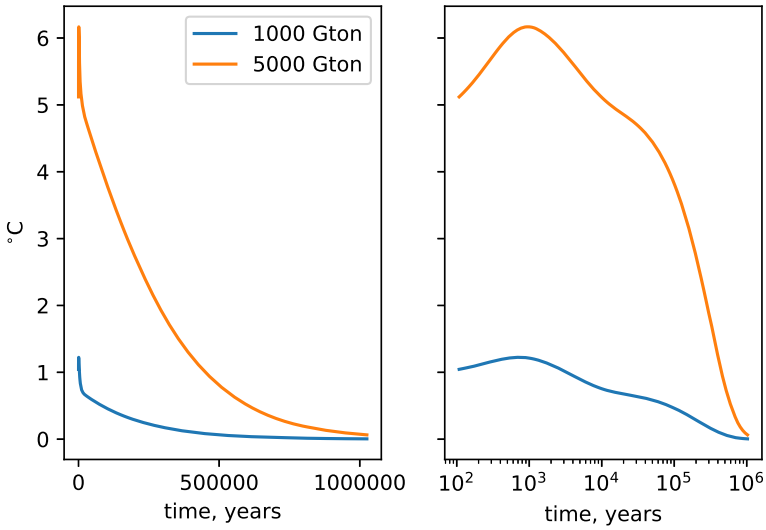

Fig. 2 Model global temperature anomalies from releases of 1000 and 5000 Gton C

2.3.3 Sea level

The time scale for the ice sheet response is thought to be a few millennia, based on ice sheet modeling (Alley et al. 2005) and the general time scale of sea level change recorded in oxygen isotopic composition of ice cores (Hays et al. 1976). However, past intervals of sea level rise have been faster than this, including the Heinrich events (Broecker et al. 1992) and deglaciation (Fairbanks 1989). A positive feedback between ice sheet melting, meltwater, and ocean stratification has been proposed to explain the fast sea level rise events of the past, suggesting a potential sea level rise time scale of centuries, rather than millennia, in our future (Hansen et al. 2016). Also, a real ice sheet grows until it melts at its base, at which point it collapses rapidly (Macayeal 1993; Paillard 1998). The simple exponential-relaxation-to-equilibrium sea level model used here is simpler than we expect from reality, and if anything conservative in response time and possible tipping behavior.

Ultimate sea level rise in the model (Fig. 3) is driven by the temperature anomaly, based on observed covariation of sea level and global temperature from paleoclimate reconstructions (Archer and Brovkin 2008). The forecast for the year 2100 is for about 1 m of sea level rise (Rahmstorf 2007, Kopp et al. 2017), but a full climate/ice sheet model run for thousands of years found sea level rise of 50 m (Alley et al. 2005; Clark et al. 2016). The discrepancy is due to timing, in that ice sheets will presumably not have time to equilibrate by the year 2100.

The ice sheets in the model recover on the time scale of the ultimate CO_2 drawdown by the weathering thermostat. This simple one-way forcing (CO_2 drives ice) is an idealization and neglects whatever mechanism or (more likely) mechanisms (Archer et al. 2000, Ganopolski and Brovkin 2017) were at work through the glacial cycles, when changes in orbital forcing and ice sheet dynamics drove a feedback atmospheric CO_2 response. Because atmospheric CO_2 is driven by human sources today, it would be speculative to predict how the natural CO_2 ice sheet deglaciation feedback might operate in the future.

