Optimal Economic Trajectories and Normalized Climate Damages that Consider Adaptation

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Abstract

Global climate damages as a fraction of GDP (normalized damages) have been decreasing since 1980. However, this trend is predicted to reverse, and normalized damages are projected to increase as the earth warms. Damage functions model rising normalized damages as a function of temperature, yet they fail to consider human's increasing ability to mitigate disaster risks (adaptation). In this study, we attempt to parameterize adaptation and add it into a damage function. We do this in the utility optimizing DICE model, and evaluate optimal economic and warming trajectories that consider adaptation. We also take 7 Shared Socio-Economic Pathway (SSP) marker scenarios from the UN's Intergovernmental Panel on Climate Change (IPCC), and evaluate normalized damages that consider adaptation. We find that considering adaptation alters the optimal scenario in the DICE model and our findings from the SSP analysis suggest that we may never see increasing normalized damages.

Introduction

The intersection of climate and economy is one of the most important fields of study as we progress through and beyond the 21st century. President Joe Biden called climate change "the number one issue facing humanity" (Presidential Campaign, 2020). Predicting and optimizing future greenhouse gas (GHG) emissions and global warming is essential. Emissions result from economic development, and economic development improves quality of life. For this reason, climate economists often ask what emissions pathway would maximize quality of life (Moore and Diaz, 2015; Nordhaus, 1992).

The Dynamic Integrated model of Climate and Economy (DICE), developed by William Nordhaus, optimizes global discounted utility of consumption out to 2300. Using exogenous assumptions about the economy such as population growth and the discount rate, to then produce endogenous variables such as economic output, warming, and climate damages. DICE includes a damage function that directly relates temperature increase to a fraction of global output loss (Nordhaus, 2016).

As the Earth warms, it is nearly certain that some types of natural disasters will become stronger, more frequent, or both (Van Aalst, 2006). In turn, damages from disasters and climate will likely increase (Nordhaus and Moffat, 2017). However, climate damages per dollar GDP, which will be referred to as normalized damages, have decreased since 1990, when the earliest global data was collected (Pielke, 2018). This is attributed to a negative relationship between wealth and vulnerability to disasters caused by adaptation (Formetta and Feyen, 2019).

The DICE model projects climate damages per dollar GDP as a function of temperature, but does not incorporate or allow for climate adaptation. As a result, damages per dollar GDP can only increase in the DICE model, even though they have recently decreased in reality (Formetta and Feyen 2019; Pielke 2020).

This paper builds on the observation that normalized damages from disasters have been decreasing since 1980, yet the severity of some types of disasters are projected to increase with climate change (IPCC, 2021). We want to know: if we consider adaptation in the temperature-damage relationship, will normalized damages ever begin to increase? Additionally, how would adaptation affect the optimal trajectory of CO_2 emissions and carbon taxes?

Literature review

The research in this paper relates to the Social Cost of Carbon (SCC), which is what economists call the marginal externality of carbon pollution. As referenced in (Rennert, et al., 2021), the SCC has been referred to as “the most important number you’ve never heard of.” This number can be directly used to calculate the optimal Pigouvian tax of carbon. It has also been used by the US government in cost-benefit analyses of policies such as fuel efficiency standards and in 2018 was used in policy determining carbon capture credits (Social Cost of Carbon Report to Congressional Requesters, 2020).

This typical cost-benefit analysis using the SCC has been criticized, most strongly by Martin L Weitzman in his paper *Fat Tails and the Social Cost of Carbon* (Weitzman, 2014). In this paper he argues that the small but “non negligible” tail of the probability of extreme climate damages can lead to a vast raising of the SCC and make climate mitigation much more beneficial than a simple cost-benefit analysis would imply (Weitzman, 2014). Weitzman also invokes the important consideration of discount rates when calculating the SCC and argues using a typical investment level of discounting does not apply to a problem with the extremely long time scale of climate change.

William Nordhaus’ Nobel-Prize-winning DICE model calculates the pathway of emissions that maximizes discounted utility of consumption, and also calculates the SCC. The DICE model uses the Solow growth theory where society invests in capital, abstaining from consumption today, in order to increase consumption in the future (Nordhaus, 1992).

Although the DICE model won acclaim, it has also been criticized. Steve Keen wrote a paper that pointedly attacked the DICE model for not using empirical evidence and instead using economists' forecasts from the Tol (2009) survey. Keen cites the fact that DICE assumes 90% of the economy occurs mainly indoors and thus would be relatively unaffected by climate change (Keen, 2020). Thus, Keen (2020) is arguing that the SCC should be much higher, and the optimal emissions pathway should be much lower than the DICE model would suggest. The actual estimate of SCC is up for debate. It has been priced as low as $30 per metric ton (Nordhaus, 2016), to over $1000 per metric ton (Rennert, et al. 2021). When on the optimal emissions pathway, the SCC is also the shadow value of emissions.

However, humanity likely will not perfectly optimize emissions in reality. Therefore, another approach to projecting damages from climate change involves exploring scenarios that simulate a range of emissions and development pathways. This is exactly what the Intergovernmental Panel on Climate Change (IPCC) does with the Shared Socioeconomic Pathways (SSP) scenarios (O'Neill et al., 2014), in its Sixth Assessment Report (IPCC, 2021). These scenarios each combine one of five SSP development storylines with a radiative forcing level by 2100 (e.g., SSP1-2.6 is a scenario using the SSP1 development storyline, and reaching approximately 2.6 W/m^2 radiative forcing by 2100; Riahi et al., 2017). The five socioeconomic 'storylines' vary in mitigation and adaptation challenges, where 'mitigation challenges' are operationalized as how expensive or technologically challenging decarbonization is, and 'adaptation challenges' are operationalized in terms of economic growth challenges and inequality (Riahi et al., 2017). The SSP scenarios do not directly model either climate damages or adaptation.

The SSP scenarios have then been run through 6 integrated assessment models (IAMs) to create 127 SSP scenarios with different cumulative CO_2 emissions and GDP per capita output (IIASA, 2018). Among these are 7 marker scenarios that the IPCC prioritized in its analysis and climate modeling. These scenarios are: SSP1-2.6, SSP2-4.5, SSP4-6.0, SSP5-8.5, SSP1-1.9, SSP2-3.4, and SSP3-7.0 (Fig. 2A; Riahi et al., 2017). Scenarios with higher radiative forcing (which in 2100 is Y.Z W/m^2 in scenario SSPX-Y.Z) have greater cumulative emissions, and lead to greater warming.

The SSP scenarios have a high-emission end with a radiative forcing level of 8.5 W/m^2 leading to 4-5 degrees Celsius warming by 2100 (SSP5-8.5; IPCC, 2021). On the low-emission end, we have 1.9 watts per meter squared of radiative forcing and approximately 1.5 degrees Celsius of warming by 2100 (RCP1-1.9; Hausfather and Peters, 2020). The International Energy Agency (IEA) has “stated policies” scenarios approximately in line with “medium emission" scenarios such as SSP2-3.4 and SSP2-4.5, and scenarios consistent with the IEA’s 2021 stated policies outlook (IEA World Energy Outlook, 2021) produce 2-3 °C warming by 2100 with median climate sensitivities (Pielke et al. 2022).

Another important factor in modeling climate damages is the damage function, which determines how much damage is caused by different warming levels. The DICE model assumes that the fraction of global output lost to climate change is equal to $0.00267(T^2)$, where T is the temperature increase above pre-Industrial levels (Nordhaus, 2016). This damage function implies that 4.2% of global output is lost to warming at 4 °C (Nordhaus, 2016). Matthew Kahn and colleagues estimated a steeper damage function, which predicts roughly 10% of global output is lost to warming at 4 °C (Kahn et al. 2021). Marshall Burke and colleagues predict 25% of global output lost to warming at 4 °C (Burke et al. 2015).

However, these damage functions do not allow the fraction of global output lost to climate change to decline due as temperature increases, despite the fact that this is precisely what has happened in recent history (Pielke, 2018; Formetta & Feyen, 2019). One possible explanation for this observation is that humans are continuously adapting and as the planet gets warmer, we get better at dealing with it, perhaps related to our level of affluence. It also raises the question of whether damages as a fraction of GDP will continue to decline during the 21st century, or whether accelerating costs of climate change will eventually reverse this trend. In this paper, we explore these issues.

Methodology

Our research questions are: (i) Will climate damages ever begin to increase in a model that considers adaptation? (ii) How would adaptation affect the optimal trajectory of CO_2 emissions and carbon taxes? We address these questions using two approaches. First, we modify the DICE model to include affluence-dependent adaptation, and use this modified DICE model to explore the consequences of adaptation on the optimal trajectory of warming, normalized damages and the SCC. We will then modify the SSP scenarios to add damage and adaptation functions to project the normalized damages in each scenario.

1. Parameterization of Adaptation

We conceptualize normalized damages as a function of exposure and proneness. Exposure refers to the level of disasters experienced (severity and frequency). Proneness refers to how vulnerable we are to experience losses from the given level of disasters. Thus, proneness is inversely related to adaptation, and normalized damages are given by:

(1) $Damages = Exposure * Proneness.$

If the level of exposure stays the same, which has been approximately the case since the late 1980s (Pielke (2020) shows there has not been a detectable trend over this period), then trends in normalized damages over this time frame (Formetta and Feyen, 2019) would reflect changes in proneness.

We define proneness, in equation (1), to lie between 0 and 1. With no further adaptation relative to the present, proneness equals 1; and zero proneness would mean that society is impervious to all disasters. It is intuitive that adaptation/proneness would be related to affluence. The richer we are, the more advanced our building, warning, and other adaptation technologies and capacities are likely to be. Globally, normalized damages from disasters were 4.75 times higher in 1980-1989 than 2007-2016 (Formetta and Feyen, 2019, appendix B). GDP per capita was 4.2 times higher in 2007-2016 than in 1980-1989 (World Bank, GDP per capita (current US $)). Based on this, we model adaptation as a negative proportional relationship between GDP per capita and proneness.

2. The DICE model: summary of key assumptions

The DICE model is an optimized IAM of climate-change economics. The goal of the DICE model is to optimize discounted global consumption. The DICE model uses the perspective of neoclassical economic growth theory and the idea that economies make investments to increase consumption in the future by investing in capital, education and technologies. Thus, we forgo consumption today in order to increase it in the future. The DICE model applies this logic to the climate and sees it as “negative capital”, where the more GHG emissions, the more warming, and the less future consumption, because warming causes climate damages (Nordhaus, 2013). By investing today's output into emissions reductions, economies prevent negative climate effects in the future.

The DICE model contains a quadratic damage function that relates normalized damages (D) to an increase in temperature (T) over 1900 levels.

(2) $D = 0.00267(T^2)$

3. Adding proneness to the DICE model

In the DICE model, GDP per capita is not a programmed output; however, consumption per capita (CPC) is. Consumption is equal to 1 minus the savings rate times output.

(3) $C = (1 - s) * Y$

The savings rate as a fraction of gross output in DICE stays between 14-16% throughout the model's 250-year time horizon. Thus, consumption increases approximately proportionally with output and GDP. We accordingly assume that proportional changes in CPC over time are equal to proportional changes in GDP per capita. We define proneness in the DICE model as

(4) $Proneness = CPC(year\ 0)/CPC(year\ t)$

We can now multiply this proneness function by the damage equation in DICE, to generate a damage function that considers adaptation.

(5) $New\ Damage\ Function = Proneness * D$

We insert equation (5) into DICE, in place of the original damage function, to project a new SCC, CPC, normalized damages, and warming. We can now evaluate if normalized damages that consider adaptation will ever begin to increase, as well as the effect of adaptation on the optimal warming and SCC. We compare these results to runs of the DICE model without adaptation (i.e. where proneness is fixed at 1).

4. Different Damage Functions

The DICE model's damage function is a simple quadratic as previously displayed. This function comes from estimates from the Tol (2009) survey. It was noted that this survey did not consider non-monetized values such as loss of biodiversity, ocean acidification and political reactions. This was informally included by raising the damage function 25%, resulting in the 0.00267 coefficient.

This however is not the only estimate relating temperature to damage. In fact, it is one of the lower ones, and the lowest one we will be using. Matthew Kahn and colleagues (Kahn, et al. 2021), and Marshall Burke and colleagues (Burke et al. 2015), both have other estimates of a temperature damage relationship. These estimates are more complicated than the one originally in DICE, however we are going to convert them to the simple quadratic form that DICE is in, which are approximately equivalent to the original estimates. Burke et al. (2015) estimates about 25% of output lost to damages at 4 degrees C of warming, and Kahn et al. (2021) estimate about 10% of damages at 4 degrees C of warming. These are both higher than DICE's about 4% of output lost at 4 degrees C of warming. We use the following quadratic functions to approximate Burke et al.'s (2015) and Kahn et al.'s (2021) damage functions, with parameters chosen to match these 4-degree-warming damages:

$$Burke\ D = 0.015(T^2)$$

$$Kahn\ D = 0.0065(T^2)$$

Note that we treat *D* as 'exposure' in our model. We can now plug these different functions, combined with our adaption function, into DICE and get new normalized damage values with adaptation.

2. Comparing to SSPs

We can now take our 7 SSP scenarios and run the same analysis of calculating damages that consider adaptation. First, because we only have emissions for them and not warming, we need to convert their emissions to warming. Pielke, et al. (2022) report 2100 warming levels (in degrees C above pre-Industrial levels) in the 127 SSP scenarios.

