Adaptation to climate damages is not inevitable

Christopher W. Callahan[1,2,3]

Understanding how climate change will affect human welfare must account for how humans will adapt to the changing environment. Adaptations are often local, unobserved, or will only emerge in the future, posing a challenge for attempts to empirically derive climate damage functions and leading to claims that such empirically based functions overestimate the future economic costs of warming. By contrast, here I argue that adaptation to the economic costs of warming is likely to be limited and ineffective. Specifically, I argue both that current climate adaptations are generally limited and that climate change is likely to undermine future adaptive capacity. As a result, future intensification of the climate damage function is as likely as adaptation to it. Effective climate adaptation will require difficult and coordinated political action and is not an inevitable consequence of rising climate damages.

Current emissions reduction policies are insufficient to limit global warming to safe levels[1,2]. Calls for adaptation to warming have been made for decades[3,4] but are growing in prominence given this mitigation gap[5–7]. Adaptation, as defined by the Intergovernmental Panel on Climate Change[8], refers to "the process of adjustment to actual or expected climate and its effects, in order to moderate harm or exploit beneficial opportunities."

Adaptation is a dynamic process whereby people respond to changes in their environments in often-unobservable ways. To date, the most common form of adaptation to climate change has been behavioral change[9,10], such as shifting work schedules to avoid outdoor labor during the hottest part of the day. Other key adaptations include changes in household or local infrastructure, such the adoption of air conditioning or the building of a seawall. The local and unobserved nature of many—though not all—of these choices means that adaptation poses a challenge for empirically grounded climate impact projections, which seek to use observed relationships between climate stress and human outcomes to project the human costs of future warming.

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[1] Program in Ecology, Evolution, Environment, & Society, Dartmouth College
[2] Department of Geography, Dartmouth College
[3] Corresponding author; `Christopher.W.Callahan.GR@dartmouth.edu`

This kind of empirical climate-economy work, combining causal inference techniques from economics with physical climate observations and projections, has gained prominence over the last several decades to quantify the welfare effects of increasing temperatures[11–13]. These empirical methods have been used to understand and project, for example, the effects of extreme temperatures on human mortality[14–17], agricultural yields[18,19], and overall economic growth[20,21]. They have similarly been applied to understand the macroeconomic consequences of more complex classes of climate extremes, such as tropical cyclones[22], El Niño[23], and extreme rainfall[24]. One of the key applications of this "new climate-economy literature"[11] is to develop damage functions that parameterize the total welfare loss in response to changes in global mean temperature. Such damage functions are an essential input into tools such as the Integrated Assessment Models (IAMs) that calculate the social cost of carbon (SCC) and optimal climate mitigation[25,26]. While attempts to empirically ground these damage functions using global-scale regression estimates are now numerous[17,27–32], it is still unclear how to account for potentially unobserved historical and future adaptations in such estimates.

It has become something of a "folk theorem" in climate-economy research that historically based damage function estimates are biased high because of unforeseen future adaptations[33]. The argument that humanity will inevitably adapt to climate damages due to long-term economic development and productivity gains was raised as early as 1984[34]. Indeed, this premise has been used to argue that economic growth is ultimately a more effective solution to the climate crisis than greenhouse gas mitigation, since rising incomes insulate societies from environmental stress[35]. Such arguments persist today. For example, the FUND IAM includes a "dynamic vulnerability" parameter that modifies specific sectoral damage functions in response to rising incomes, and whether IAMs include such an endogenous adaptation mechanism helps explain why they might return different answers for the SCC or other metrics[26]. The newest generation of studies that empirically ground the SCC allow currently observed adaptations to smoothly continue into the future with rising incomes and temperature, generally lowering SCC estimates relative to those without adaptation[17,29–31].