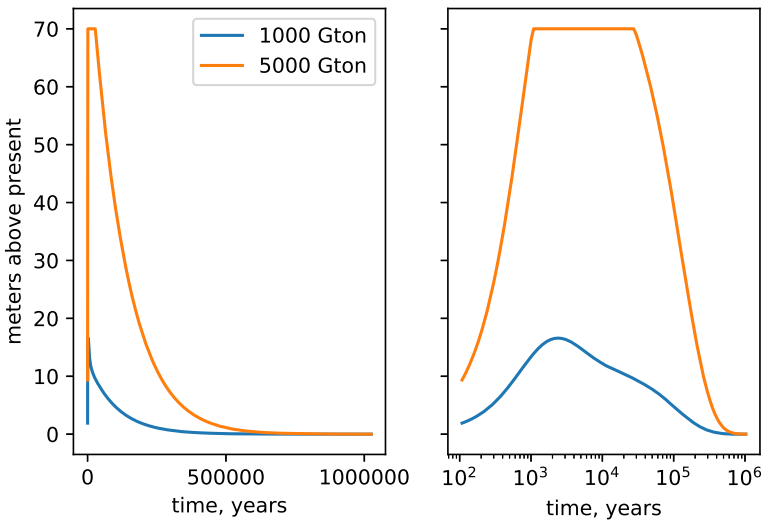

Fig. 3 Sea level responses of the model

2.4 Impacts

In our formulation, costs accrue due to two factors: directly due to an altered climate and due to sea level rise. Both are calculated based on coefficients in % GWP/°C and % GWP/meter (Table 3).

2.4.1 Costs due to climate

Economics models have been used to predict the impact of warming on the economic productivity of the near future. From the perspective of deep time, this scenario consists of a short-term impact of a sudden shift in climate on an existing population and infrastructure. Remembering that our formulation is an idealization in which technological innovation is not allowed, we project these global costs forward into the deep future as a provisional starting point.

For relatively conservative temperature changes of 3 °C, the models that are used in SCC calculations predict 0–1%/°C (Greenstone et al. 2013). Studies cited in the IPCC scientific assessments, for temperature changes of 2.5 °C, had mean values of about 0.6%/°C (Tol 2016). Values from Burke et al. (2015), for 3 °C of warming, range between 2.6 and 20%/°C. Based on these results, our analysis assumes 1% GDP/°C in damages directly from climate change. The linear dependence of the model will be conservative in that it excludes the possible catastrophic changes at high degrees of warming (Weitzman 2009).

On time scales longer than a few human generation times, we might expect a human population response to changes in agricultural potential. Crop yields decrease significantly at temperatures above 30–34 °C (Porter et al. 2014), and continental interiors are expected to systematically dry in a warming world (Byrne and O'Gorman 2015). These constraints suggest that the agricultural capacity of a 3 °C warmer world could be decreased by 10% relative to the no-warming control case (Hsiang et al. 2017), or about 3%/°C.

2.4.2 Costs due to sea level rise

The long-term costs of sea level rise become significant if we assume a human population response to the loss of present-day agricultural land.

Figure 4 a shows the cumulative fraction of land area, crop and pasture land, and population as a function of elevation above sea level. These curves were generated from digital gridded density fields for population (SEDAC, NASA, 2.5 min grid), and crop and pasture land (Ramankutty et al. 2008), interpolated into a gridded field of elevation (ETOPO2, National

Table 3 Parameters to the economic component of the model

Parameter name	Description	Value note
climCostFactor	Economic penalty due to climate change, in percent GDP per degree C	1%/°C is in the range of IAM results
seaLevelCostFactor	Economic penalty due to sea level rise, in percent GDP for complete melting (70 m)	15% of present-day cropland could be flooded (Fig. 4)
econRecoveryTime	Economic recovery time scale for both types of cost.	This could be a soil generation time scale of 10 kyr or a CO_2 thermostat time of 200 kyr

Geophysical Data Center 2006). The cumulative areal loss of cropland increases more quickly with sea level rise than total land area loss, reflecting higher than average agricultural productivity in low-lying soils, especially fertile river deltas near sea level.

A sea level rise of 70 m would inundate about 15% of present-day cropland (and 5% of pasture land). We postulate that a decrease in agricultural land would translate eventually into a decrease in human population and economic activity, with 70 m thus reducing GWP by 15%.

