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Break-even year: A concept for understanding intergenerational trade-offs in climate change mitigation policy

Patrick T. Brown
San Jose State University, patrick.brown@sjsu.edu

Juan Moreno-Cruz
University of Waterloo

Ken Caldeira
Carnegie Institution of Washington

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Patrick T Brown¹ , Juan Moreno-Cruz² and Ken Caldeira³ ¹ Department of Meteorology and Climate Science, San José State University, San José, California, United States of America² School of Environment, Enterprise and Development, University of Waterloo, Waterloo, Ontario, Canada³ Department of Global Ecology, Carnegie Institution for Science, Stanford, California, United States of AmericaE-mail: patrick.brown@sjsu.edu**Keywords:** integrated assessment, climate-economy, damage function, social planner, DICE, mitigation cost, climate damage function**Abstract**

Global climate change mitigation is often framed in public discussions as a tradeoff between environmental protection and harm to the economy. However, climate-economy models have consistently calculated that the immediate implementation of greenhouse gas emissions restriction (via e.g. a global carbon price) would be in humanity's best interest on purely economic grounds. Despite this, the implementation of global climate policy has been notoriously difficult to achieve. This evokes an apparent paradox: if the implementation of a global carbon price is not only beneficial to the environment, but is also 'economically optimal', why has it been so difficult to enact? One potential reason for this difficulty is that economically optimal greenhouse gas emissions restrictions are *not* economically beneficial for the generation of people that launch them. The purpose of this article is to explore this issue by introducing the concept of the break-even year, which we define as the year when the economically optimal policy begins to produce global mean net economic benefits. We show that in a commonly used climate-economy model (DICE), the break-even year is relatively far into the future—around 2080 for mitigation policy beginning in the early 2020s. Notably, the break-even year is not sensitive to the uncertain magnitudes of the costs of climate change mitigation policy or the costs of economic damages from climate change. This result makes it explicit and understandable why an economically optimal policy can be difficult to implement in practice.

Introduction

Potential solutions to climate change are often framed as a tradeoff between reducing humanity's impact on the environment on one hand and harming the economy on the other. More specifically, it is thought that we can reduce our climate change related impact by imposing a global price on carbon that results in an increase in the price of energy which entails a reduction in production and consumption (van Vuuren *et al* 2020). Under this framing, it is natural for people to strongly disagree about climate policy prescriptions since individuals will inevitably diverge in the relative value they place on environmental versus economic concerns.

However, the issue of whether or not it is in humanity's collective best-interest to reduce greenhouse gas emissions may not be as complicated and subjective as the above framing makes it seem. In fact, as long as climate change costs the economy anything (and the cost increases steadily with emissions), then it is in humanity's collective best interest, on purely economic grounds, to restrict greenhouse gas emissions (Nordhaus 1977). In particular, it has been consistently calculated for decades that the 'economically optimal' greenhouse gas emissions pathway is one of immediate restraint, followed by consistent reduction to net zero emissions within about a century or sooner (Nordhaus 1992, Nordhaus 2017, Glanemann *et al* 2020). Despite this, climate change mitigation policy has been notoriously difficult to implement at the global level even with a United Nations Convention (UNFCCC 1992) long dedicated to doing just that.

This gives rise to an apparent paradox: Why is it so difficult to motivate global society to implement greenhouse gas emissions reduction policies if these policies confer not only environmental but also economic benefit?

One well-studied reason is related to the so-called tragedy of the commons (Hardin 1968) where each agent appreciates that it is in their own best-interest not to reduce their emissions despite it being in the global best-interest to do so. An intergenerational version of the tragedy of the commons, that we investigate here, has to do with *when* emissions reduction policies would become economically beneficial.

Economically optimal emissions reductions pathways (and their associated carbon price trajectories) are often calculated with Integrated Assessment Models (IAMs) like the Dynamic Integrated Climate Economy model (DICE) (Nordhaus 1992, Nordhaus 2017). These models weigh the benefits of avoided economic damages from climate change against the costs of mitigating greenhouse gas emissions and calculate the single emissions pathway that maximizes the present discounted value of global social welfare (W),

$$W = \sum_t L(t) \cdot \left[\frac{c(t)^{1-\alpha}}{1-\alpha} \right] \cdot (1 + \rho)^{-t}. \quad (1)$$

In equation (1), $L(t)$, is the global population, ρ is the pure rate of social time preference or the generational discount rate on welfare, $c(t)$ is per-capita consumption and α is the elasticity of marginal utility of consumption (which can also be interpreted as generational inequality aversion, since economic growth implies that consumption increases for future generations).