The logic of the adaptation argument is sound: Humans are not passive victims of our environments. We use technology and innovation to make our lives and livelihoods easier given our circumstances, and this process is likely to continue in response to climate change[36]. That being said, I argue here that optimistic visions of adaptation are misguided. Reviewing the evidence for and against adaptation from the climate-economic literature and synthesizing it with both the science of climate change and its political economy, I argue that climate adaptation is likely to be limited and broadly ineffective. I make two specific arguments: (1) that *current climate adaptations are incomplete*, providing evidence that people are often poor at adapting to their environments and that rising incomes have not insulated economies from climate stress; and (2) that *climate change may undermine the capacity for adaptation*, providing evidence that the impacts of climate change will both make adaptation itself more difficult and exceed the capacity for adaptation broadly. As a result, I argue that historically grounded damage functions are just as likely to be underestimates than overestimates. Researchers should not downplay the economic risks of climate change by arguing that we will adapt to rising temperatures.

I emphasize that the literature on climate adaptation is immense and may be examined from many angles[9]. I focus on adaptation in the context of the empirical climate-economy literature to make the subject contained and tractable, and because this literature exerts a major influence on policymaking through metrics such as the SCC. While this focus is inherently limited, it provides fruitful ground for understanding how adaptation will affect climate risk and vice versa.

Current climate adaptations are incomplete

In the empirical climate-economy literature, adaptation is often identified using heterogeneity in response functions across space and/or time[37] (Fig. 1). For example, if we observe the response of human mortality to extreme temperatures to be strongest in low-income regions and weakest in high-income regions, even given similar exposure of these regions to extreme heat (Fig. 1a), we infer that higher income allows people to purchase air conditioning or work indoor service-sector jobs rather than outdoor manual labor. Similarly, if we observe that regions which are more exposed to extreme heat experience reduced heat-driven mortality relative to regions that are less exposed (Fig. 1b), we infer that these regions have chosen to invest in adaptations due to the high returns on such adaptations.

Mortality is, indeed, one of the clearest large-scale adaptation success stories. In the contexts of both extreme heat specifically and natural disasters generally, mortality from extreme climate events has fallen dramatically. In the United States, the effect of extreme heat on mortality has steadily declined, especially in warm areas[15,16]. Because these warm areas in the southern and western U.S. are heavily exposed to extreme heat, they have chosen to invest in air conditioning, making hot areas less vulnerable to heat extremes[17,38]. In this regard, both greater incomes and increased heat exposure produce adaptation to extreme temperatures (Fig. 1). More generally, across regions and hazards, the death tolls of natural disasters has fallen substantially over the last several decades[39,40]. These reductions are strongest in areas with high incomes and strong political institutions[41], as such areas have the resources and political will to safeguard their populations from natural disasters.