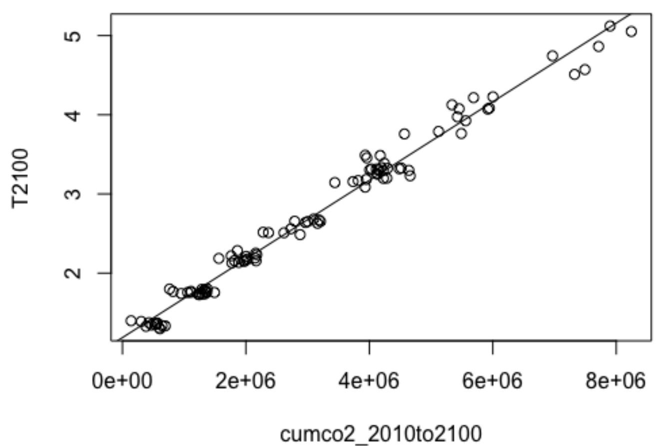

Figure 1.1: Cumulative 2010 to 2100 C02 emissions relating to 2100 temperature increase

```
lm(formula = T2100 ~ cumco2_2010to2100, data = sspcumco2temp)

Residuals:
     Min       1Q   Median       3Q      Max 
-0.33490 -0.09510 -0.01488  0.08443  0.35077 

Coefficients:
                   Estimate Std. Error t value Pr(>|t|)    
(Intercept)       1.186e+00  2.491e-02   47.62   <2e-16 ***
cumco2_2010to2100 4.964e-07  6.920e-09   71.74   <2e-16 ***
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Residual standard error: 0.1367 on 97 degrees of freedom
Multiple R-squared:  0.9815,    Adjusted R-squared:  0.9813
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Figure 1.2: Showing our regression has an R-squared of 0.9815, showing there is a clear relationship between cumulative emissions and temperature in 2100.

We calculate yearly cumulative CO_2 emissions from 2010-2100 in each SSP scenario, and fit a linear model between cumulative CO_2 and temperature increase (Figure 1.1; R^2 = 0.9815). We use this fit to project approximate yearly warming in each SSP scenario, from which we calculate exposure using each (Nordhaus', Khan's and Burke's) damage functions. We then use the output of GDP per capita from the scenarios and the assumption of proneness being inversely proportional to GDP per capita (and equal 1 in 2010). These calculations go into equation (5) and produce projections of normalized damages, considering adaptation, with each damage function in each SSP scenario. For brevity, we only show the output from the 7 marker scenarios.

Results

DICE Results

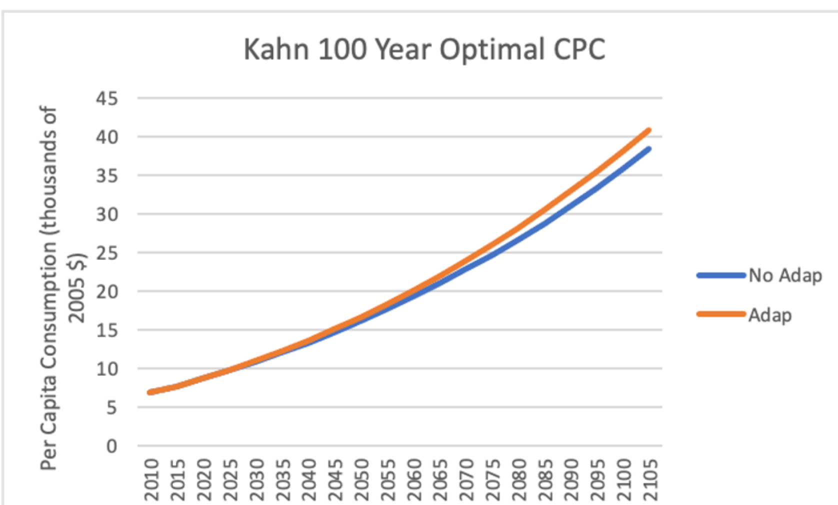

Figure 2.1 Kahn Damage Function, 100-year optimal per capita consumption

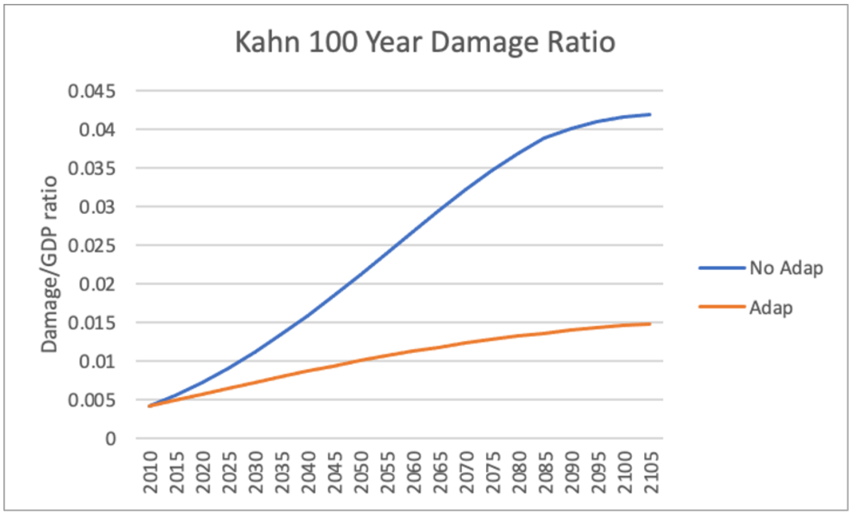

Figure 2.2 Kahn Damage Function, 100-year normalized damages

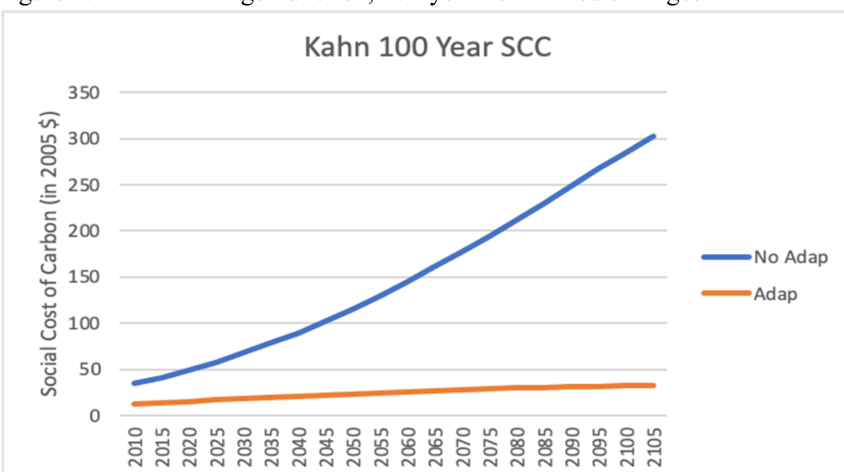

Figure 2.3 Kahn Damage Function, 100-year Social Cost of Carbon

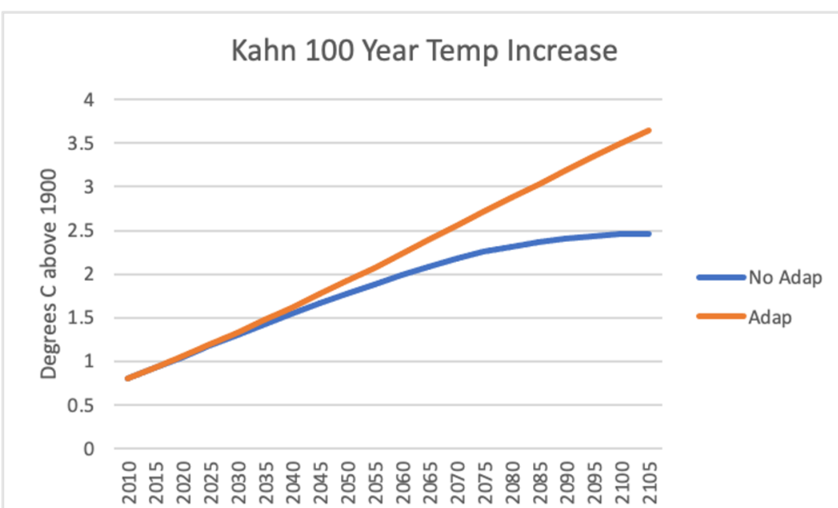

Figure 2.4 Kahn Damage Function, 100-year temp increase