2.4.3 Mechanism and time scale for economic recovery

A major uncertainty in the model is how long the climate impacts would persist as costs (as per the formulation, in the absence of technology change or adaptation to climate). Both types of costs, due to climate change and sea level rise, might be ameliorated by human migration to higher latitudes. It is possible that some low-latitude regions might become uninhabitable wastelands in a much warmer world (Sherwood and Huber 2010), but there is a lot of currently uninhabited land area in the high latitudes that could be more hospitable to human societies in a warmer world (Fig. 5). A limitation on how quickly humankind could move to high latitudes might arise from the time scales of soil formation, for example, in the Canadian Shield region. If the opening of new landscapes for human habitation compensates for loss of habitability in the topics, then the time scale for economic recovery might be set by the soil formation time scale, rather than that for ultimate CO_2 drawdown.

It has been argued that the abundance and quality of the soil have been a strong determinant in the rise and fall of civilizations through the past 5000 years (Montgomery 2007). Soil is derived from weathering of primary bedrock reacting with water, catalyzed biologically by bacteria, plant roots, and deposit-feeding animals. The rate of production of soil is slow by human standards; accumulation rates of a few centimeters per century or less are common,

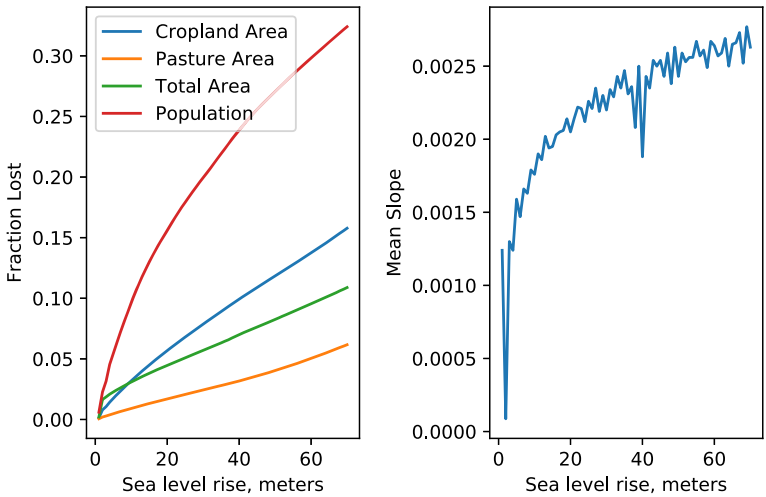

Fig. 4 **a** Cumulative area fractions lost of present-day land surface, cropland, pasture land, and population, as a function of sea level rise. Generated from digital gridded density fields for population (SEDAC, NASA, 2.5-min grid), and crop and pasture land (Ramankutty et al. 2008), interpolated into a gridded field of elevation (ETOPO2, National Geophysical Data Center, 2006). **b** Mean land surface slope as a function of elevation above present-day sea level (ETOPO2, National Geophysical Data Center, 2006)

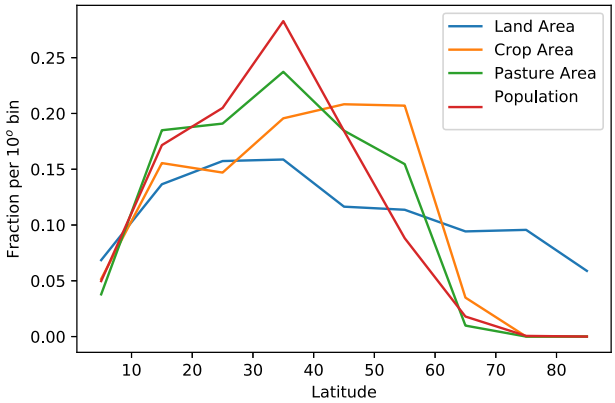

Fig. 5 The distribution of land surface area, croplands, pasture lands, and population as a function of latitude (data from SEDAC, NASA, 2.5-min grid and Ramankutty et al. 2008)

resulting in an overall soil formation time scale that might be of order 10 kyr (Minasny and McBratney 2001).