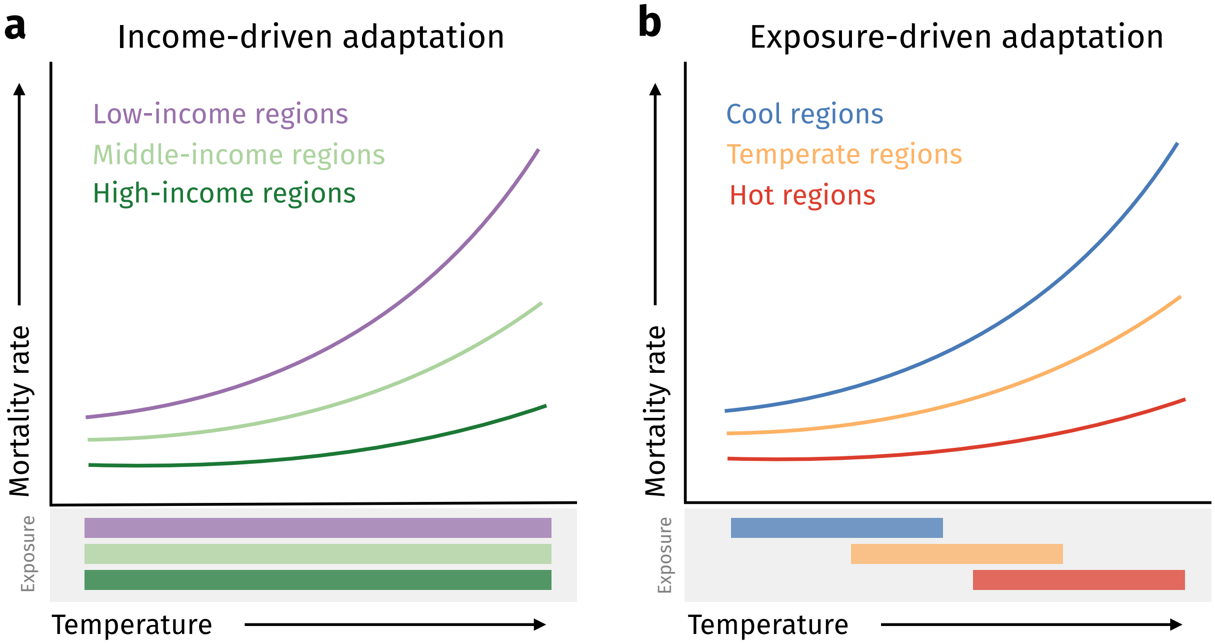

Figure 1: Schematics of income- and exposure-based adaptation. Each schematic shows a stylized response of the human mortality rate to high temperatures, where adaptation occurs due to income (a) or exposure (b). In (a), lines differ according to the income of the sample that each line corresponds to. In (b), lines differ according to the temperature exposure that each line corresponds to. Bars under the graphs denote the temperature exposure of each sample.

Alongside the benefits of income for adaptation, we should expect adaptation to be most extensive in contexts where actors have high-quality information about their present and future climates as well as strong incentives to act on that information. One such context is agriculture in the U.S., where farmers have historically adjusted to conditions previously considered inhospitable[42]. Maize yields in the U.S. do appear adapted to their local climate, as areas with greater extreme heat incidence also experience reduced impacts from that extreme heat[43]. Farmers in warmer areas may choose, for example, to plant cultivars with more heat-resistant proteins. Evidence is mixed, however, on whether these adaptations over space will translate into adaptations to a changing climate[44]. Advances in agricultural technology appear to be flowing to areas most exposed to extreme heat, potentially reducing the sensitivity of farm profits to extreme heat[45]. But the sensitivity of U.S. crop yields does not appear to have meaningfully declined over the last several decades[19,46], and areas with stronger climate trends do not appear to have systematically reduced their extreme heat sensitivity, even in areas where perception of climate change is highly likely[47]. One part of this story may be crop insurance in the U.S., which creates a perverse incentive to avoid adaptation by compensating farmers for climate-driven losses[48]. Perhaps more concerningly, corn in the U.S. appears to be growing *more* sensitive to drought over time, rather than less, due to crop intensification and increased planting density[49,50].

There is suggestive evidence of adaptation in response to climate exposure in other contexts. Countries who are more frequently exposed to tropical cyclones experience reduced economic damage from those cyclones[22,51], suggesting that such countries invest in protective measures such as seawalls, evacuation preparations, or early warning systems. That being said, cyclone strikes still have devastating economic effects in these adapted countries, and cyclone damages tend to *rise* with income in the United States[52], suggesting that such adaptations are highly costly or only partially effective[22,51]. Separately, there is an ongoing debate over whether the effect of temperature shocks on economic growth is moderated by climate or income; some evidence points towards high-income countries being insulated from temperature shocks[53,54], while other studies argue that high-income countries simply lie in a different location on a single underlying response function[27,55].

But regardless of the equivocal evidence for adaptation in the context of average temperature, income does not appear to moderate the effects of other extreme events. Within the United States, perhaps the most highly resourced polity in world history, large economic damages have been driven by extreme heat and drought[56] as well as rainfall[57], *prima facie* evidence that high incomes and advanced technologies do not insulate us from environmental stress. And while the spread of air conditioning in the U.S. has moderated the effect of extreme heat on mortality, it does not appear to have reduced the overall productivity costs of non-optimal temperatures[33]. Outside the U.S., higher incomes have not reduced the effect of crop-damaging temperatures on suicides in India[58], nor have they moderated the infant mortality effects of air pollution in Africa[59].

Globally, the macroeconomic effects of extreme rainfall[24] and El Niño[23] are similar in low- and high-income regions, providing additional evidence that higher incomes do not automatically translate into adaptive investments. Indeed, in the case of El Niño, the most strongly exposed countries are also the most strongly affected, rather than the least[23]. Additionally, while higher average temperatures appear to moderate the effects of extreme heat on mortality[17] and crop yields[43], higher average temperatures appear to *intensify* the effect of extreme heat on overall economic growth globally[20].