We find that a semi-empirically parameterized function of adaptation reliably increases the optimal warming, per capita consumption, and normalized damages; while lowering the SCC. In the DICE model, we find the world looks significantly different when considering adaptation. We see nearly a degree higher optimal temperature increase in a model that considers adaptation in every damage function (Figure 2.4, Appendix B). While warming is costly as the damage functions show, we see adaptation playing a stronger role and allowing for more warming. Using Kahn's damage function we see a 400% increase in the SCC when not considering adaptation by the end of the century (Figure 2.3). This again shows the power of adaptation, carbon is not as costly if we factor in our ability to adapt to warming as the world gets wealthier. In figure 2.2 we again see the power of adaptation to limit normalized climate damages.

SSP Results

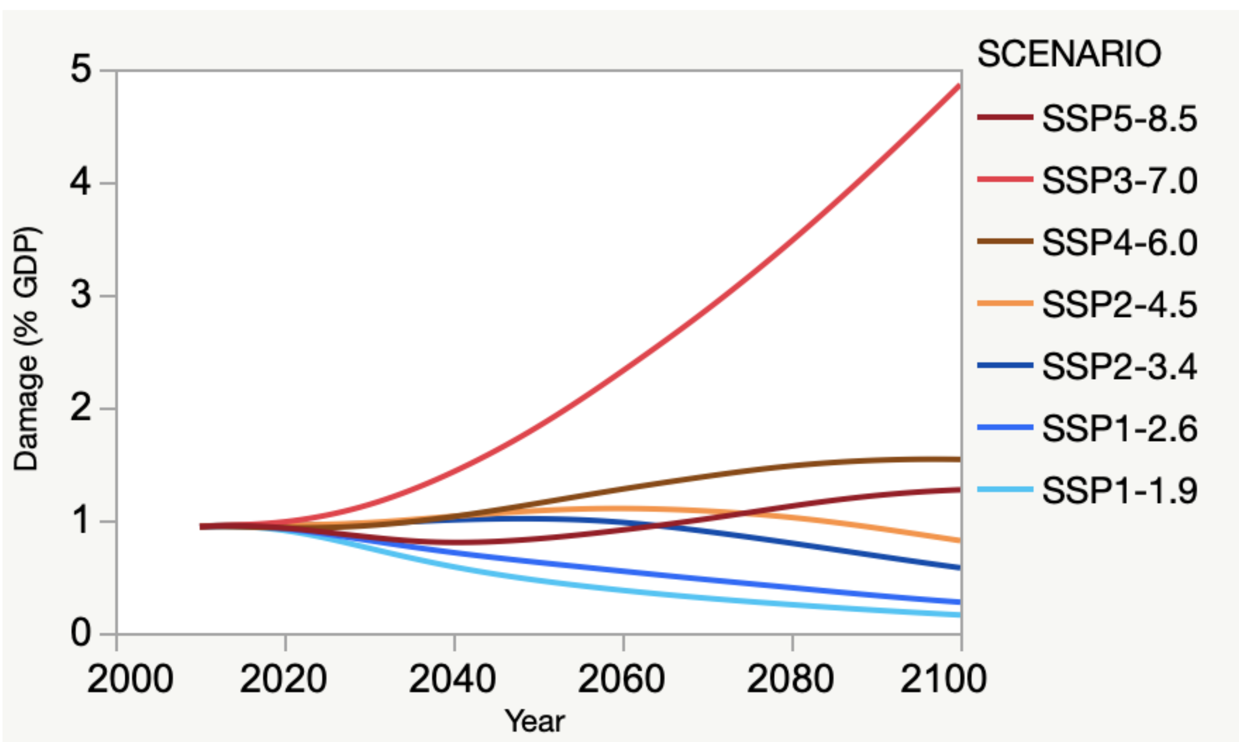

Figure 3.1 100-year normalized damages in each SSP scenario, assuming the Kahn damage function.

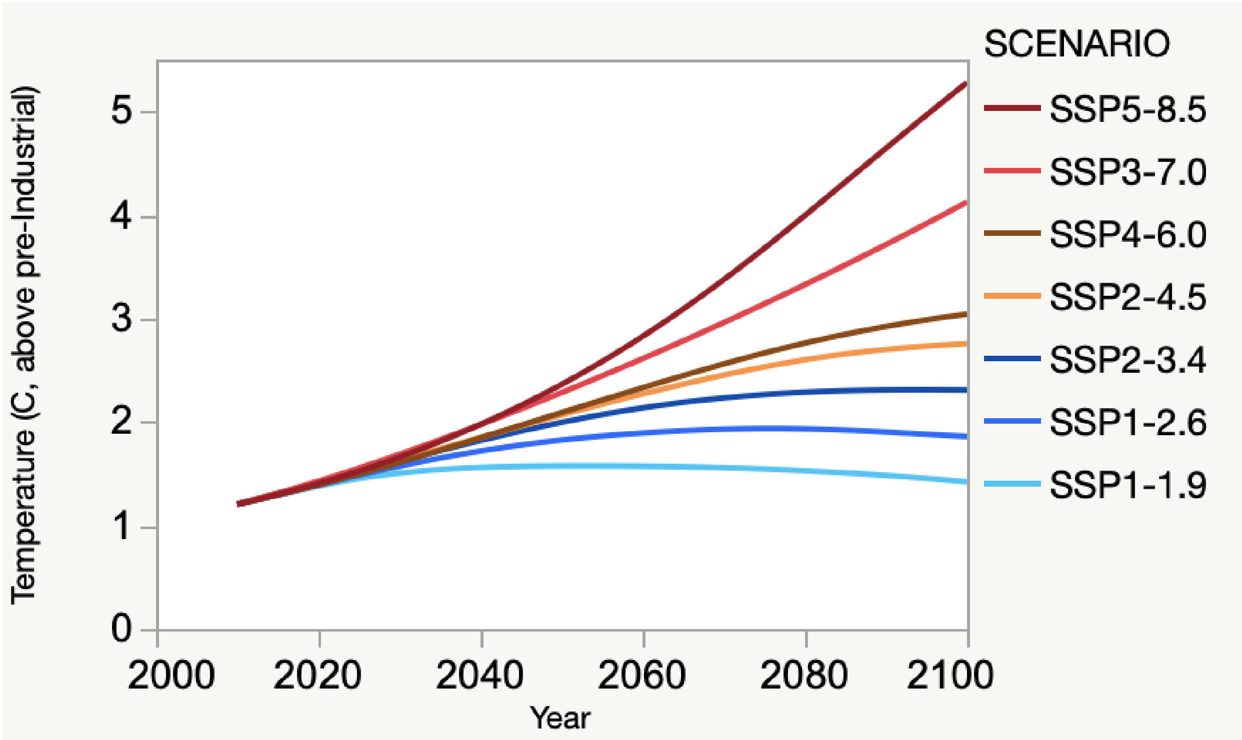

Figure 3.2 100-year temperature increase in each SSP scenario, assuming the Kahn damage function.

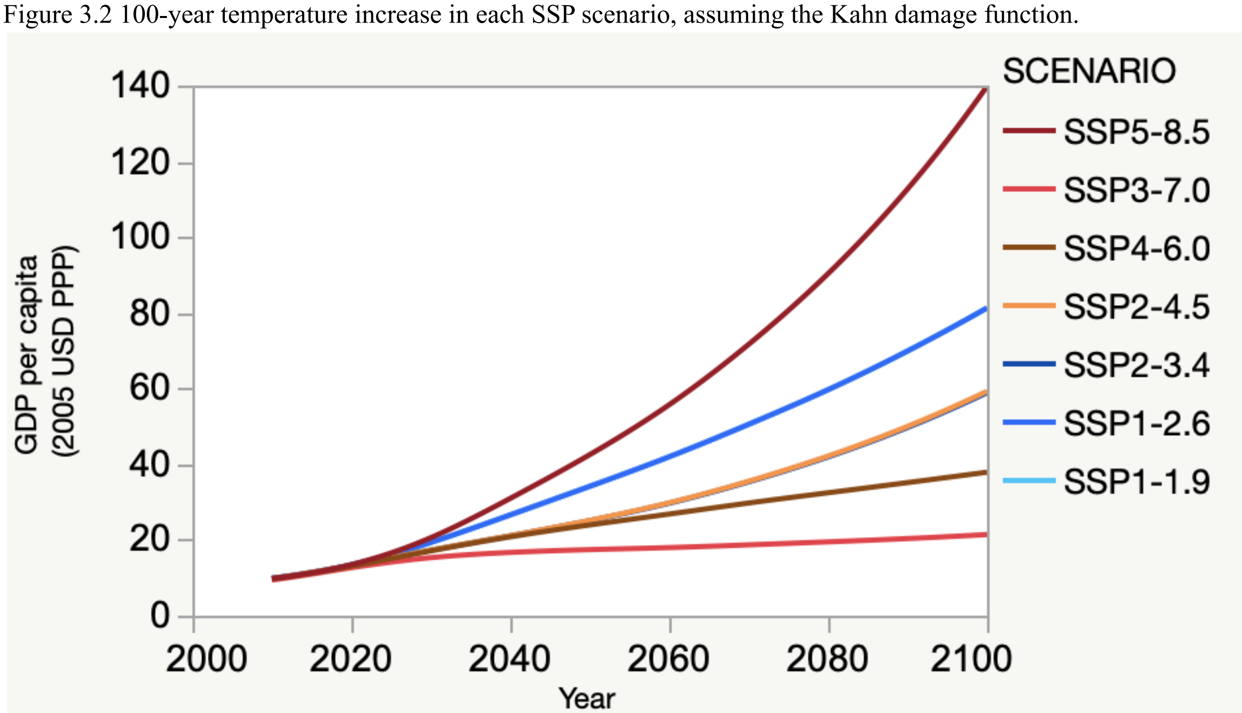

Figure 3.3 100-year per capita GDP in each SSP scenario, assuming the Kahn damage function.

In the SSP analysis, we find that normalized damages in SSP1-2.6, SSP1-1.9 and SSP 2-3.4 always decrease using the Kahn damage function (Figure 3.1). SSP4-6.0 has damages that decrease and then increases. SSP2-4.5 increases slightly and then decreases to a level below where it started. SSP4-6.0 increases and then plateaus. SSP3-7.0 increases at an increasing rate. Given that SSP2-3.4 and SSP2-4.5 may be more plausible scenarios (according to Pielke et al., 2022), this raises the possibility that normalized damages may never begin to meaningfully increase, following historical trends (Formetta and Feyen, 2019).

Discussion

1. Limitations