On time scales of 10 to 100 millennia, the global soil reservoir will have time to evolve through a series of steady states where soil loss must be balanced by soil production. The impact of human soil stewardship will be a primary driver, but it is impossible to predict, so we are left to consider long-term changes in the potential of the land surface to create new soil. This might be affected by the changes in climate (in particular the drying of continental interiors) and by the change in the landscape due to sea level rise. Soil naturally travels downslope, accumulating in flat lowland valleys. Figure 6 shows the average landscape grade derived from ETOPO2 plotted as a function of the elevation above sea level. The average grade at an elevation of 50 m is twice as steep on average as it is a sea level. The sediment transport in riverine flow that currently deposits in low-lying river deltas (at 50-m elevation or less) would be lost to the ocean in a higher sea level world. This effect would subside as flooded valleys become filled with sediment, as is happening today after deglacial sea level rise in, for example, Chesapeake Bay, on a time scale of up to tens of thousands of years.

Leaving unresolved the question of whether the pace of economic recovery will be set by the time scales of soil development or ultimate carbon cycle, our analysis posits a range of possibilities from 10 to 200 kyr (Table 4).

2.5 Sensitivity analysis

Uncertainty ranges for the parameters are estimated in Table 5 and propagated to cost estimates using a Monte Carlo method (Suppl. Fig. 1). The model is run, varying one parameter at a time, with log-uniform probability across a specified range, holding all other parameter values unvarying at the mean between their minimum and maximum values. Then the model is run varying all parameters simultaneously but independently, first for just the geophysical parameters, then for all parameters, economic and geophysical. The total amount of C emitted is varied along with the rest of the parameters, through a range of 1000–5000 Gton C, but the results are normalized into units of $/Gton C for all statistical treatment. Increasing the number of realizations beyond 10,000 has only a small impact on the results.