In DICE, ‘economically optimal’ refers to the emissions pathway that optimizes W —the present discounted value of total human utility integrated over time. In other words, DICE calculates the policy that would be put into place by an omniscient utilitarian social planner whose goal is to maximize global human well-being. The planner’s goal is to maximize economic well-being for all present and future humans from a standpoint in time, where it assigns value to the present and future exclusively based on the discount rate. This framing is useful because it allows for the calculation of a single optimal policy for all people through time. However, when net costs and benefits are collapsed back into a time-integrated welfare function (W), it can obscure the question of *when* climate change mitigation begins to produce net economic benefits and thus where the dividing line is between generational sacrifice and generational benefit.

There has been a great deal of discussion in the literature regarding how to weigh the wellbeing of different generations in the context of climate policy which has played out largely in debates over the appropriate choice for the rate of social time preference, ρ (Nordhaus 2007, Arrow *et al* 2013). Despite this vigorous discussion on trading off the wellbeing of current versus future generations, the specific point in time for which policy begins to confer net benefits to society is rarely highlighted.

The purpose of the present paper is to highlight that this point in time exists and to discuss when it might be. Towards this end, we use the DICE model (Nordhaus 1992, Nordhaus 2017) to identify the *break-even year*: the year when net global per-capita consumption, under economically optimal policy, begins to exceed net per-capita consumption under a no-policy case.

We hope that this metric will be useful in not only explaining why climate policies can be difficult to implement but also that it will help facilitate the design of solutions like e.g. subsidizing the generation prior to the break-even year with additional taxes originating from the generation subsequent the break-even year (Kotlikoff *et al* 2019).

Methods

We investigate the break-even year with the DICE model (Nordhaus 1992, Nordhaus 2017) which is an idealized cost-benefit model for climate change mitigation policy. Below we briefly discuss the mathematical representations of how both climate change and climate change mitigation inhibits economic output in DICE.

Economic damages from climate change

Climate change is expected to negatively impact global economic output through numerous possible pathways (Carleton and Hsiang 2016, Hsiang *et al* 2017) including increased infrastructural damage from more intense cyclones (Hsiang and Narita 2012) sea level rise (Anthoff *et al* 2010), decreased crop yields (Schlenker and Roberts 2009, Lobell *et al* 2011), decreased labor productivity (Zivin and Neidell 2014, Sudarshan *et al* 2015), increased crime (Jacob *et al* 2007, Ranson 2014), increased energy demand (Auffhammer and Mansur 2014, Auffhammer *et al* 2017), increased human mortality (Deschenes 2014, Hsiang *et al* 2017) and generally decreased total factor productivity (Moyer *et al* 2014, Dietz and Stern 2015).

These impacts are complex functions of space and time but DICE attempts to aggregate their net effect in a simple ‘damage function’ which relates global economic output loss (Ω) to increases in global temperature above preindustrial levels (T) via a simple quadratic relationship,

$$\Omega(t) = \varphi_1 T(t)^2 \quad (2)$$

The parameters in this equation are tuned to literature surveys on estimated economic damages at various levels of warming (Tol 2009, Tol 2018) and from there, are adjusted upward by 25% in an effort to account for non-monetizable impacts to e.g. biodiversity (Nordhaus 2013). The climate sensitivity used in DICE is 3.1 °C per CO₂-doubling, consistent with recent estimates (e.g. Sherwood *et al* 2020).

As we show below, the break-even year is not sensitive to the magnitude of this function (e.g. the magnitude of φ_1). However, the break-even year would be sensitive to the shape and fundamental character of this function.