One major limitation of the study is assuming the constant proportional relationship between per capita GDP increase and proneness decrease. For one, adaptation likely experiences diminishing marginal returns. Although we have historically seen returns to adaptation proportional to per capita GDP increase, it is possible we would reach a point where additional wealth no longer helps us mitigate disasters. Additionally, the possibility of limited economic growth throughout the 21st century (Burgess et al., 2021 *Nat. Hum. Behav.*; Burgess et al., (2021) *Environ. Ress. Lett.*) would limit the world's ability to keep getting wealthier and adapting.

The fact that major damage functions estimate between 4.2% (Nordhaus, 2016) and 25% (Burke et al., 2015) of global output loss at 4 °C shows the massive uncertainty in how much damage climate change will cause. On the low end of damage estimates, adaptation would overpower climate damages and we would be incentivized to warm up to 6 °C by 2200 (Nordhaus 200-Year Warming, Appendix B). This raises questions about the realism of the Nordhaus function, since this well exceeds the warming projected to occur under stated policies

(Pielke et al., 2022). It does not make sense for emissions to be higher in the optimum than in the base case, given that emissions are a negative externality, unless somehow governments are already reducing emissions faster than is economically optimal, which seems unlikely. With a high damage function and no adaptation, we are incentivized to stay under 2 °C by the end of the century as suggested by the Paris Climate Accords. Having a more accurate damage function is critical when exploring optimal emissions trajectories.

The DICE model's damage function is quadratic as is our representation of Kahn et al. (2021)'s and Burke et al. (2019)'s. This form of equation mostly ignores the idea of climate tipping points, particularly as warming rises above 3 °C. Ice sheets, which play a major role in the climate system and melting would have some unknown consequences are predicted to melt at warming as low as 1.5 to 2 °C (Wunderling et al. 2020). This goes to point that damages may occur in an unexpected way and the possibility is endless for how damages could increase quicker than when described quadratically.

2. Policy Implications and Future Research

The major takeaway of this study is to encourage the climate discussion to not just consider the negative effects of warming, but the positive effects of prosperity through adaptation to the changing climate. Prosperity can be a tool to lower the SCC and damages from a changing climate.