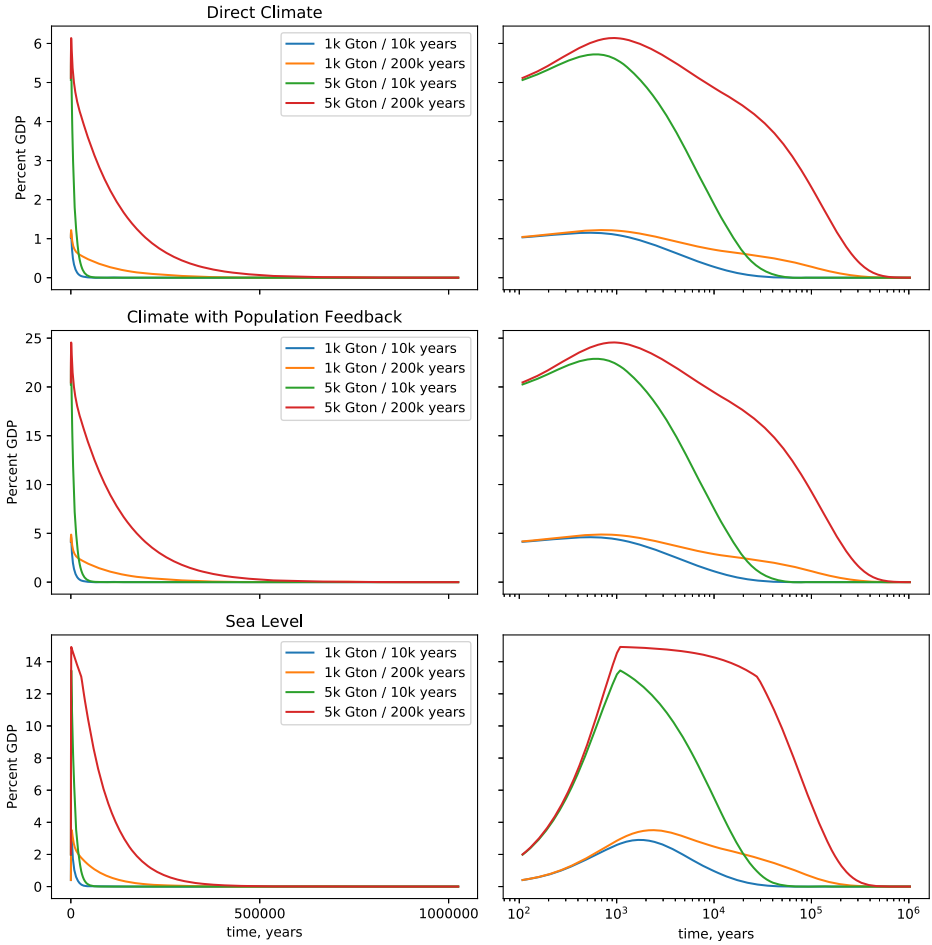

Fig. 6 The time trajectory of economic costs from the model

3 Results

Projected costs are plotted in Fig. 6 and summarized in Table 4, for two values of the carbon release magnitude (1000 and 5000 Gton C) and two values of the time scale for economic recovery (10,000

Table 4 Costs, in $1000/ton C

Carbon release, Gton C	Recovery time scale, years	Direct climate cost	Costs assuming a population feedback		
			Climate	Sea level	Total
1000	10 kyr	8.3	33.1	25.8	59.0
	200 kyr	75.2	301.0	180.3	481.3
5000	10 kyr	10.2	40.8	27.5	68.3
	200 kyr	121.2	484.9	265.1	750.1

Table 5 Monte Carlo uncertainty analysis

	Parameter range			Climate cost $k/ton			Sea level cost $k/ton			Total cost		
	Low	High	Base	Median	Sigma	pct	Median	Sigma	pct	Median	Sigma	pct
Base				70.9			27.3			98.2		
CReleaseGton	1000	5000	2236	70.8	7.5	11%	27.3	2.7	10%	98.1	10.1	11%
CFeedbackFactor	0.1	0.5	0.2	71.4	3.1	4%	27.5	1.2	4%	98.9	4.3	4%
oceanAcidTime	2000	8000	4000	70.7	1.4	2%	27.2	0.6	2%	97.9	2.0	2%
thermostatTime	100,000	400,000	200,000	69.2	4.3	6%	26.1	3.1	12%	95.4	7.4	8%
warmingTime	100	1000	316	70.9	0.0	0%	27.3	0.0	0%	98.2	0.1	0%
iceMeltingTime	300	3000	949	70.9	0.0	0%	27.4	0.7	3%	98.2	0.7	1%
dT2x	1.5	4.5	2.6	70.2	21.1	29%	27.1	8.1	29%	97.3	29.2	29%
climCostFactor	1	4	2	68.6	30.1	40%	27.3	0.0	0%	95.9	30.1	29%
SLCostFactor	1	15	3.9	70.9	0.0	0%	35.0	29.7	72%	105.9	29.7	27%
econRecoveryTime	10,000	200,000	44,721.4	71.8	55.2	64%	27.6	16.5	54%	99.5	71.7	61%
AllGeo				66.4	23.1	33%	26.4	8.7	32%	92.6	31.6	32%
All				87.1	76.1	75%	29.7	57.1	105%	135.5	120.3	77%

and 200,000 years). The coefficient for direct climate costs is 1% GWP/°C, while accounting for a human population feedback raises the value to 4%/°C, and that for 70 m sea level rise to 15% GWP.