For example, there is an active discussion in the literature on the degree to which economic damages to climate change are felt primarily instantaneously at each timestep (level effects) or if they are felt primarily on economic growth (growth effects) (Weitzman 2010, Dell *et al* 2012, Moyer *et al* 2014, Burke *et al* 2015, Dietz and Stern 2015, Moore and Diaz 2015, Burke *et al* 2018, Letta and Tol 2018, Newell *et al* 2018, Kahn *et al* 2019). DICE models damages as being primarily expressed on levels but if they are in fact expressed more on growth, this could have implications for the break-even year.

Also, even if global economic damages are felt on levels of production and they can be approximated roughly with a quadratic function of global temperature (equation (2)), specific regions will inevitably experience fundamentally different damage trajectories. For example, in some regions, there is reason to believe that economic damages may have a concave relationship with temperature rather than a convex relationship (i.e. damages experience saturation or diminishing returns with warming) (Ricke *et al* 2016). In regions dominated by such effects, the benefits of avoided damages from climate change mitigation may be weighted more towards the near-term which could push the break-even year nearer in time.

Economic costs of mitigating climate change

DICE models global aggregate mitigation costs as an instantaneous (i.e. in that timestep) loss of global output via a simple power function of the fraction of greenhouse gas emissions abated $\mu(t)$,

$$\Lambda(t) = h \cdot \beta(t) \cdot \xi(t) \cdot \mu(t)^\theta. \quad (3)$$

$\beta(t)$ represents the larger cost of carbon emission-free energy, like renewable wind and solar energy, relative to the combustion of fossil fuels (or equivalently, the cost of carbon capture and storage and/or atmospheric CO₂ removal). $\xi(t)$ accounts for the non-policy induced reduction in the greenhouse gas emissions intensity of the economy through natural increases in energy efficiency (e.g. via improved technology or a transition to a more service-oriented economy) and increases in the fraction of primary energy produced from non-carbon emitting sources. The fraction of greenhouse gas emissions controlled, $\mu(t)$, is the choice variable in the DICE optimization framework. The convexity parameter $\theta > 1$ represents the notion that the expense of marginal emissions reductions increases with the fraction of emissions abated (Nordhaus 1991).