The fact that adaptation is not a part of the mainstream climate conversation shows room for future research. This study uses the assumption that per capita GDP growth and adaptation are proportionally related. This is likely not the case for a myriad of reasons including: diminishing marginal returns to adaptation, slow growth in the 21st century, climate tipping points and randomness in exposure to disasters. If a future study can better model a relationship of adaptation, this will give us a better understanding of future normalized damages and the optimal trajectory of emissions.

Conclusion

This study highlights the importance of considering the entire human-environment system when thinking about climate change. We add to the discussion on the effects of warming by showing the power of human innovation. It would be mistaken to only think about the impacts of climate change in terms of environment, we must also think about it in terms of human adaptation. If a policy maker today claims "this is the maximum level of warming we can accept 100 years from now", they would be apt to see that the effects of that warming may be less severe to that society 100 years from now with greater technology and innovation than is available today.

If the results of our SSP analysis are correct, and we never see meaningful increases in normalized damages even with significant warming, we may need to question if economics is the proper subject to evaluate the issue of climate change. Additionally, it is not the intent of the study to minimize the impact of climate change and suggest that we tolerate such a high level of warming as is seen in the DICE model. Attention should be drawn to the SCC and carbon price in the DICE model, that at whatever level it optimizes to, is above the world's and United States' carbon price as both have none.

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Appendix A

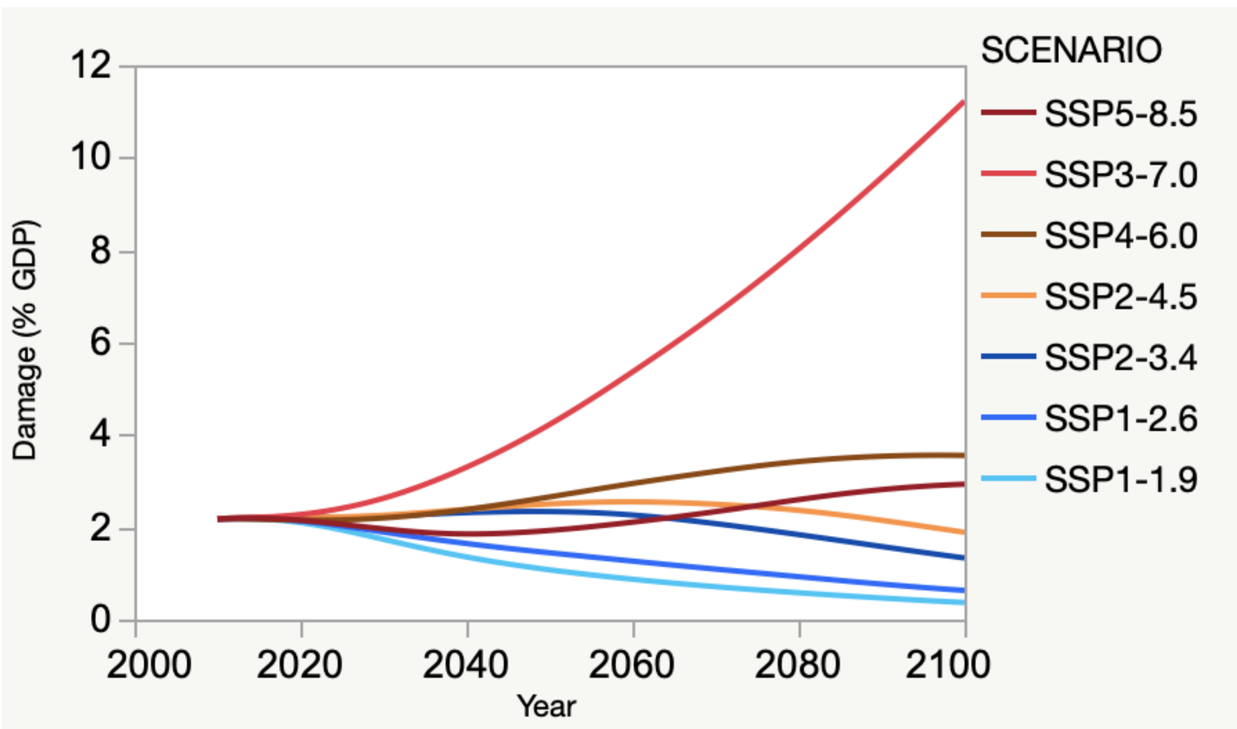


Figure 3.2 SSP normalized damages, assuming Burke damage function