The costs per ton C are relatively similar between 1000 and 5000 Gton C scenarios, compared with much larger differences between the cases of slow versus fast economic recovery. For direct climate costs only, the total cost is around $10k per ton if the recovery rate is set by soil formation in high latitudes, or roundly $100k per ton if the economic recovery has to await the ultimate drawdown of CO_2. The costs that presume a population feedback come to roundly $60k/ton and $600k/ton for the fast and slow recovery rates, respectively.

Using the median values of all input parameters, the costs are about $98k/ton C. The 1σ uncertainty due to the geophysical parameters is about $34k, and due to geophysical plus economic parameters, about $116k, with the distribution skewed toward higher costs in all cases. Costs are simply linearly proportional to the cost coefficients, and nearly linearly dependent on the economic recovery time scale (Suppl Fig. 2). Among the geophysical parameters, the climate sensitivity contributes the most overall uncertainty, followed by the amount of carbon released and the time scale for ultimate CO_2 drawdown.

4 Discussion

The cost of abating our ongoing CO_2 emissions has been estimated to be in the range $10–100 per ton of C (Enkvist et al. 2009). Failing that, the cost of chemically removing a ton of C as CO_2 from the atmosphere using industrial chemical engineering methods has been estimated to be $2200 (Socolow et al. 2011) or $360 (Keith et al. 2018). These estimates are much lower than the ultimate cost of carbon and would be a bargain if the UCC was directly fungible with present-day mitigation costs. However, it might not in the self-interest of any single generation to pay to clean it up, since no single generation would pay the entire ultimate climate costs.

The total cleanup costs would be enormous. A return to a "safe" atmospheric CO_2 concentration of 350 ppm (Hansen et al. 2005) within a few decades would require removing about 440 Gton C (using the ISAM carbon cycle/integrated assessment model at http://climatemodels.uchicago.edu/isam/(Cao and Jain 2005)). At a cost of $360 per ton of C (Keith et al. 2018), the total cleanup debt today is about $160 trillion, about 1.6 years of present-day GWP. The cleanup debt is accumulating at a rate of about $3.6 trillion per year, about 3.6% of GWP.

Humanity could defend some fraction of the inundating land surface using dikes. Based on a contemporary Dutch cost of about $10/m^3 of dam, assuming triple dike walls 60 m high and 120 m wide at the base, we calculate a cost of about $100,000 per meter of coastline, coming to $10^{14} ($100 trillion, 1-year GWP) for the entire million-kilometer coastline of the world. Dividing by the amount of carbon emitted results in a cost of about $5/ton of CO_2 emitted. This effort would ameliorate land loss by sea level rise, but it would obviously not change the impacts of a warmer climate. A downside is that this strategy would commit future generations to ongoing maintenance of the dikes. The almost absurd global scale of the proposal, and its relatively inexpensive price tag, is another demonstration of the massive scale of the ultimate damage from carbon energy.

5 Conclusions

This paper presents a formulation for assessing deep-time climate change in units of present-day dollars per ton of carbon. The scope of the definition for such a cost is limited by what is

tractable, and the result is only valid under particular, idealized circumstances including zero growth or technology change, and human population in steady state with Earth's carrying capacity. The UCC is unrealistic as a forecast for the future, in and of itself, but it is easy to visualize and provides a scale bar for ultimate climate damage in present-day terms.

The UCC in our formulation ranges from \$10k to \$750k per ton of C, with a central value about \$100k per ton. The 1σ uncertainty due to geophysical parameters is about \$34k, and due to geophysical plus economic, about \$116k, skewing to higher values in all cases. Among geophysical parameters to the model, the climate sensitivity contributes the most to the uncertainty in the result.

The UCC is not directly comparable with the social cost of carbon, or costs of mitigation, because of fundamental differences in their assumptions and formulations, and the fact that they apply over different time scales. Assuming that the climate impacts from fossil carbon use will persist much longer than any economic infrastructure that we use fossil fuels today to build, the UCC can be seen as a first approximation of our culpability to future generations, expressed in terms that are relevant to us.

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