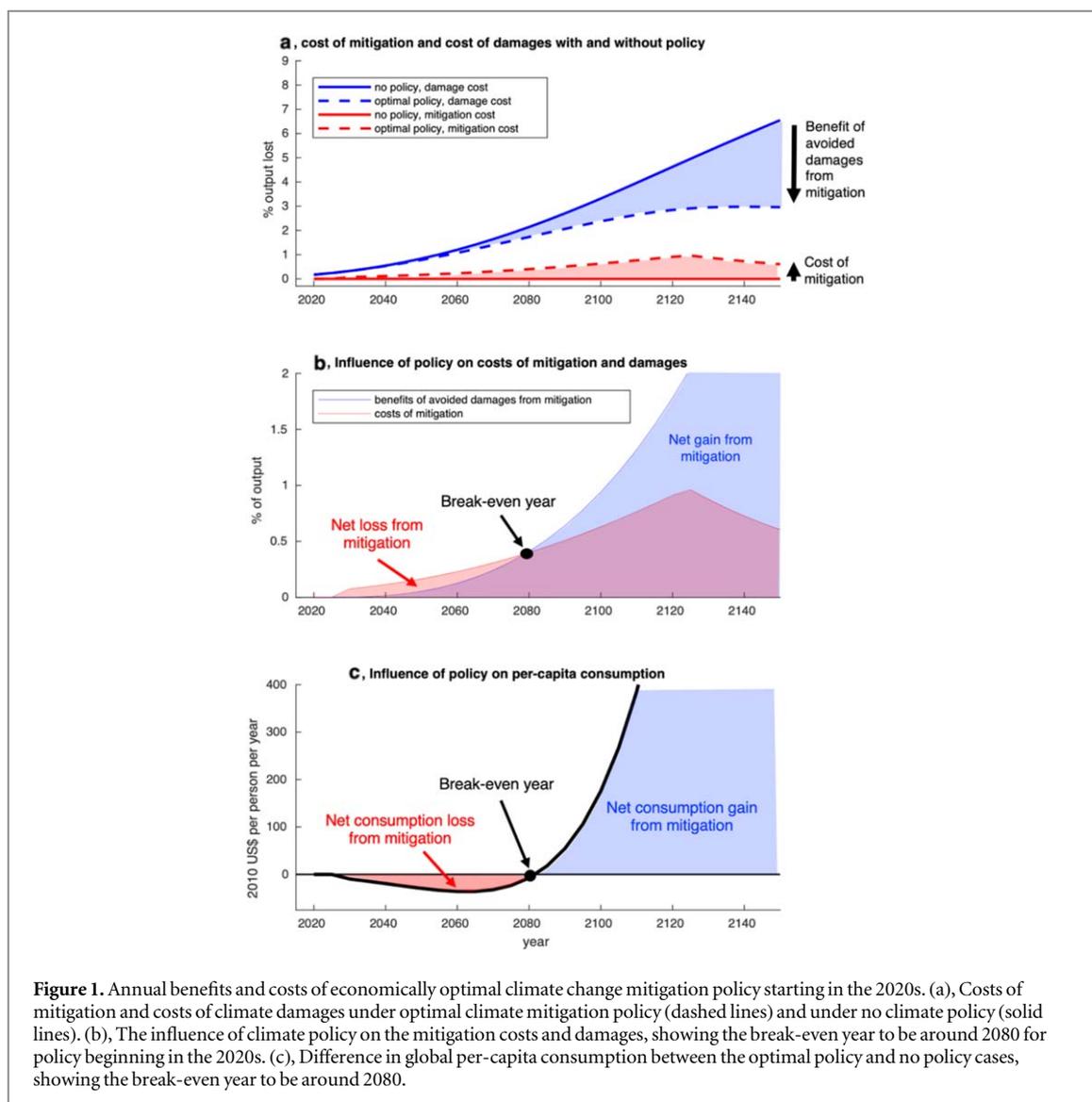
Although this representation of mitigation cost is highly idealized, it is calibrated against, and thus produces similar results to, those originating from disaggregated process-based IAMs that simulate a full energy technology portfolio, cost reduction through learning, technology diffusion rates, regional disaggregation, capital costs, etc (Blanford *et al* 2009, Clarke *et al* 2009, Rogelj *et al* 2013, Kriegler *et al* 2014, Gillingham *et al* 2018).

Similar to the damage function, the break-even year is not sensitive to the magnitude of the mitigation cost function but it would be sensitive to the shape and fundamental character of this function.

Results

Figure 1 illustrates the calculation of the break-even year using default parameter values in DICE (Nordhaus 2017). Figure 1(a) shows the mitigation costs and climate change induced economic losses (damages) as a fraction of total global economic output for both the optimal implementation of climate change mitigation policy (dashed lines) and a no policy case (solid lines). In the no policy case, there is no mitigation cost by definition, and the climate-change induced economic damages grow continuously, reaching ~7% of global output lost per year by the middle of the 22nd century (figure 1(a)). Under the optimal policy case, the cost of mitigation starts small and ramps up slowly over the 20th century, peaking at ~1% of gross output spent per year on mitigation in the 2120s. This mitigation cost is sufficient to limit damages such that they stabilize at ~3% of gross output lost per year by the 2120s (figure 1(a)).