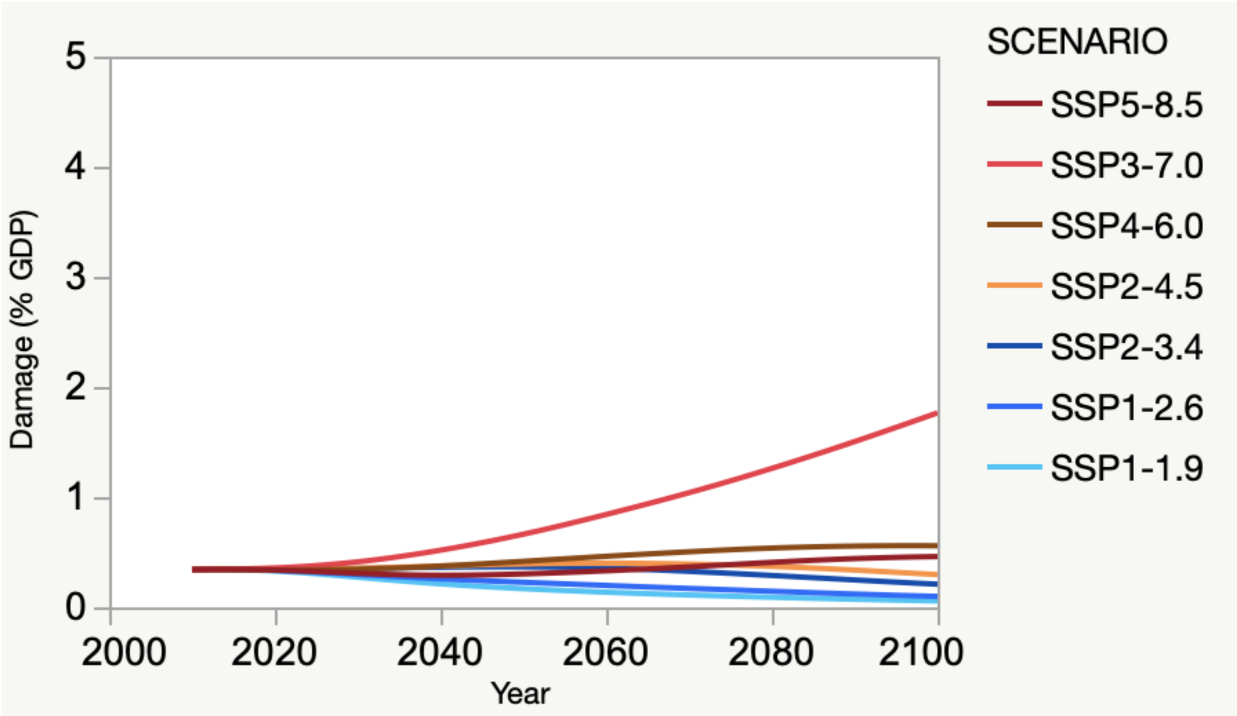


Figure 3.3 SSP normalized damages, assuming Nordhaus' damage function

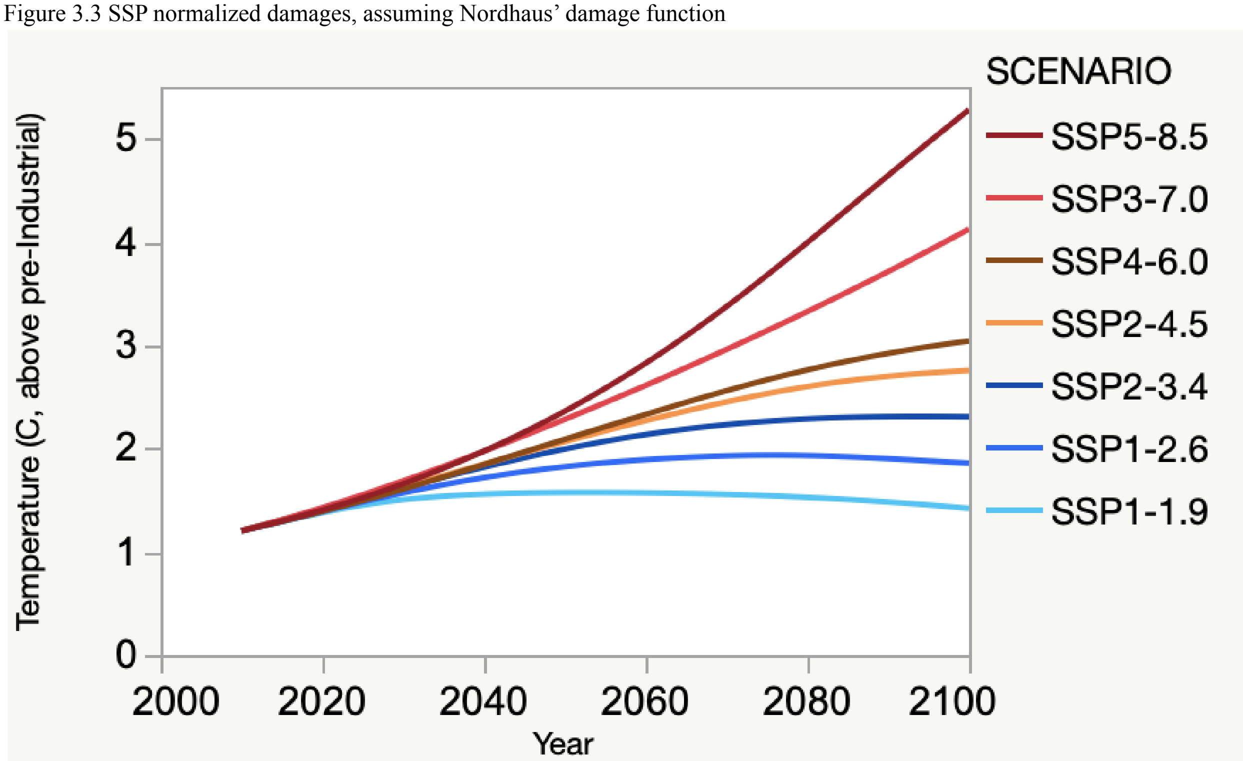


Figure 4.1 SSP Temperatures increases over pre-industrial levels

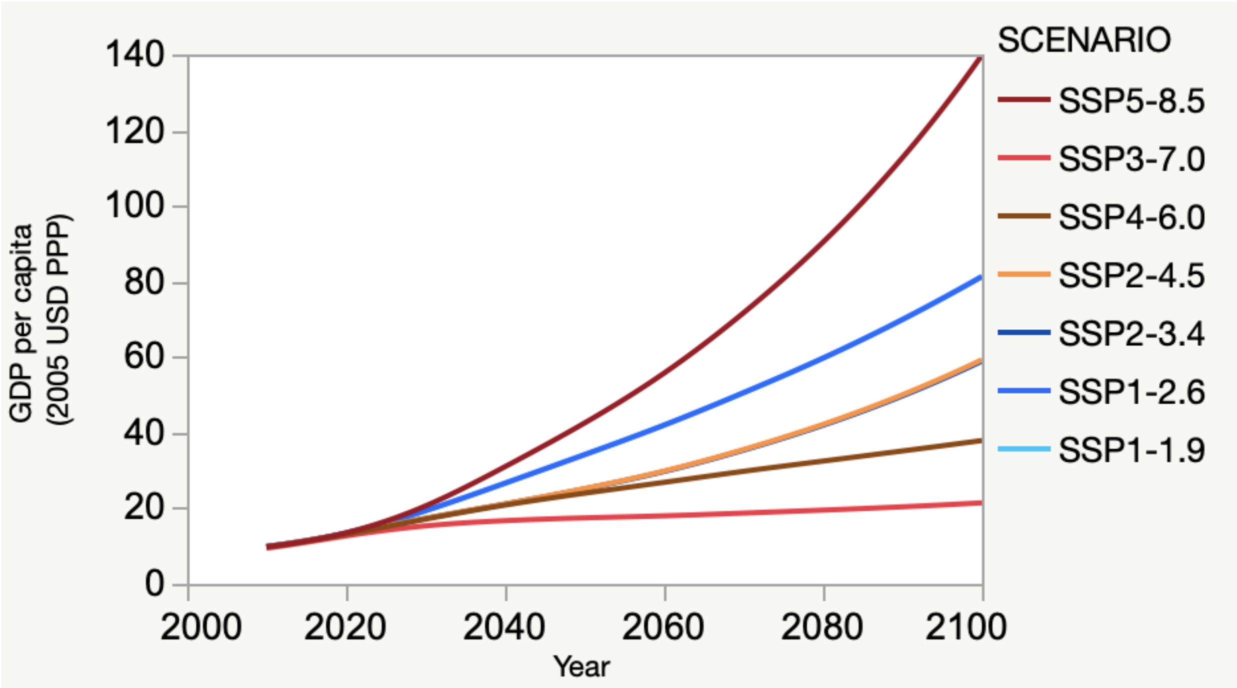
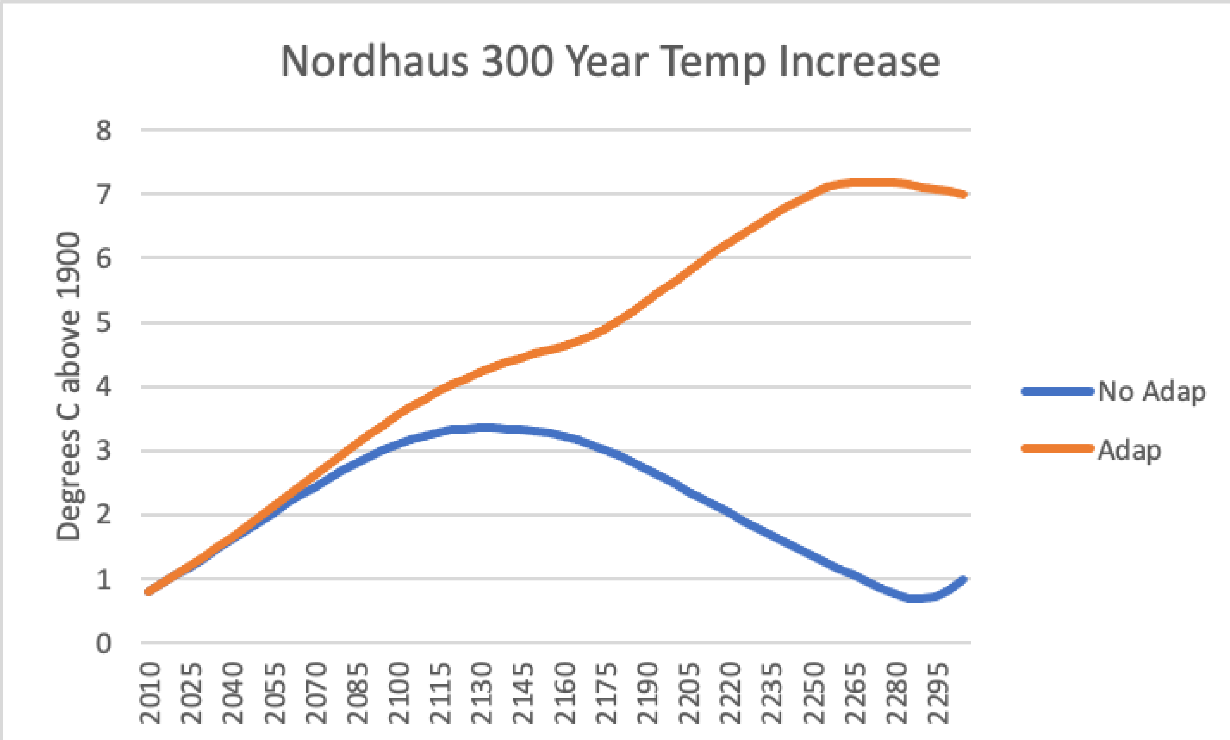
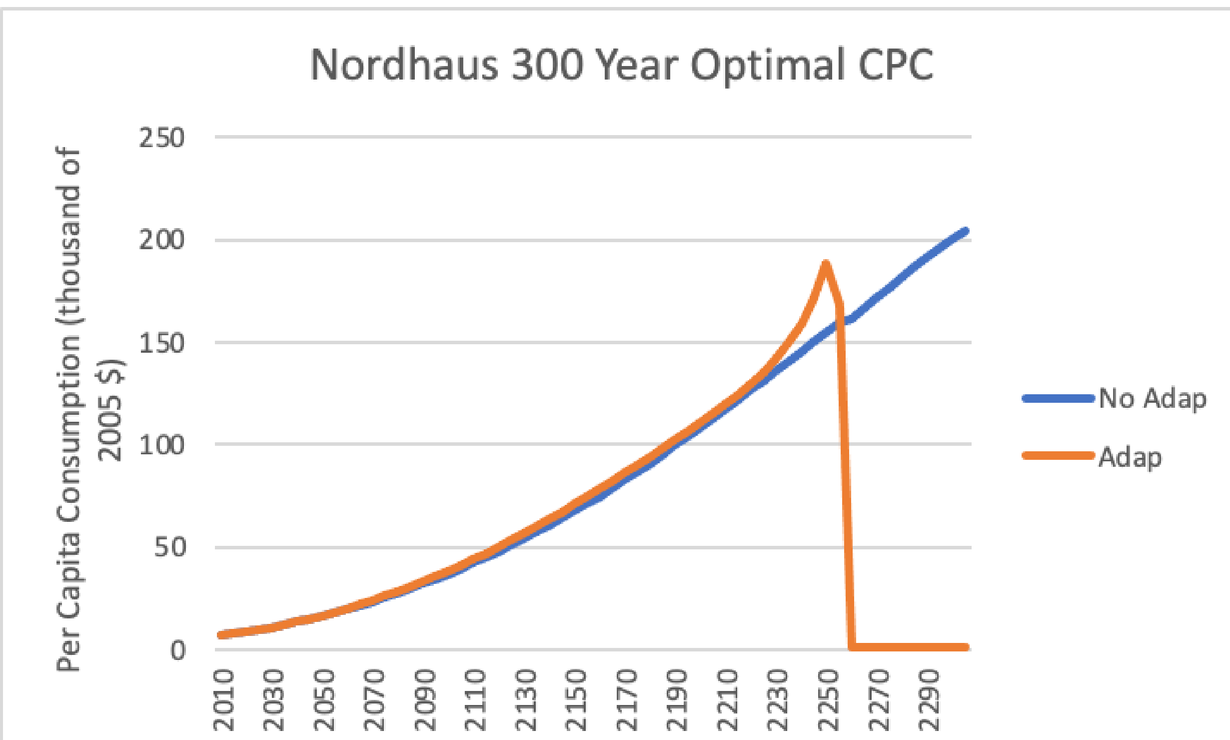


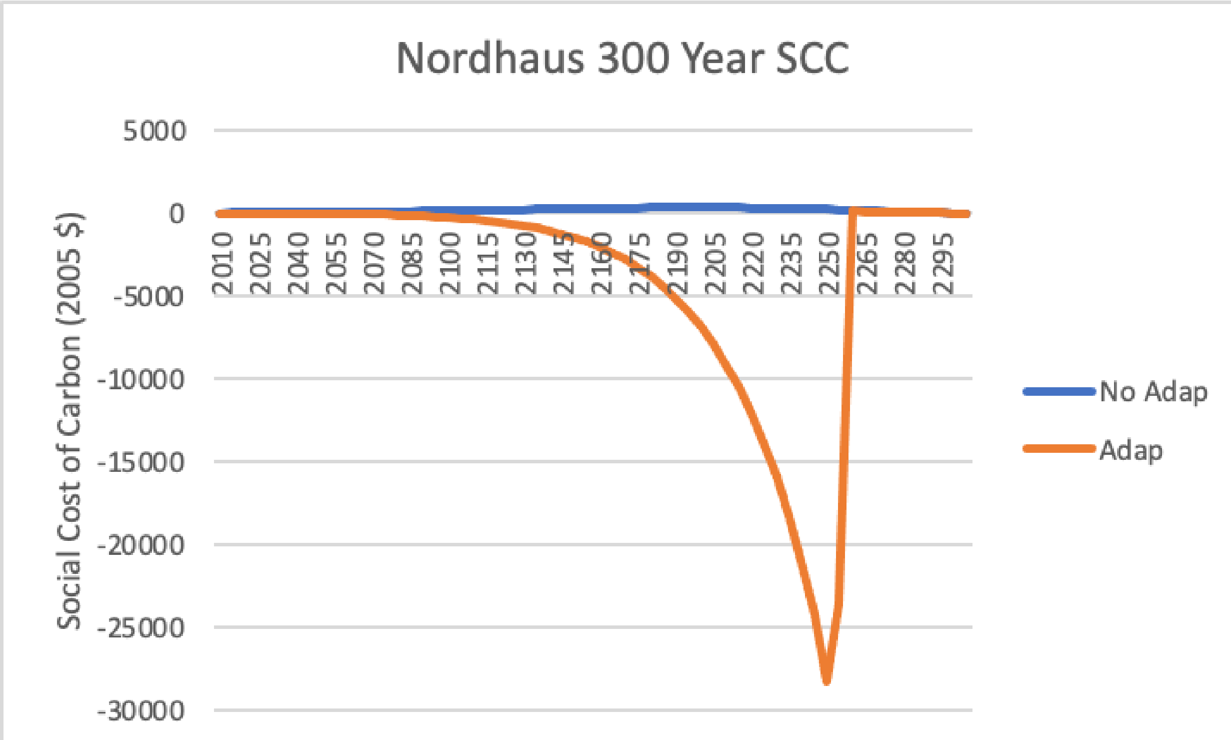
Figure 4.2 SSP GDP per capita

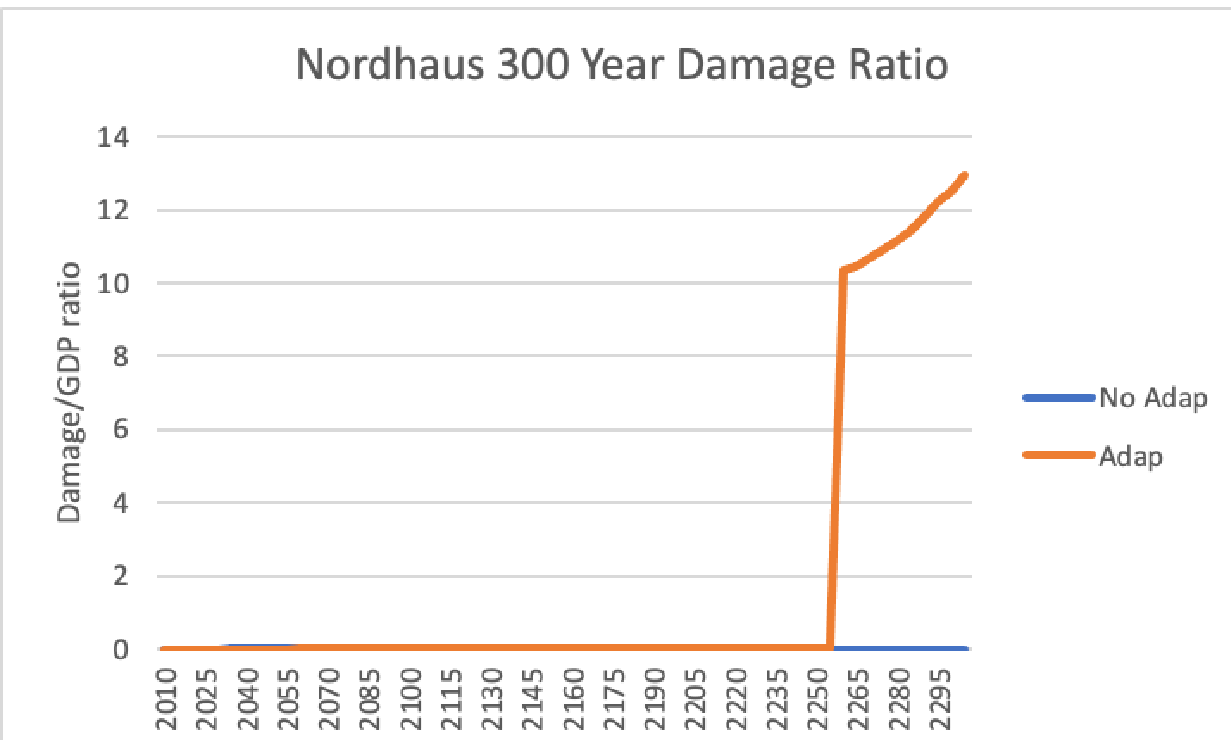
Appendix B

Nordhaus (0.00267T^2)

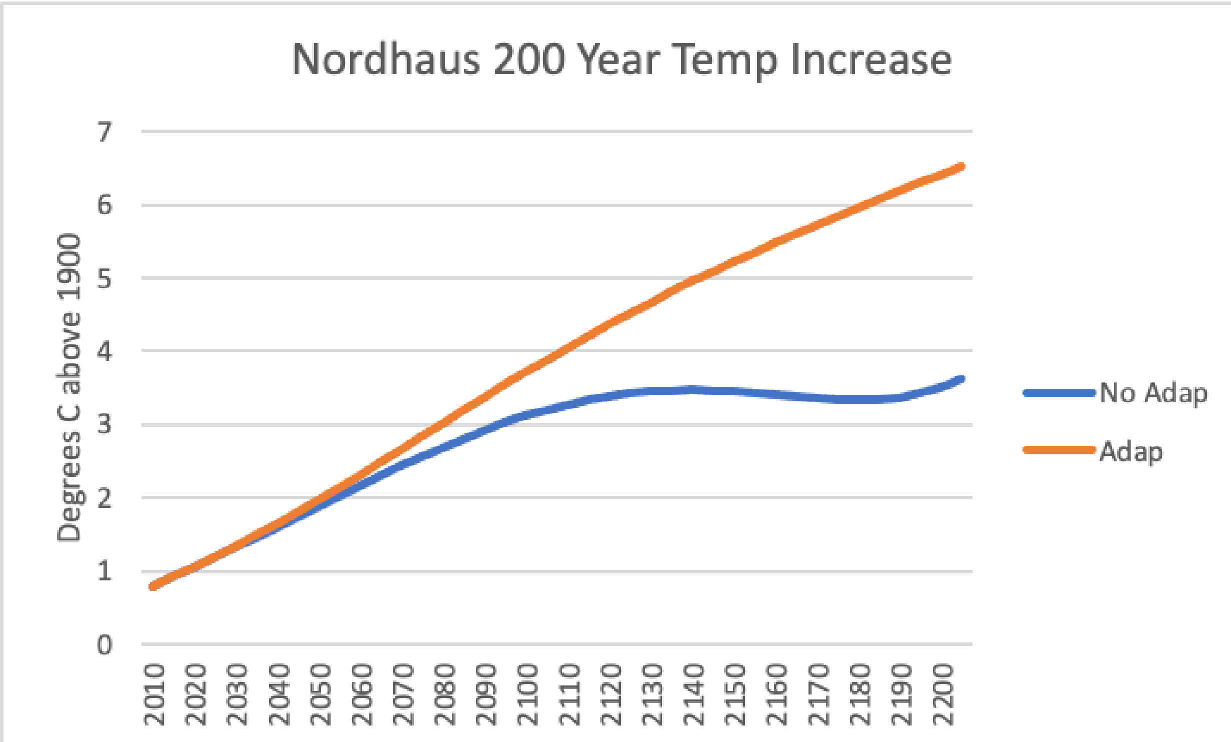




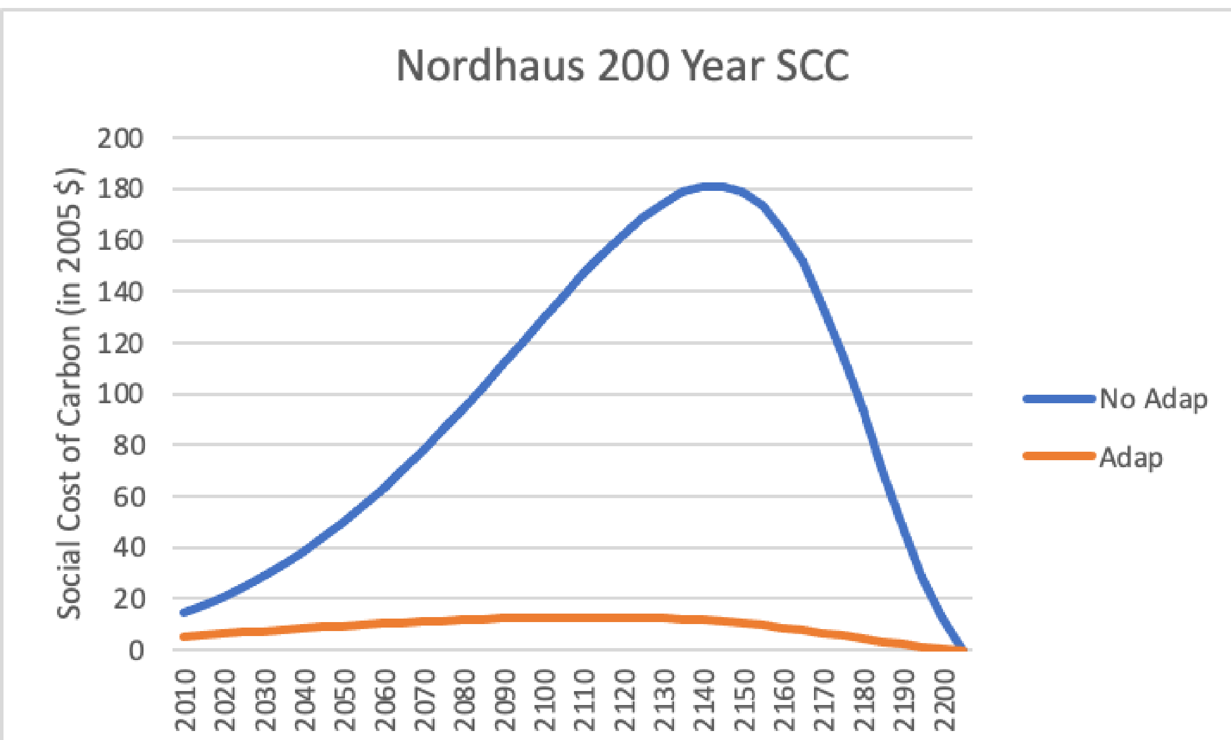

Nordhaus 300 Year SCC
5000
0
-5000
-10000
-15000
-20000
-25000
-30000
Social Cost of Carbon (2005 $)
2010
2025
2040
2055
2070
2085
2100
2115
2130
2145
2160
2175
2190
2205
2220
2235
2250
2265
2280
2295
No Adap
Adap


Nordhaus 300 Year Damage Ratio
14
12
10
8
6
4
2
0
Damage/GDP ratio
2010
2025
2040
2055
2070
2085
2100
2115
2130
2145
2160
2175
2190
2205
2220
2235
2250
2265
2280
2295
No Adap
Adap

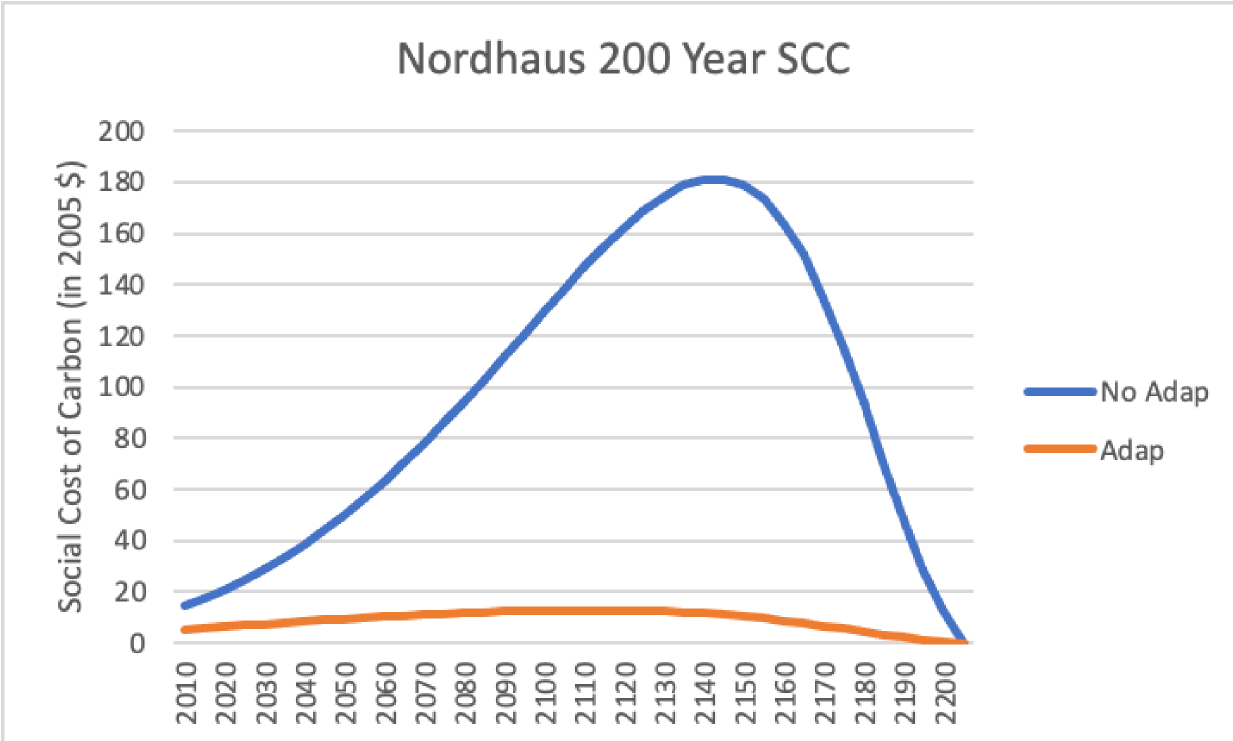
200 year



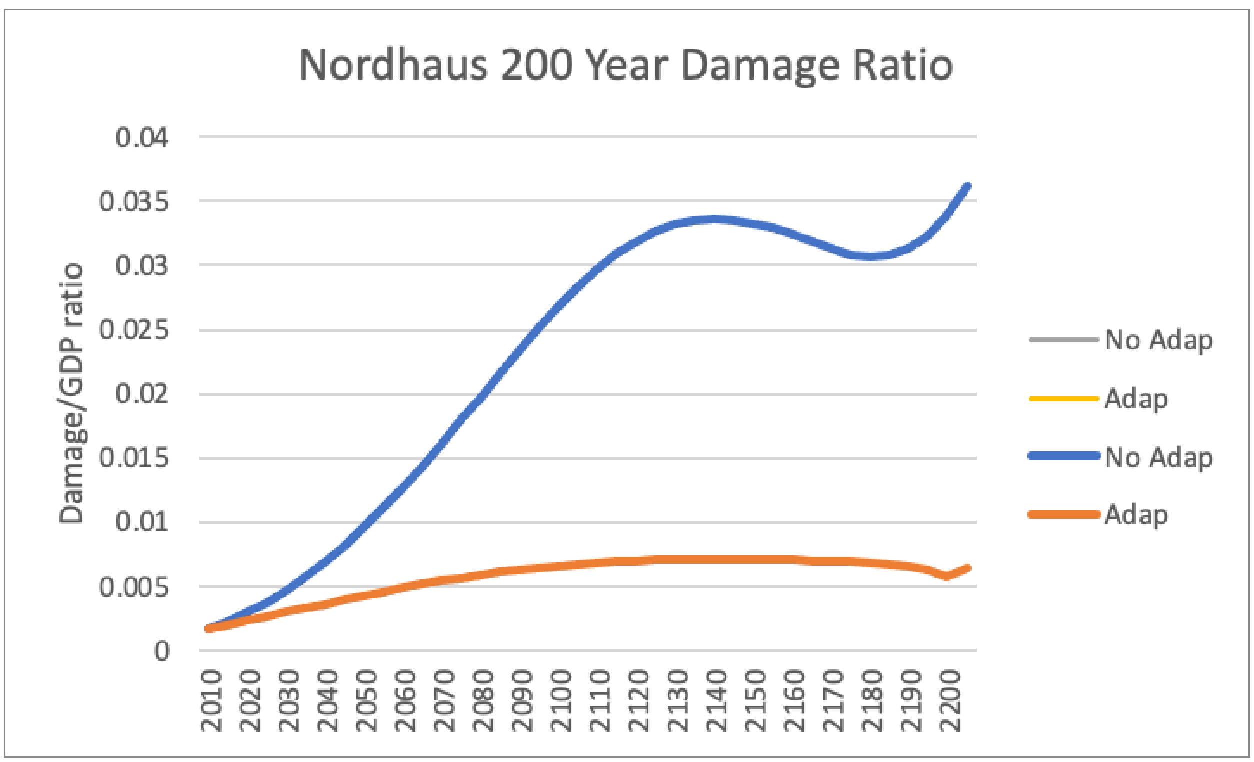
Nordhaus 200 Year Temp Increase
Degrees C above 1900
7
6
5
4
3
2
1
0
2010
2020
2030
2040
2050
2060
2070
2080
2090
2100
2110
2120
2130
2140
2150
2160
2170
2180
2190
2200
No Adap
Adap



Nordhaus 200 Year SCC
Social Cost of Carbon (in 2005 $)
200
180
160
140
120
100
80
60
40
20
0
2010
2020
2030
2040
2050
2060
2070
2080
2090
2100
2110
2120
2130
2140
2150
2160
2170
2180
2190
2200
No Adap
Adap

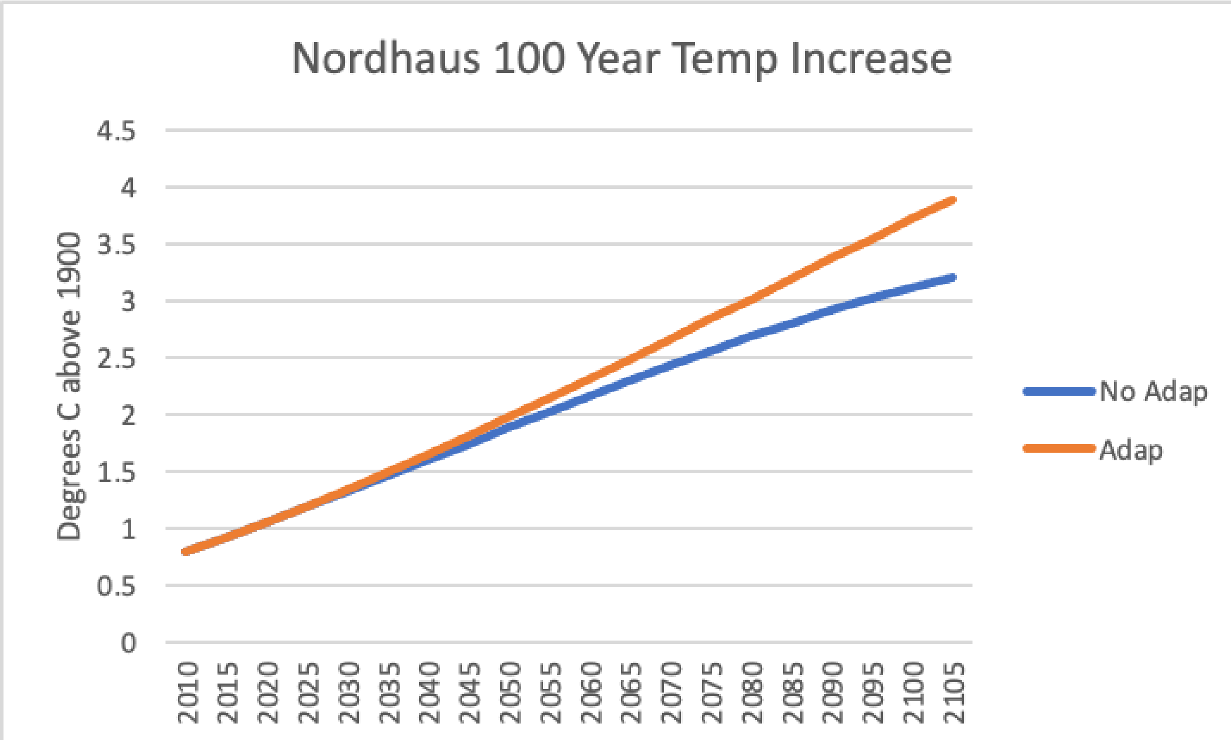


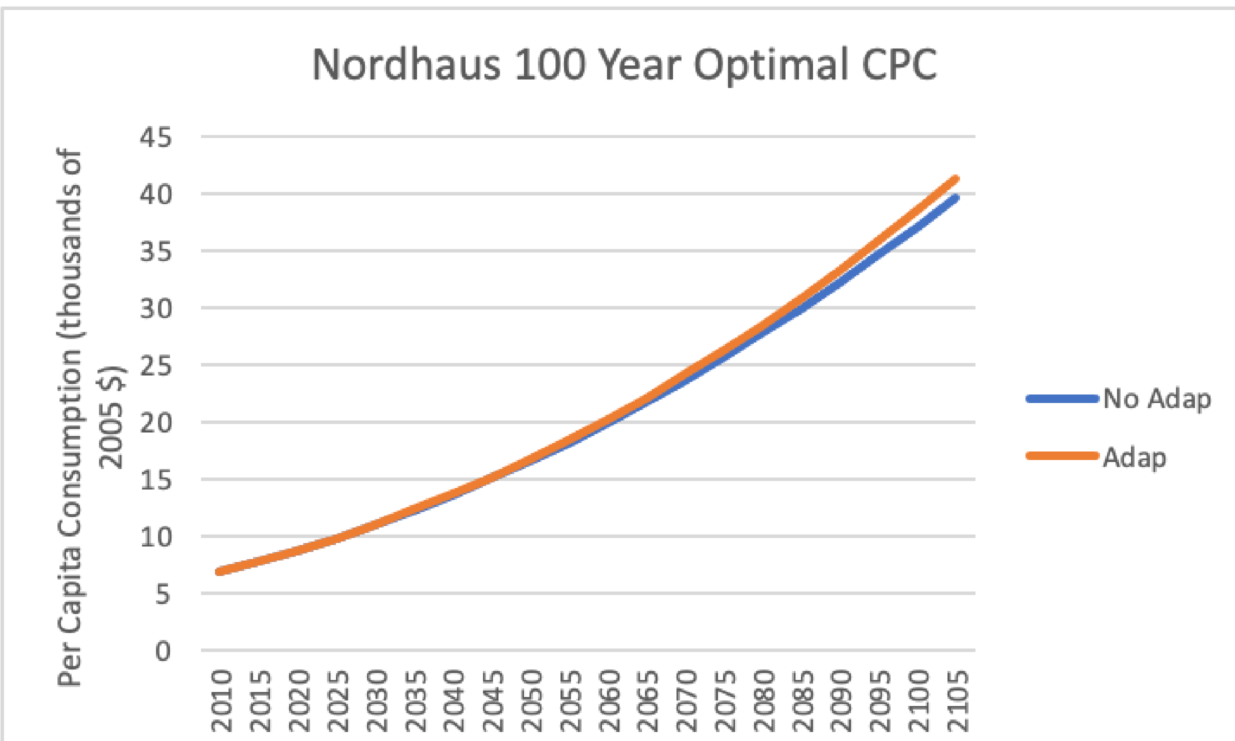
Nordhaus 200 Year SCC
Social Cost of Carbon (in 2005 $)
200
180
160
140
120
100
80
60
40
20
0
2010
2020
2030
2040
2050
2060
2070
2080
2090
2100
2110
2120
2130
2140
2150
2160
2170
2180
2190
2200
No Adap
Adap

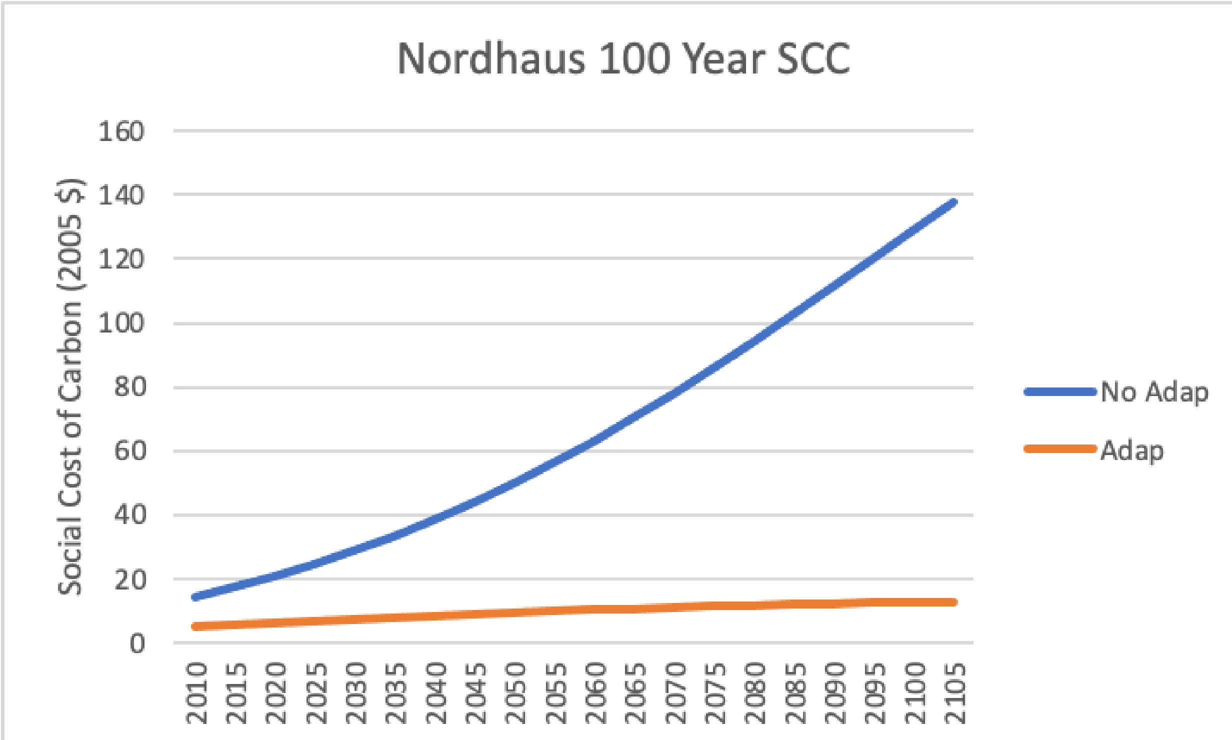


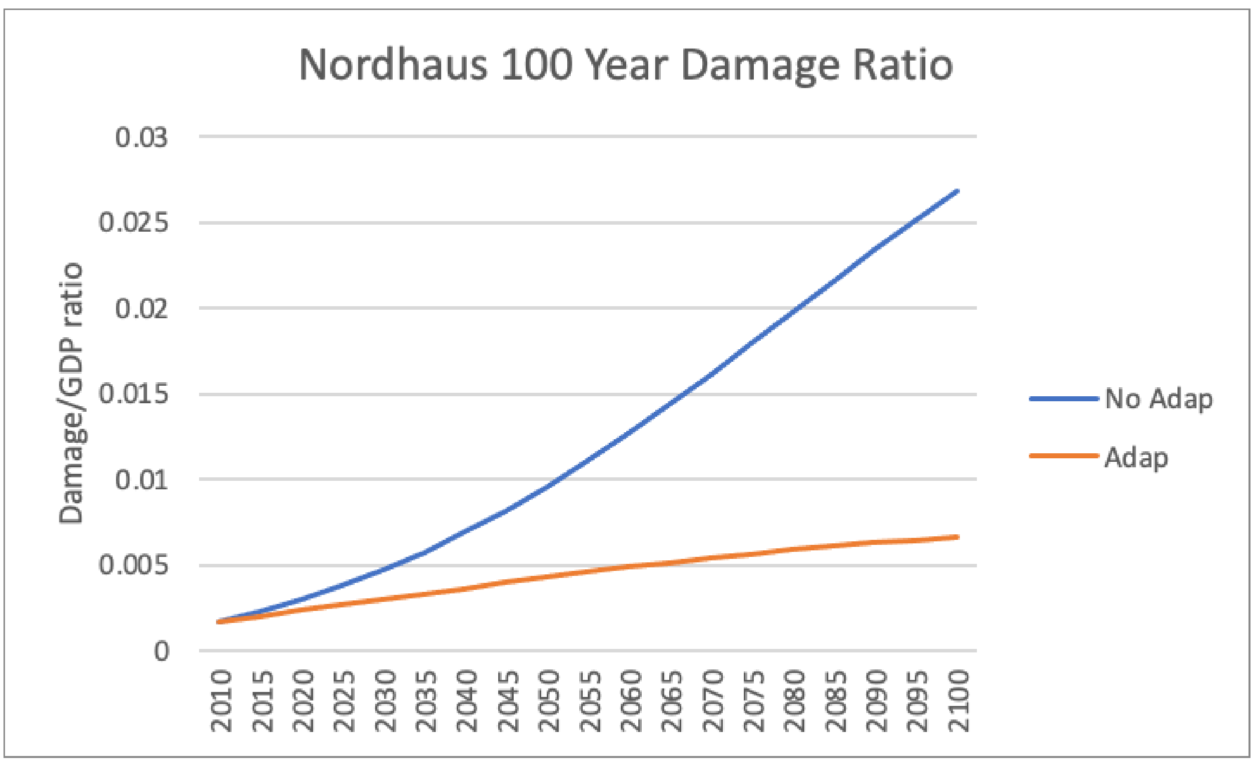
Nordhaus 200 Year Damage Ratio
Damage/GDP ratio
0.04
0.035
0.03
0.025
0.02
0.015
0.01
0.005
0
2010
2020
2030
2040
2050
2060
2070
2080
2090
2100
2110
2120
2130
2140
2150
2160
2170
2180
2190
2200
No Adap
Adap
No Adap
Adap

100 year

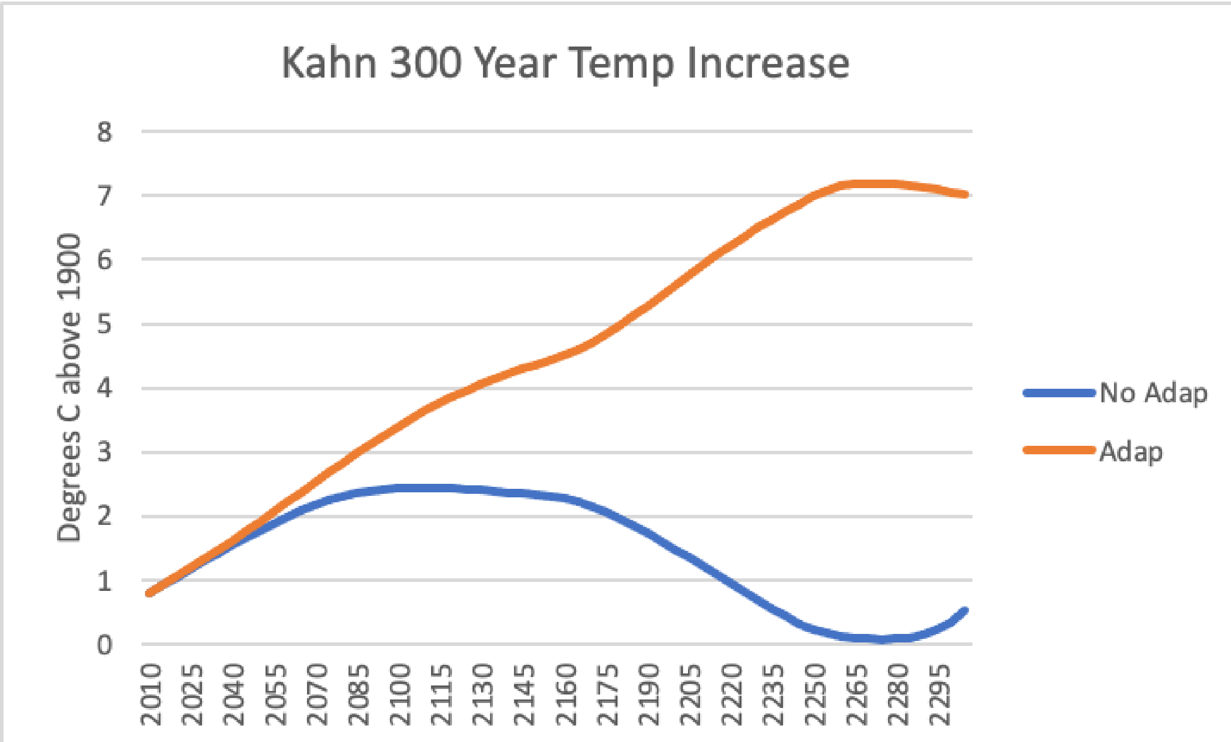

Nordhaus 100 Year Temp Increase
Degrees C above 1900
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
2010
2015
2020
2025
2030
2035
2040
2045
2050
2055
2060
2065
2070
2075
2080
2085
2090
2095
2100
2105
No Adap
Adap

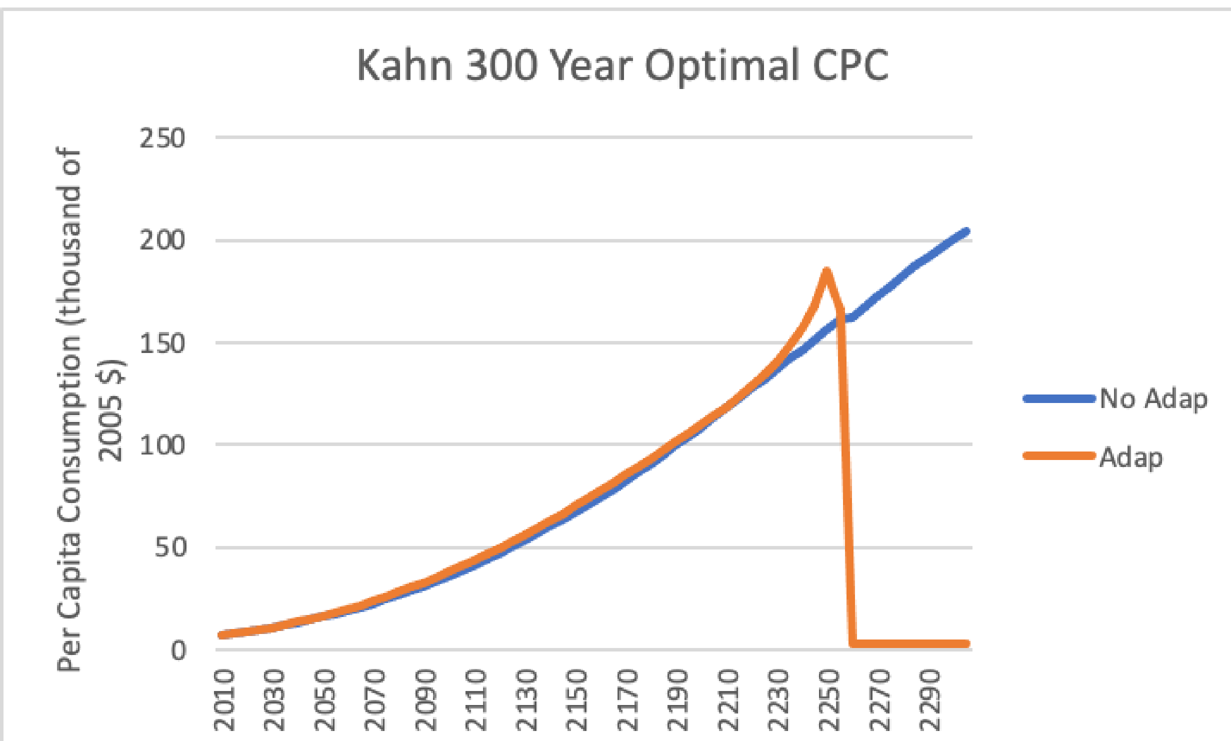

Nordhaus 100 Year Optimal CPC
Per Capita Consumption (thousands of 2005 $)
45
40
35
30
25
20
15
10
5
0
2010
2015
2020
2025
2030
2035
2040
2045
2050
2055
2060
2065
2070
2075
2080
2085
2090
2095
2100
2105
No Adap
Adap

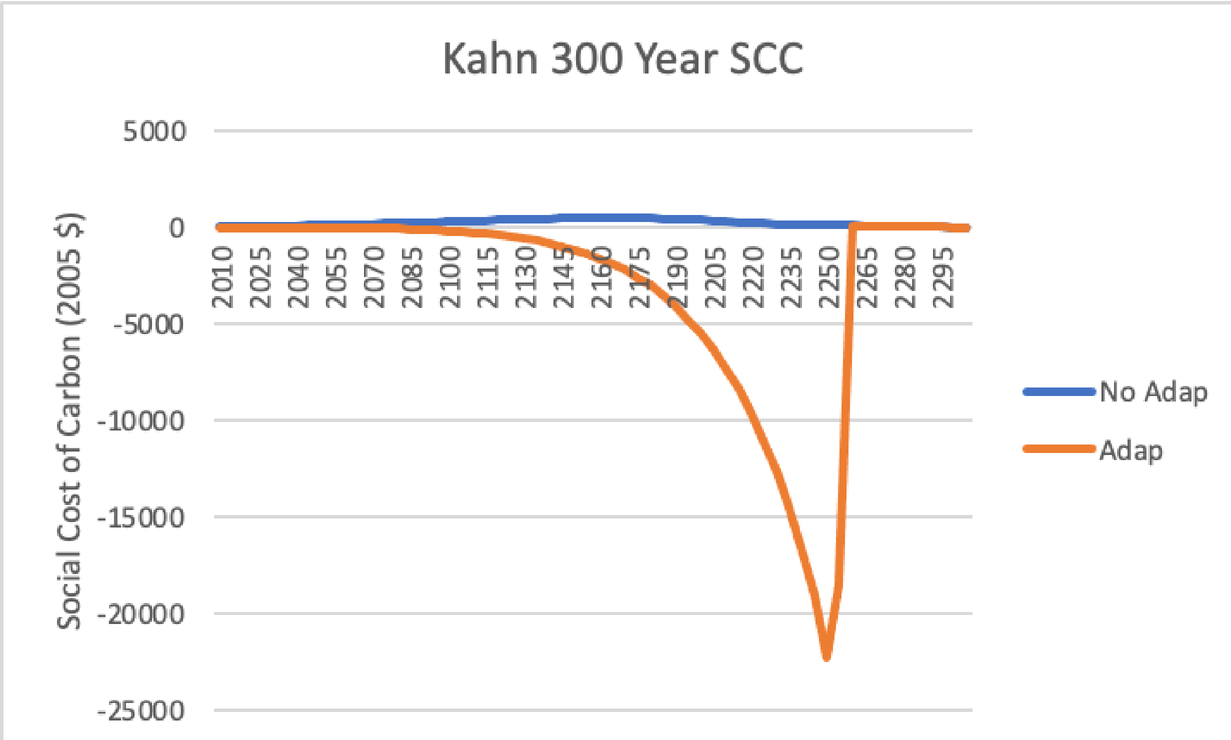

Nordhaus 100 Year SCC
Social Cost of Carbon (2005 $)
160
140
120
100
80
60
40
20
0
2010 2015 2020 2025 2030 2035 2040 2045 2050 2055 2060 2065 2070 2075 2080 2085 2090 2095 2100 2105
No Adap
Adap

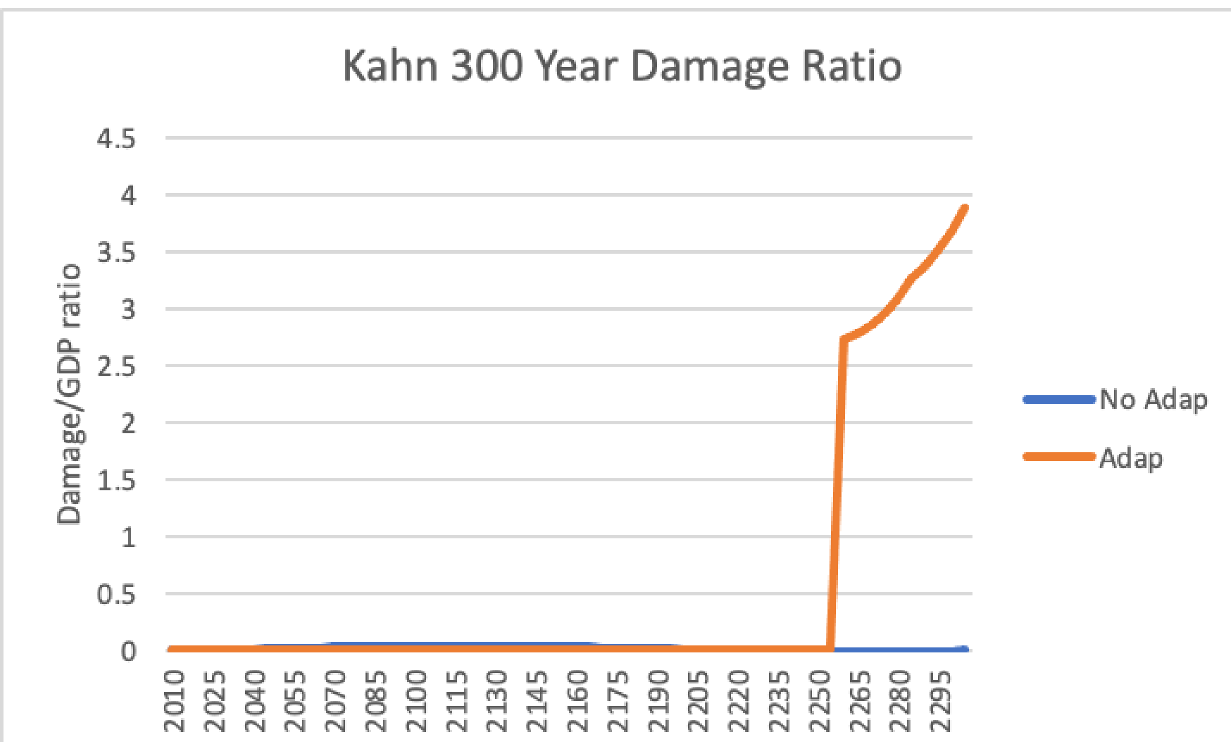

Nordhaus 100 Year Damage Ratio
Damage/GDP ratio
0.03
0.025
0.02
0.015
0.01
0.005
0
2010 2015 2020 2025 2030 2035 2040 2045 2050 2055 2060 2065 2070 2075 2080 2085 2090 2095 2100
No Adap
Adap

Kahn (0.0065T^2)

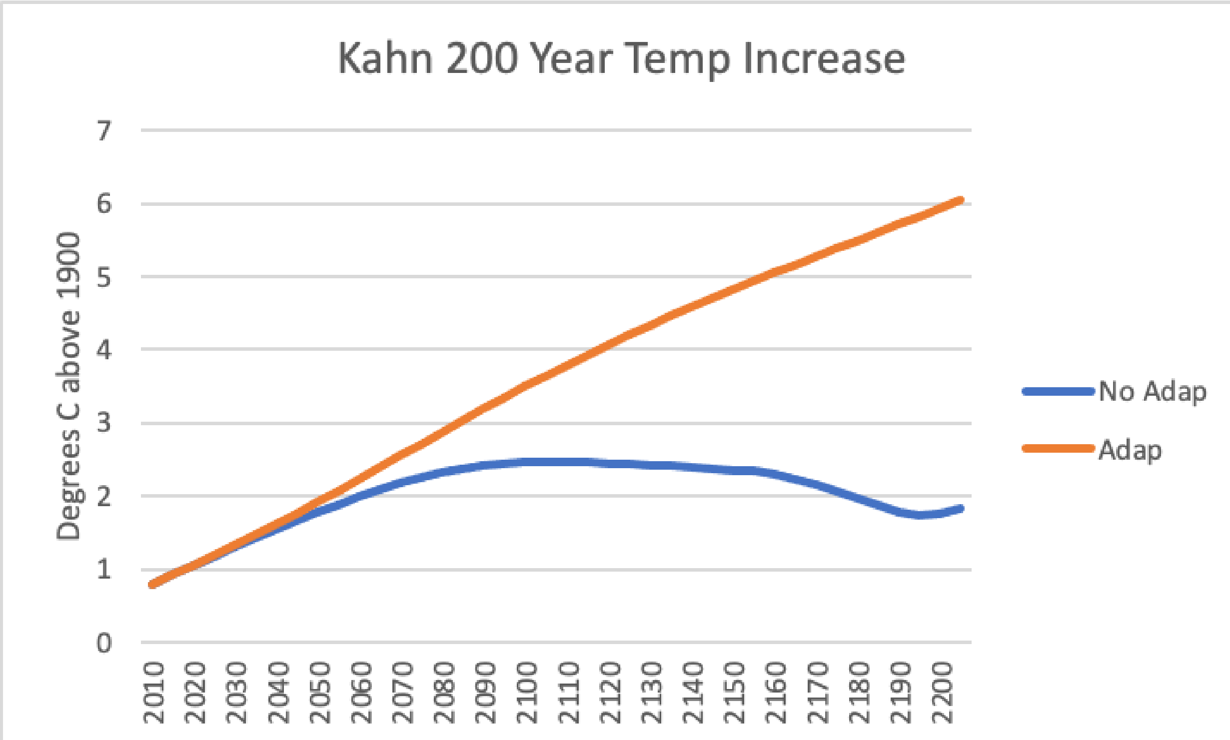


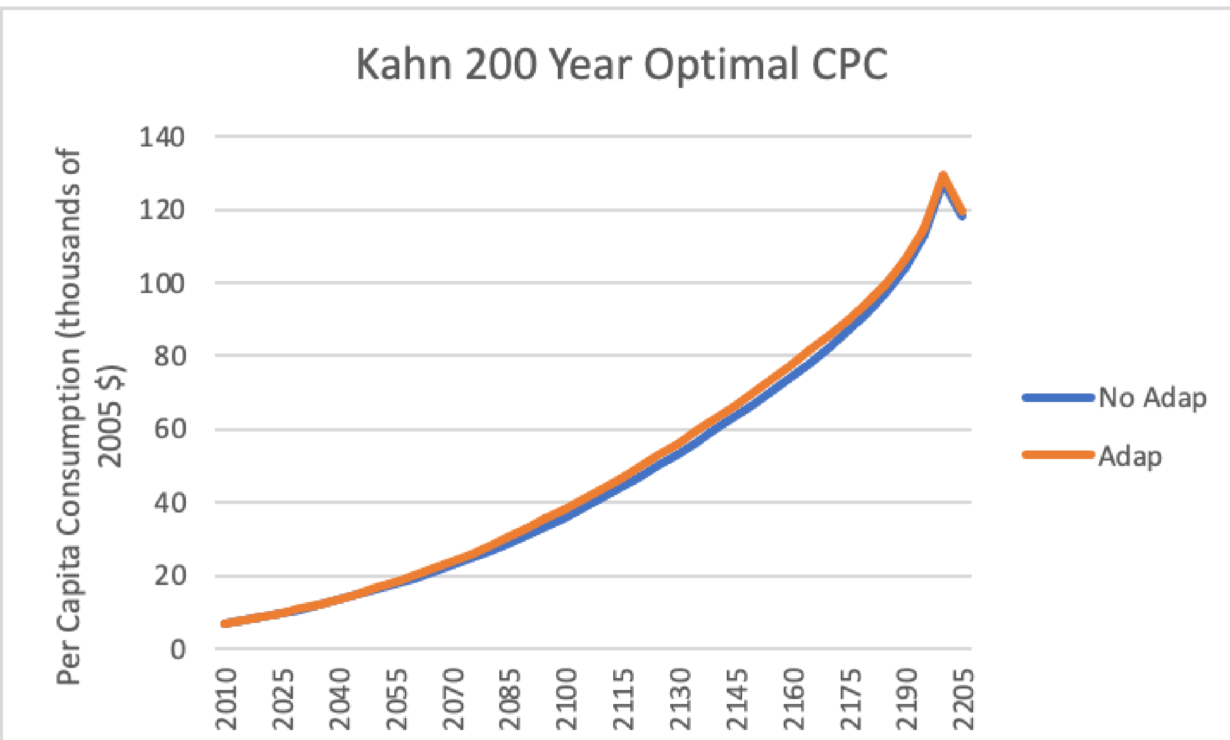


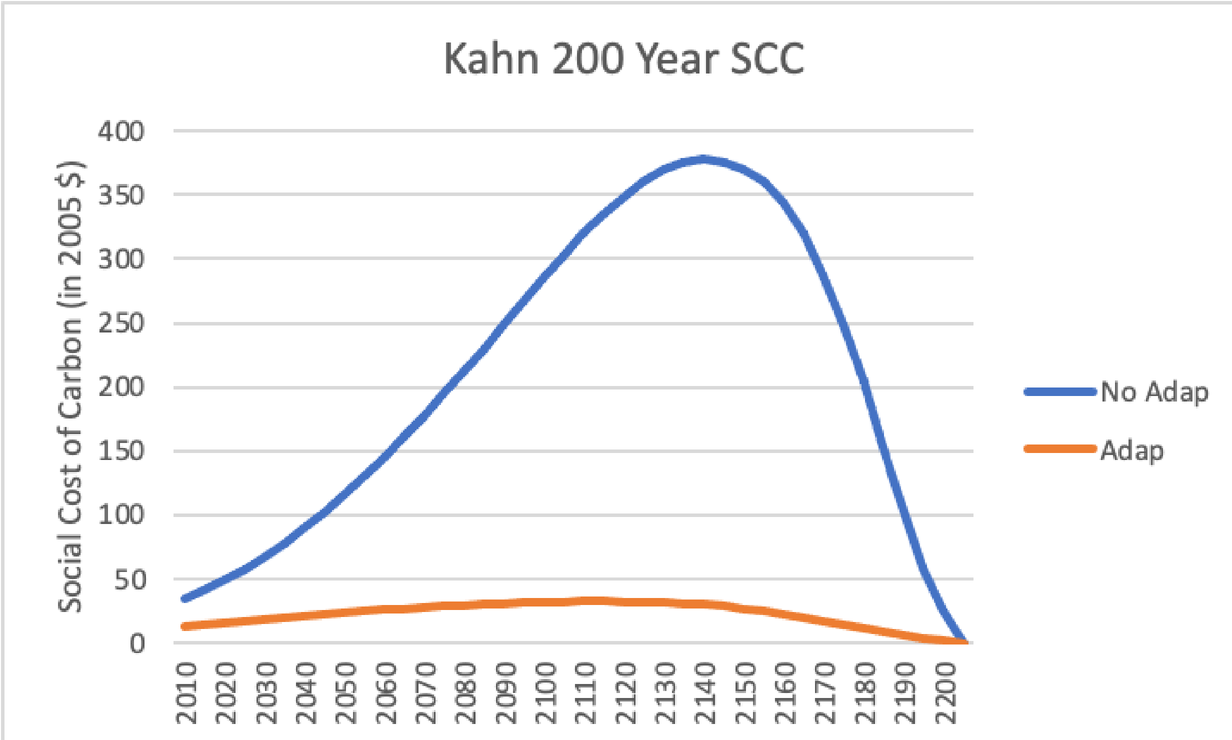

Kahn 300 Year SCC
Social Cost of Carbon (2005 $)
5000
0
-5000
-10000
-15000
-20000
-25000
2010
2025
2040
2055
2070
2085
2100
2115
2130
2145
2160
2175
2190
2205
2220
2235
2250
2265
2280
2295
No Adap
Adap

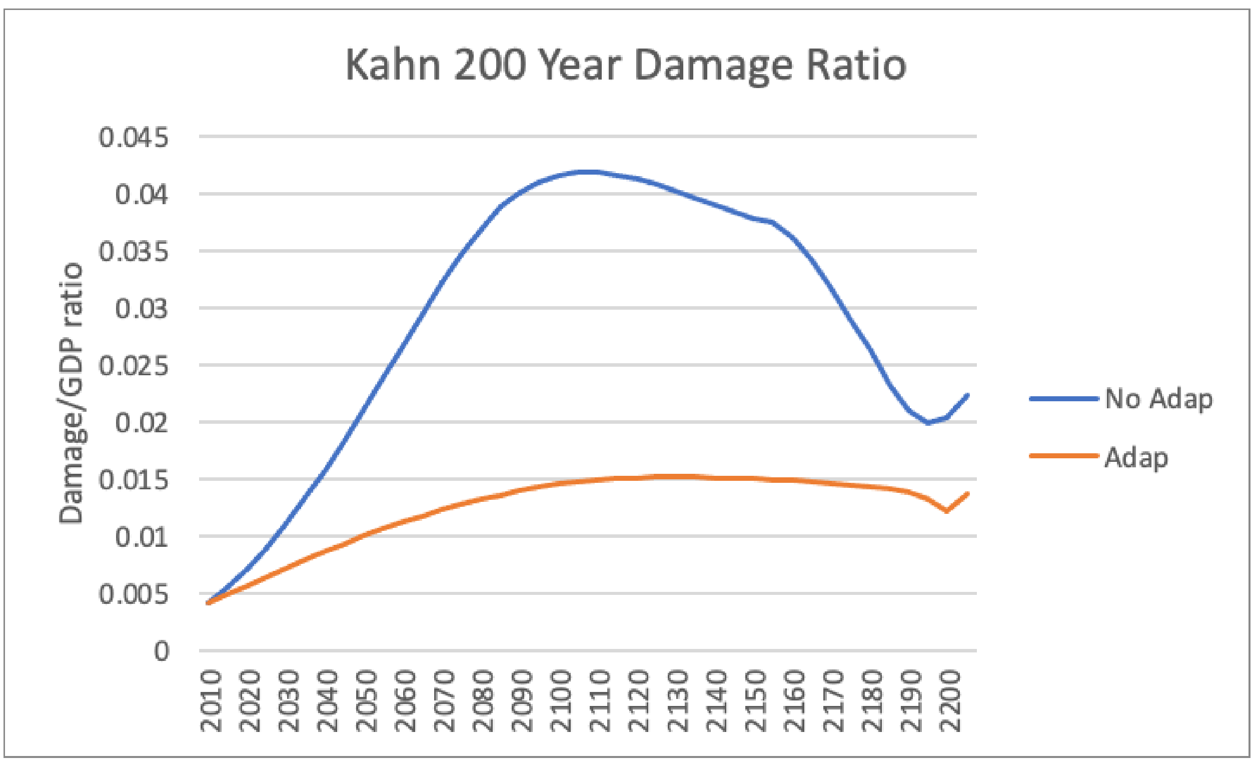

Kahn 300 Year Damage Ratio
Damage/GDP ratio
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
2010
2025
2040
2055
2070
2085
2100
2115
2130
2145
2160
2175
2190
2205
2220
2235
2250
2265
2280
2295
No Adap
Adap

200 year

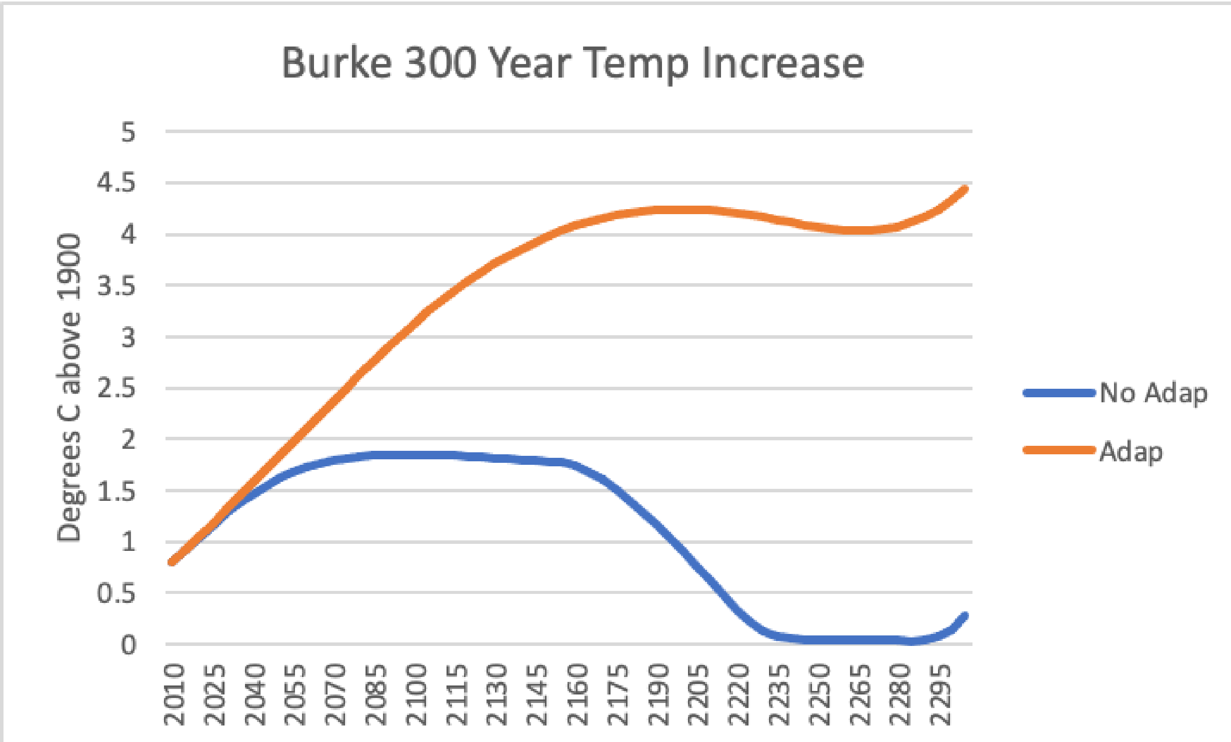

Kahn 200 Year Temp Increase
Degrees C above 1900
0
1
2
3
4
5
6
7
2010
2020
2030
2040
2050
2060
2070
2080
2090
2100
2110
2120
2130
2140
2150
2160
2170
2180
2190
2200
No Adap
Adap

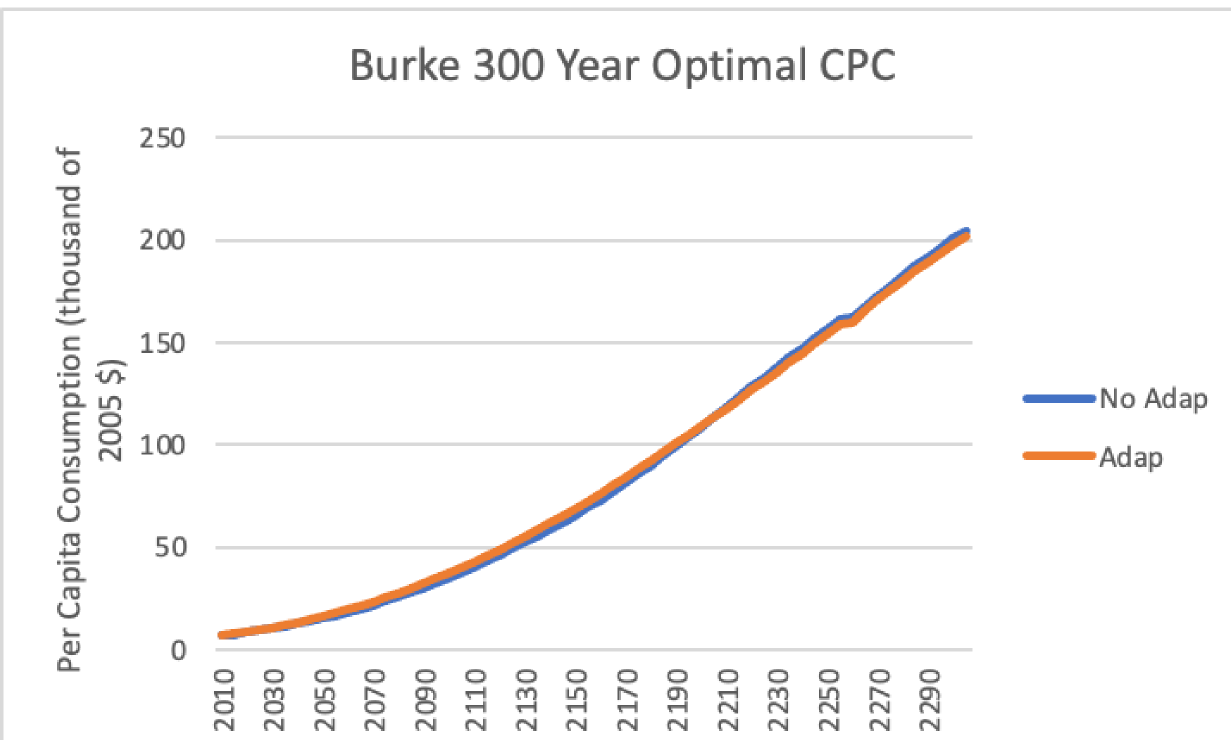

Kahn 200 Year Optimal CPC
Per Capita Consumption (thousands of 2005 $)
0
20
40
60
80
100
120
140
2010
2025
2040
2055
2070
2085
2100
2115
2130
2145
2160
2175
2190
2205
No Adap
Adap

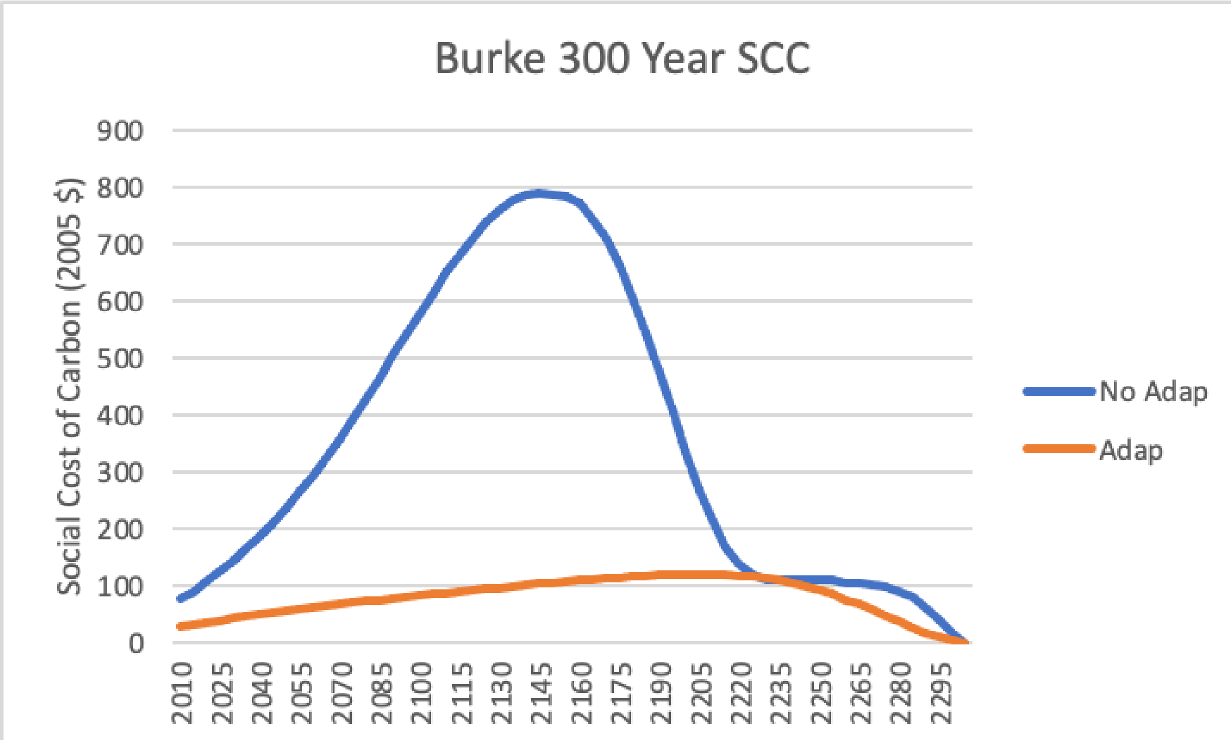

Kahn 200 Year SCC
Social Cost of Carbon (in 2005 $)
400
350
300
250
200
150
100
50
0
2010
2020
2030
2040
2050
2060
2070
2080
2090
2100
2110
2120
2130
2140
2150
2160
2170
2180
2190
2200
No Adap
Adap

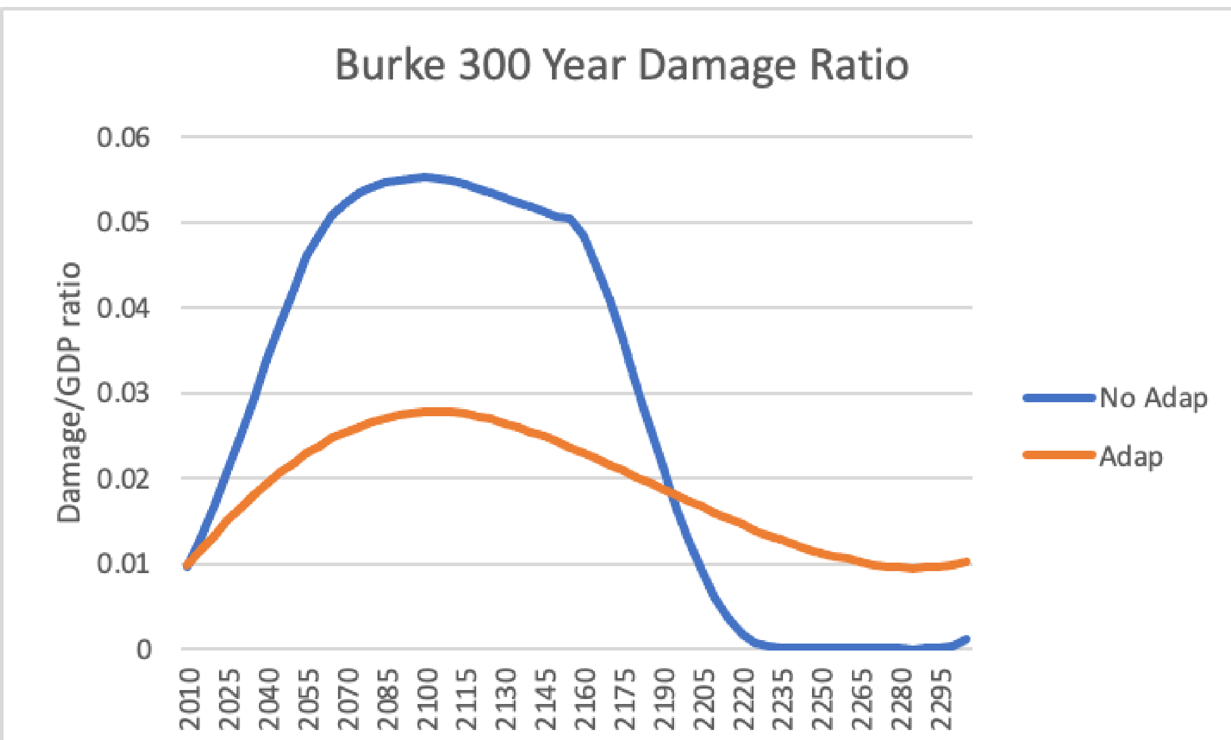