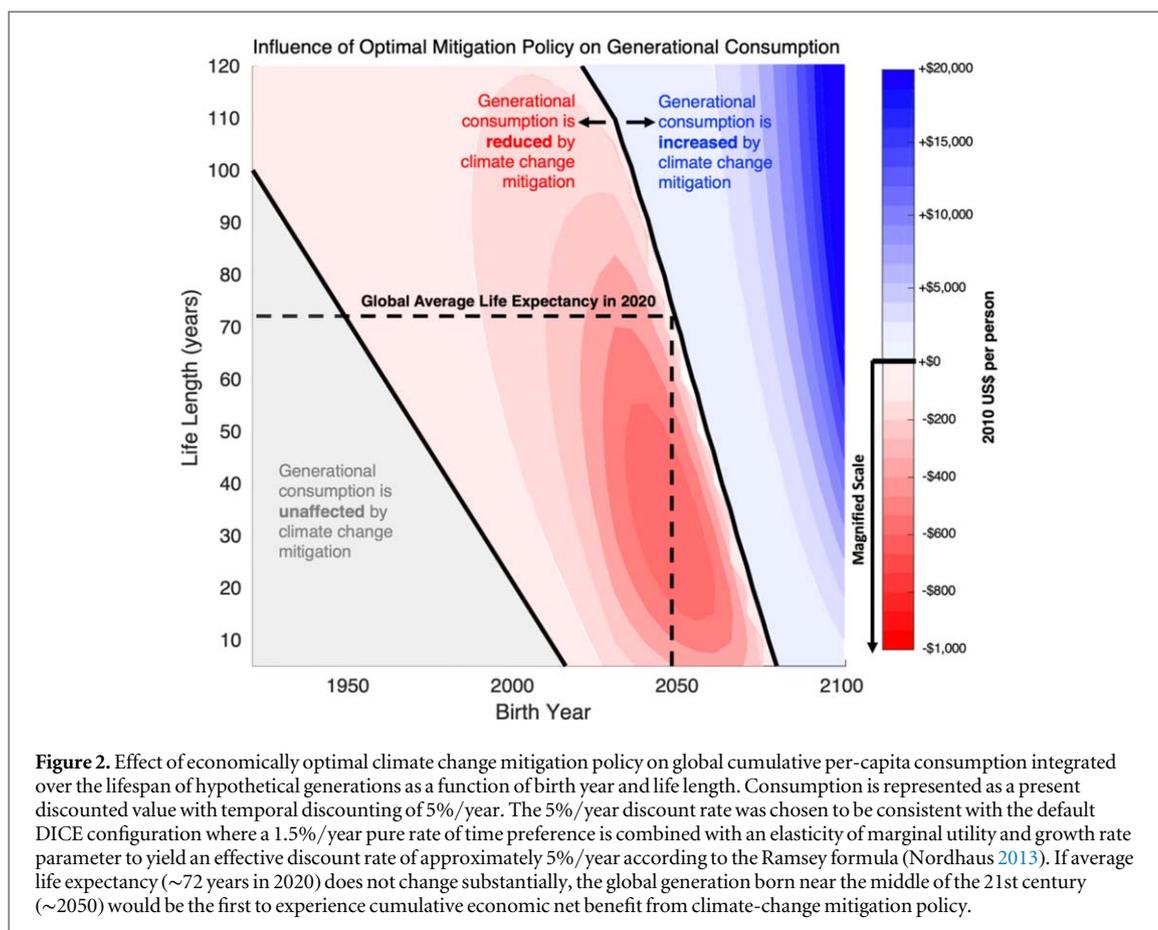
In DICE, damages from climate change are perpetually higher than mitigation costs (figure 1(a)). However, the break-even year depends on when the current year benefits of cumulative mitigation effort exceed the current year costs associated with that ongoing effort. Thus, the break-even year can be illustrated schematically by subtracting the damage costs in the optimal policy case from the damage costs in the no-policy case and displaying the absolute value of this benefit of avoided damages against the cost of mitigation (figure 1(b)). The



equivalent break-even year expressed in terms of the mitigation policy's impact on global per-capita consumption is shown in figure 1(c).

The calculated economically optimal policy entails an initially modest and slowly ramped reduction of greenhouse gas emissions, which effectively spreads mitigation costs over time (Tol 1997). The benefits of avoided damages are subject to geophysical time lags (Tebaldi and Friedlingstein 2013, Samset *et al* 2020) and thus they do not emerge strongly until the 22nd century. Thus, despite the higher weighing of the present compared to the future (a positive value of ρ in equation (1)), the near term is characterized by mitigation costs that are higher than avoided damages and the long term is characterized by avoided damages that are higher than mitigation costs. The point of cross-over, or the break-even year, is late in the century, approximately 2080 for economically optimal policy that begins in the early 2020s. Because mitigation costs eventually peak and then decrease with time (as technology progresses) but damages from climate change increase super-linearly, the benefits of mitigation in the 22nd century are much larger than the costs of mitigation over the 21st century (cf red area to blue area in figure 1(c)).