Kahn 200 Year Damage Ratio
Damage/GDP ratio
0.045
0.04
0.035
0.03
0.025
0.02
0.015
0.01
0.005
0
2010
2020
2030
2040
2050
2060
2070
2080
2090
2100
2110
2120
2130
2140
2150
2160
2170
2180
2190
2200
No Adap
Adap

Burke (0.015T^2)

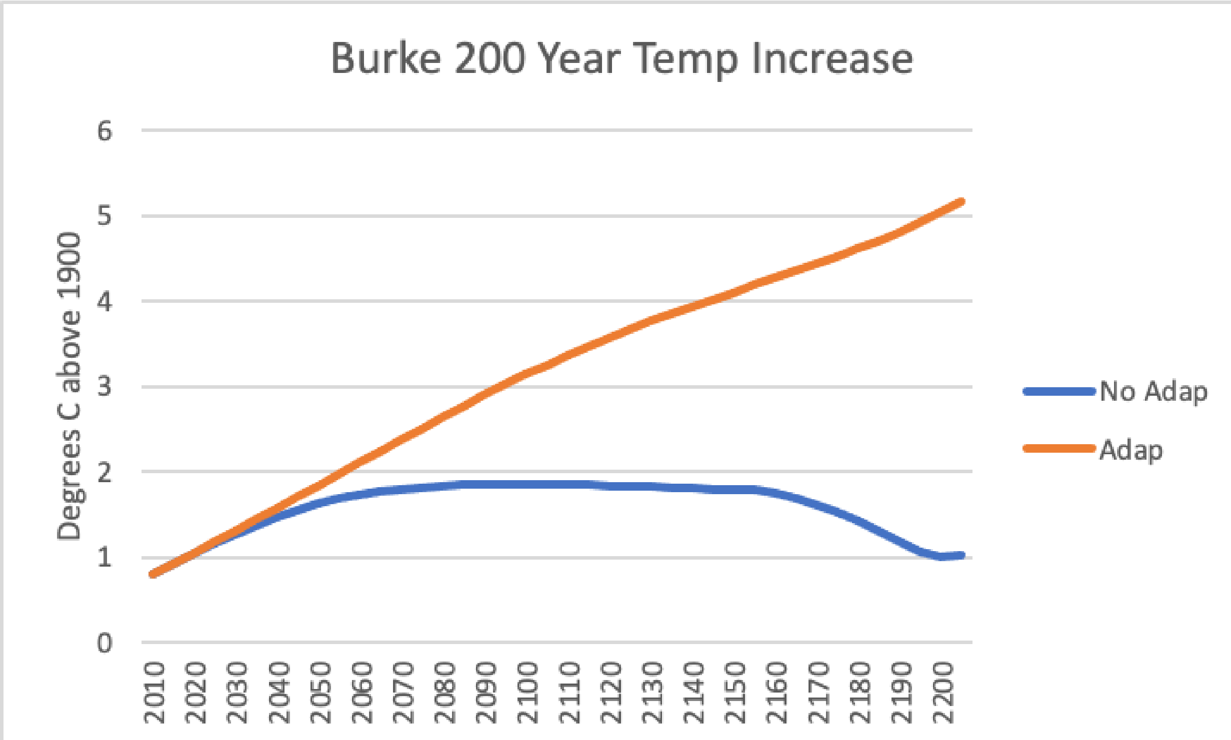


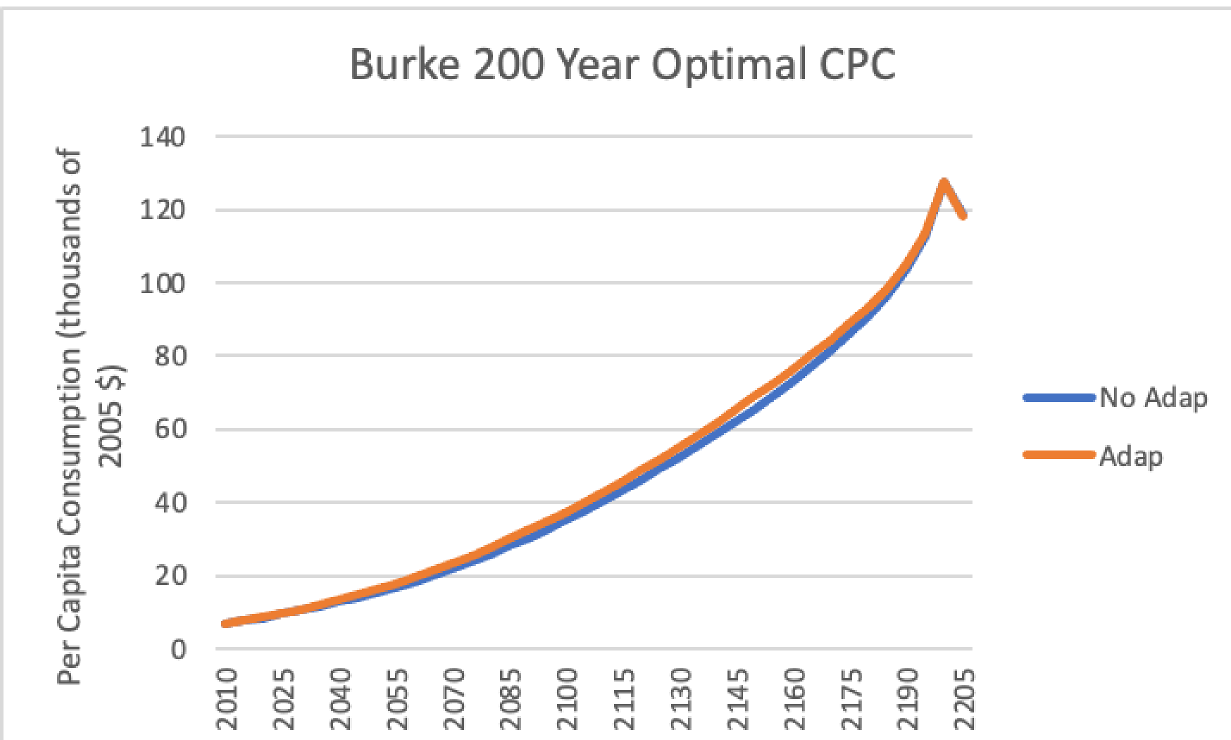


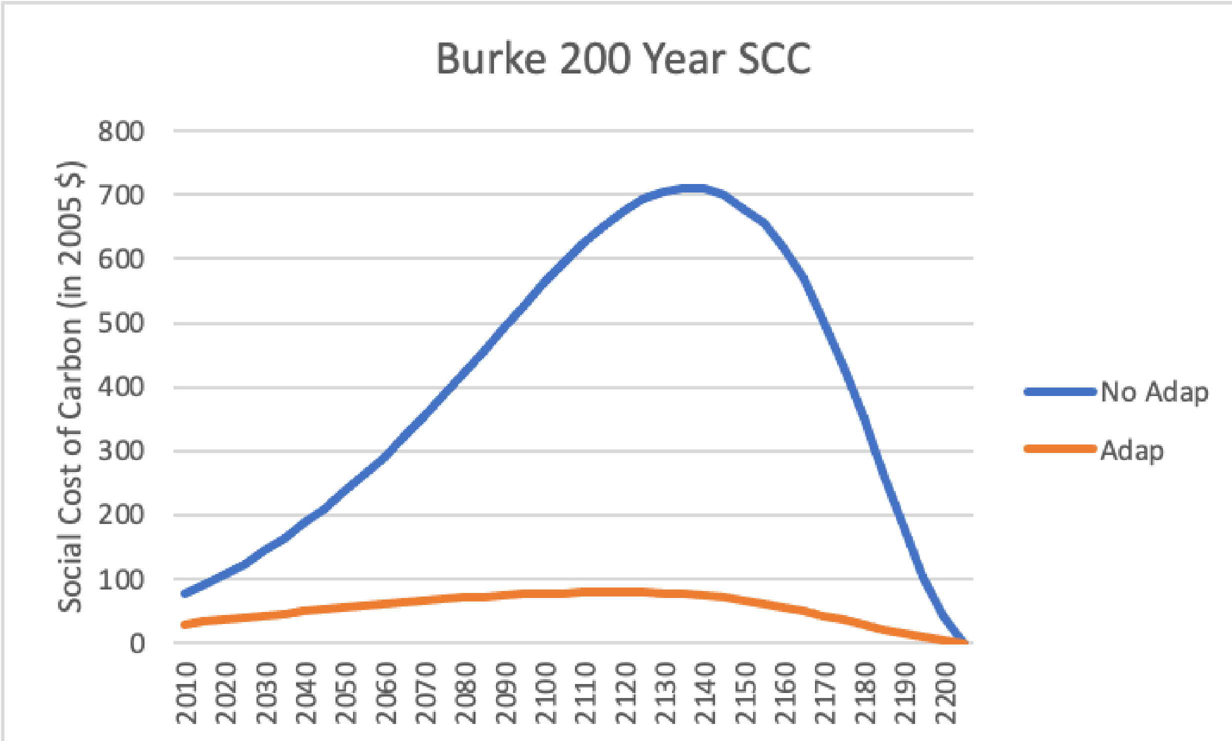

Burke 300 Year SCC
Social Cost of Carbon (2005 $)
900
800
700
600
500
400
300
200
100
0
2010
2025
2040
2055
2070
2085
2100
2115
2130
2145
2160
2175
2190
2205
2220
2235
2250
2265
2280
2295
No Adap
Adap

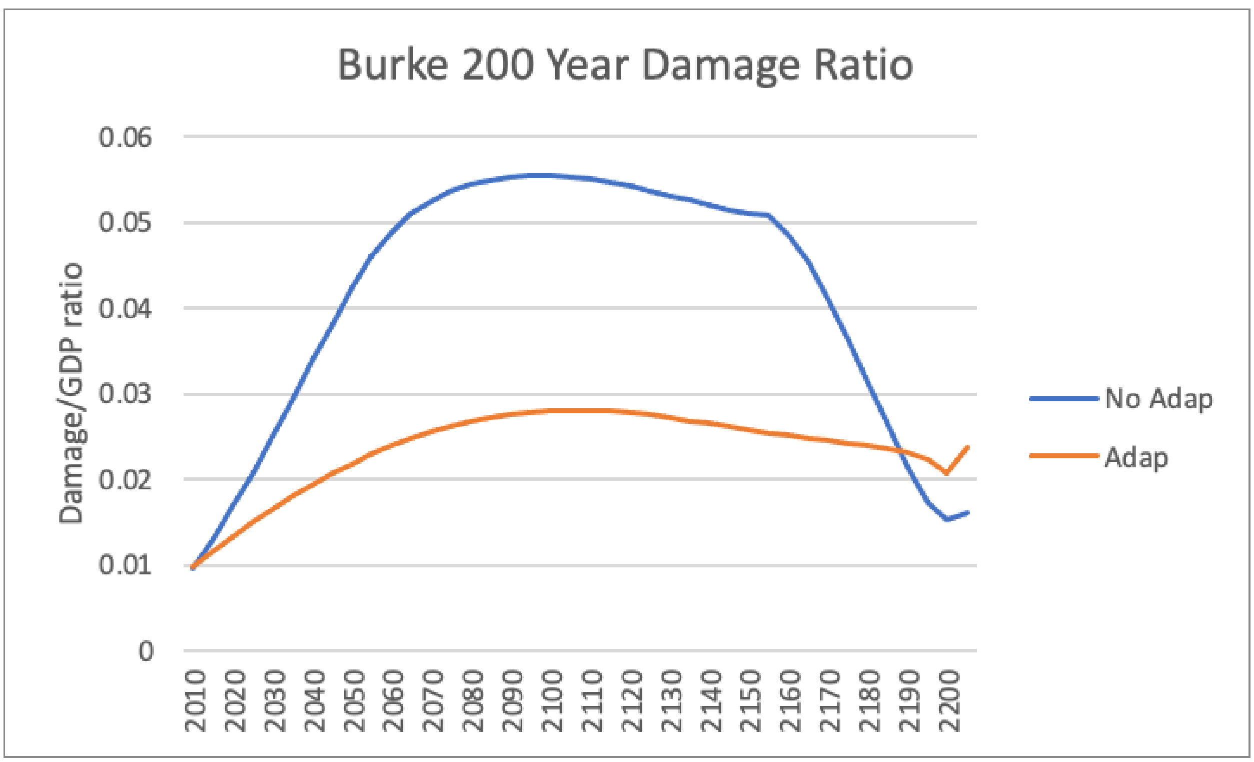

Burke 300 Year Damage Ratio
Damage/GDP ratio
0.06
0.05
0.04
0.03
0.02
0.01
0
2010
2025
2040
2055
2070
2085
2100
2115
2130
2145
2160
2175
2190
2205
2220
2235
2250
2265
2280
2295
No Adap
Adap

200 year

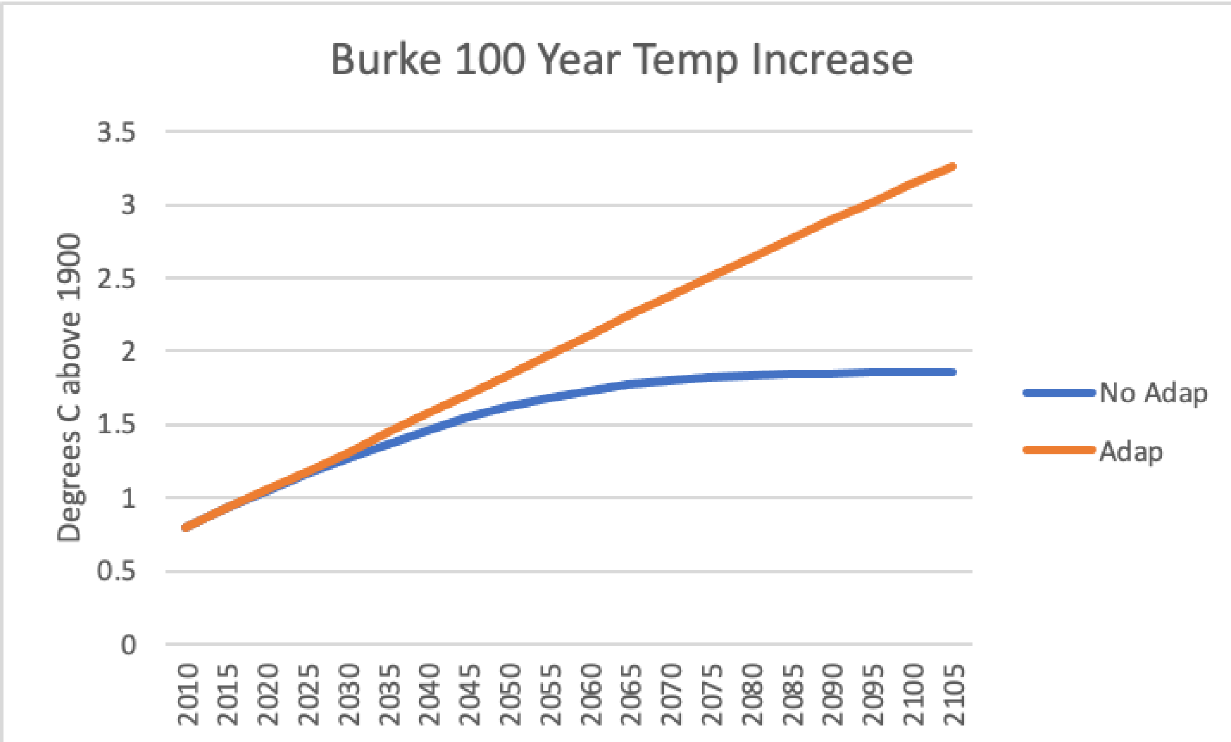

Burke 200 Year Temp Increase
Degrees C above 1900
6
5
4
3
2
1
0
2010
2020
2030
2040
2050
2060
2070
2080
2090
2100
2110
2120
2130
2140
2150
2160
2170
2180
2190
2200
No Adap
Adap


Burke 200 Year Optimal CPC
Per Capita Consumption (thousands of 2005 $)
140
120
100
80
60
40
20
0
2010
2025
2040
2055
2070
2085
2100
2115
2130
2145
2160
2175
2190
2205
No Adap
Adap

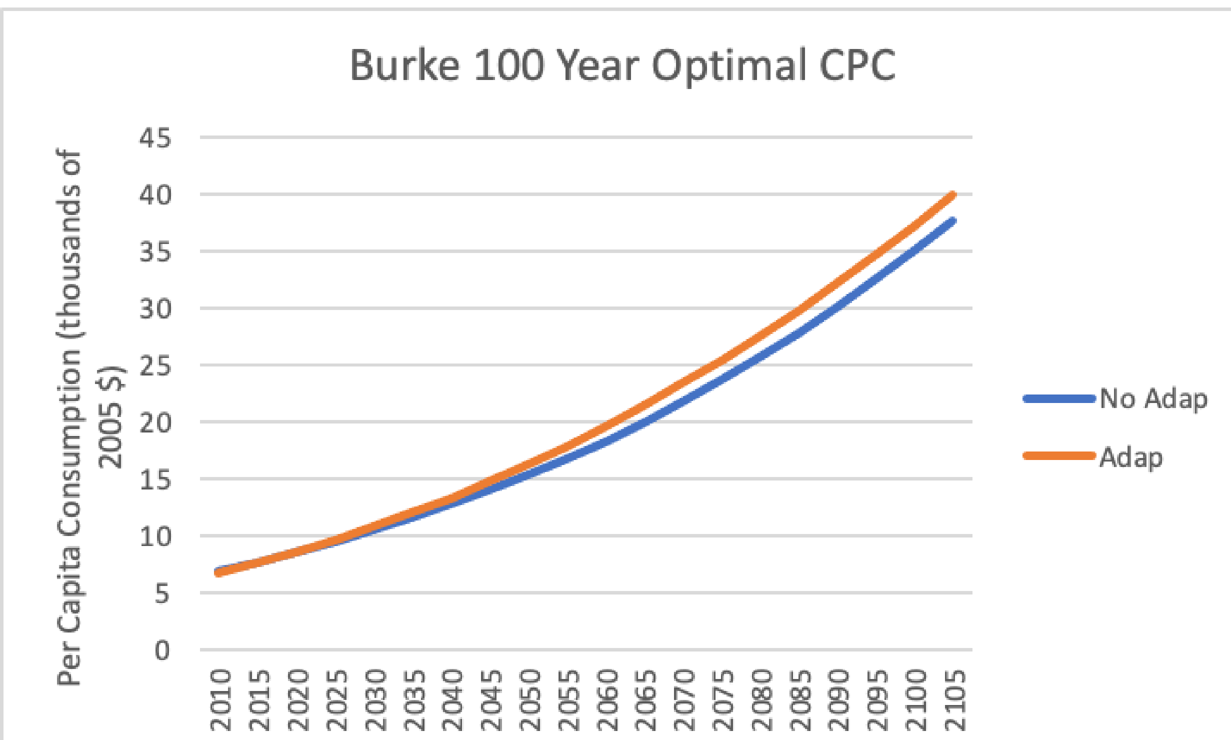

Burke 200 Year SCC
Social Cost of Carbon (in 2005 $)
800
700
600
500
400
300
200
100
0
2010
2020
2030
2040
2050
2060
2070
2080
2090
2100
2110
2120
2130
2140
2150
2160
2170
2180
2190
2200
No Adap
Adap


Burke 200 Year Damage Ratio
Damage/GDP ratio
0.06
0.05
0.04
0.03
0.02
0.01
0
2010
2020
2030
2040
2050
2060
2070
2080
2090
2100
2110
2120
2130
2140
2150
2160
2170
2180
2190
2200
No Adap
Adap

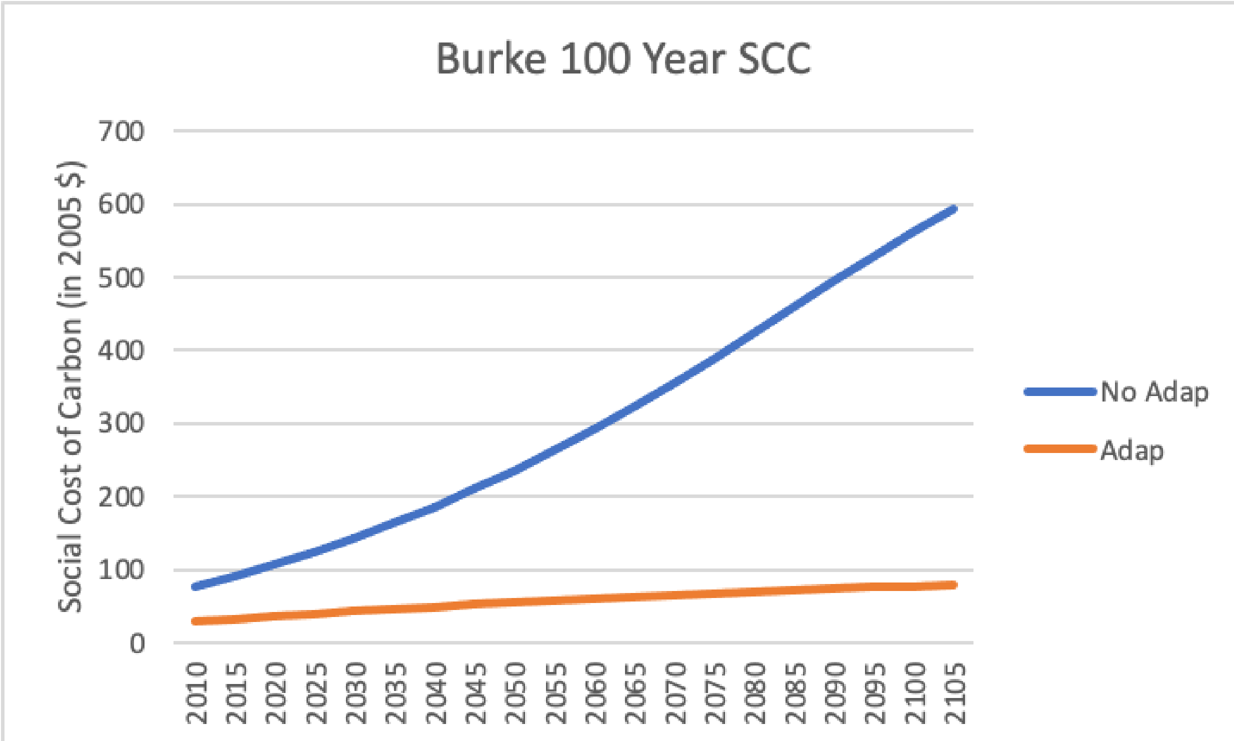
100 year

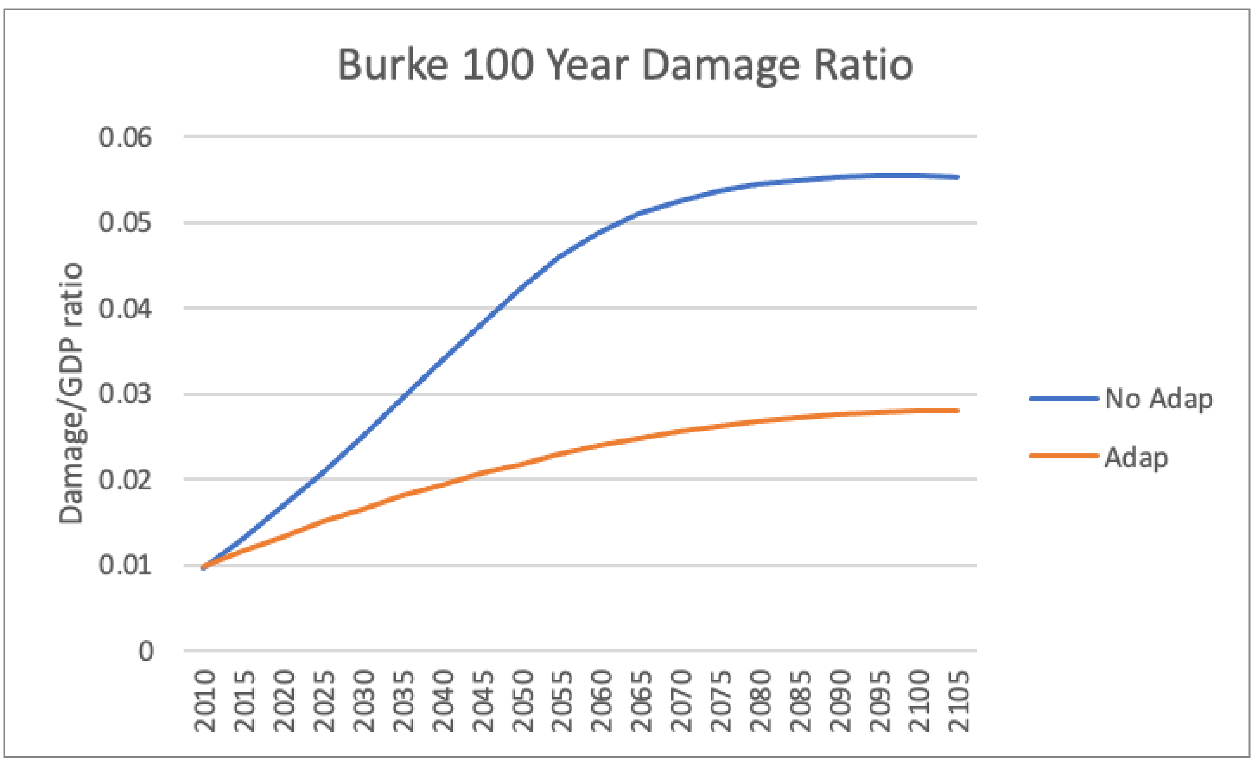


Burke 100 Year Temp Increase
Degrees C above 1900
3.5
3
2.5
2
1.5
1
0.5
0
2010
2015
2020
2025
2030
2035
2040
2045
2050
2055
2060
2065
2070
2075
2080
2085
2090
2095
2100
2105
No Adap
Adap



Burke 100 Year Optimal CPC
Per Capita Consumption (thousands of 2005 $)
45
40
35
30
25
20
15
10
5
0
2010
2015
2020
2025
2030
2035
2040
2045
2050
2055
2060
2065
2070
2075
2080
2085
2090
2095
2100
2105
No Adap
Adap





$$P = pcGDP(year\ 0)/pcGDP(year\ t)$$