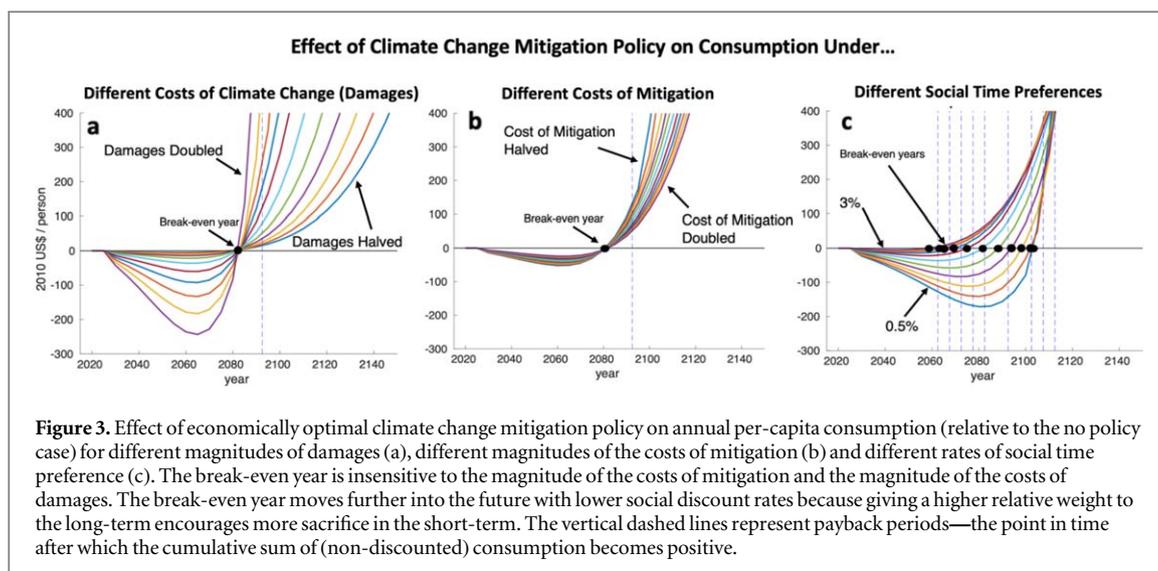
We can now see explicitly why an economically optimal emissions reduction pathway may be difficult to implement in practice. For DICE's social planner, global society can be thought of as a perpetual single entity. For that entity, the specific break-even year of the mitigation policy is of little consequence since welfare is maximized regardless of when the break-even year occurs and mitigation costs can be thought of as society investing in the near term *for its own benefit* in the long-term. However, if the level of focus is shifted from perpetual global society, towards the level of discrete generations of people, then the break-even year becomes consequential since generations' lifespans will disproportionately sample time periods of either economic loss or gain. Specifically, figure 1(c) shows that the economically optimal policy is not economically beneficial for global society over the next 60 years which is the majority of an average human lifetime.



To examine this idea further, we calculate the effect of climate change mitigation policy on global lifetime per-capita consumption for various generations, as a function of birth year and lifespan (figure 2). This further illustrates that the net economic benefits from climate change mitigation policy may not be realized for some time. Specifically, every generation born prior to ~2025 would need to live past their 120th birthdays for mitigation policy to induce an increase in time-discounted consumption. On the other hand, every generation born after ~2075 would experience net gains in time-discounted consumption due to climate change mitigation no matter how long their lives are. Global life expectancy at birth in 2020 was around 72 years (WHO 2018), which if it were to persist, would indicate that people born near 2050 would be the first global generation to experience an increase in time-discounted consumption due to climate change mitigation policy. As was noted in relation to figure 1, the policy-induced gains in consumption for future generations are very large compared to the near-term losses for the current generations (note the change in scale of the color bar in figure 2).

There is great uncertainty in both the costs of mitigating climate change as well as the economic damages from climate change (Diaz and Moore 2017, van Vuuren *et al* 2020). However, the break-even year for the optimal climate change mitigation policy is largely insensitive to the magnitude of these factors (figures 3(a) and (b)). When damages per degree of global warming increase, it is economically optimal to mitigate more in the near term, sacrificing more consumption in the near term, in order to limit more global warming in the long term and reap more benefits of avoided damages (figure 3(a)). When mitigation costs increase per ton of CO₂ abated, it is economically optimal to mitigate less in the near term, sacrificing less consumption in the near term, which results in more global warming and less avoided damages in the long-term (figure 3(b)). In both cases (changing the magnitude of mitigation costs and changing the magnitude of damages), however, the temporal asymmetry between the mitigation costs and the benefits of avoided damages remain proportional and thus the break-even year holds late in the 21st century (around 2080).

The break-even year is sensitive to the social time preference (ρ) on the benefits and costs of implementing the optimal mitigation policy (figure 3(c)). Lower time preference rates indicate a higher relative weight put on the well-being of future generations and thus encourages expanded and intensified near-term mitigation costs for the sake of reaping more benefits of avoided damages further into the future. Thus, weighing the future relatively *more*, moves the break-even year *further* into the future (figure 3(c)).



Discussion and conclusion

Economically optimal climate change mitigation policy maximizes global social welfare integrated through time. Exploring costs and benefits as a function of time, however, reveals that there is a break-even year before which climate policy imposes a net loss on welfare. We have illustrated that the break-even year is insensitive to the magnitude of the costs of mitigation and to the magnitude of the benefits of avoided damages.

We have studied global aggregate outcomes, but the break-even year would of course be sensitive to the sign of the costs and benefits of climate policy which might vary from country to country. For example, (Burke *et al* 2015) suggested that there was an optimal temperature for economic growth and that many high-income countries are currently on the cold side of this optimum. Thus, for these high-income countries, warming is initially beneficial and thus climate change mitigation represents a lose-lose for some period of time. This effect would likely push their country-level break-even year further into the future than the global break-even year.

On the other hand, some countries may stand to gain immediately from climate change mitigation policy, if for example the policy made a naturally endowed resource relatively more attractive in the global market (e.g. uranium, lithium or wind and solar resources). If such a country was on the warm side of the optimum for economic growth (Burke *et al* 2015) then there may be no break-even year for that country because climate change mitigation policy would be a win-win from the outset.

There are of course other barriers to implementing climate policy beyond the idea that it may not be in the economic best interest of the implementing generations or that it may be a lose-lose prospect for some countries. These include many cognitive biases that may cause humans to act less-than fully rationally. For example, the property that CO₂ is not detectible by human senses makes its danger inherently less salient. Furthermore, the deleterious impacts of CO₂ tend not to produce novel events but rather they alter the probability of familiar events like heatwaves, floods and droughts. Assessing these impacts thus requires a type of probabilistic thinking that is not intuitive (Newell and Pitman 2010). Another hurdle is that concern about global warming has become intrinsically tied to political identity in several countries (Unsworth and Fielding 2014) which makes evidence-based reasoning less persuasive than it would be otherwise.

One way to potentially overcome some of the above barriers would be to emphasize the air-quality co-benefits of climate change mitigation. The DICE model estimates economic damages associated only with the CO₂ release from fossil fuel burning and it does not incorporate estimates of economic damages from degraded air quality (from the negative health effect from sulphate aerosols, photochemical smog, etc). This is relevant because air pollution impacts are much more salient than climate impacts (e.g. you can see and smell air pollution) and they are experienced locally in both space and time (Peng *et al* 2017, Markandya *et al* 2018). These characteristics mean that their alleviation represents a benefit that is not subject to the same long delay that the climate-related benefit would be and they are benefits that could be appreciated within a term of a politician.

Overall, the schematic, first order calculations presented here highlight that the implementation of an economically optimal global climate change mitigation policy will impose a net cost on the current generation. This clarifies one reason why it is practically difficult to implement a policy that is supposedly both environmentally beneficial and economically optimal. Our purpose is to bring this important issue to the foreground in order to stimulate discussions of potential solutions. Regardless of the specific solution to this problem we believe that in order for it to be overcome, it should be grappled with explicitly rather than obscured.

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ORCID iDs

Patrick T Brown  <https://orcid.org/0000-0002-5058-1718>

Ken Caldeira  <https://orcid.org/0000-0002-4591-643X>

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