Thus, across contexts and sectors, I argue that the empirical evidence demonstrates only limited and contingent adaptations to our current climate. Why might adaptation be limited? There are some things to which adaptation is simply not possible[60]. Humans[61] and crops[62] face temperature limits beyond which physiological adaptations generally fail, for example, and the inundation of low-lying nations due to sea level rise produces damages that cannot be adapted to or recovered[63].

Even where adaptation is possible, misaligned incentives may contribute to a lack of adaptation progress. Insurance mechanisms such as crop insurance might create a moral hazard that disincentivizes adaptation[48,64]. Lack of up-to-date knowledge on climate exposure, such as outdated flood maps, may also contribute to a perceived lack of need for adaptation[64]. It is also possible that the costs of adaptation are simply too high, especially for nations in the global South who may not be able to afford new crop varieties or technologies[65]. Critically, international financial mechanisms have broadly failed to deliver on targeted adaptation investments to low-income regions. It is estimated that current adaptation finance is five to ten times below what would be necessary to fund truly transformative adaptations[7]. Low institutional capacity and local power imbalances in low-income regions also mean that adaptation funds do not reach the people who need them[66,67]. But regardless of the reason, the empirical record does not support the conclusion that humans will smoothly and effectively adapt to increasing climate stress.

Climate change may undermine the capacity for adaptation

Perhaps the present is not a reliable guide to the future. As climate damages intensify, people and governments may face incentives for adaptation that they have not previously faced, accelerating adaptation progress[9,36]. Additionally, as secular trends in technology and productivity enable greater economic output, resilience to climate stress may similarly increase (e.g.,[17]).

But these trends may not be enough. There is ample evidence to suggest that the consequences of climate change may make adaptation more, rather than less, difficult[7] (Fig. 2).

Consider the example of mortality. Adaptations that reduce the mortality effects of extreme heat at present have depended on the widespread adoption of air conditioning[16]. Air conditioning depends on consistent electricity access, and as climate change increases extreme heat incidence, demand for electricity is likely to increase substantially[68,69]. Rising energy demand means additional costs and potential utility disconnections for households who cannot afford those costs. Extreme heat events have already led utilities to disconnect the electricity of some low-income households, a pattern which is likely to increase as temperatures rise[70]. This problem worsens when the overall vulnerability of the electricity system is considered. Much of the power generation in the United States depends on access to water, either for cooling thermal power generation or for directly producing hydropower. As climate change raises water temperatures and reduces streamflow, power generation may need to be curtailed substantially[71–73], even under optimistic scenarios of a renewable energy transition[72]. Loss of power generation during heat waves could amplify the effects of such heat waves and greatly increase morbidity and mortality risk[74]. Finally, the compounding of multiple hazards, such as a tropical cyclone followed by a heat wave[75], have been highlighted as key emerging risks[76]. If a cyclone disrupts energy infrastructure and causes a blackout[77], air conditioning will not mitigate the mortality risks of extreme heat that may follow such a storm.

These and other limits to adaptation grow more severe when one considers other compound and interconnected risks[6,78,79]. For example, international trade has been proposed as an adaptation option in the context of food security: reductions in agricultural production in one area may be compensated by surpluses in other areas[80,81]. But globally synchronized production shocks compromise such trade networks by damaging crops worldwide[82], making it difficult to compensate one area's losses with surpluses from another. Given the rise of globally synchronized heat and drought due to anthropogenic forcing[83,84], simultaneous "breadbasket failure" may challenge trade networks and jeopardize global food security[85,86].

Together, these risks demonstrate how the direct and indirect effects of climate change may counteract adaptations that have been successful to date. More broadly, climate change may undermine the precise monetary and institutional resources that are themselves critical to adaptation. If long-run economic growth is slowed by rising temperatures[32], more intense tropical cyclones[22,87], or more frequent El Niño events[23,88], societies may not have the resources or democratic stability to safeguard their populations from natural hazards[89,90] or access the international funds that enable adaptation[66]. Every dollar spent on recovery efforts for an unprecedented tropical cyclone or drought is another dollar that cannot be spent installing air conditioning, putting houses on stilts, or building seawalls. As a result, nations or regions may be locked-in to vicious cycles of "adaptation-constrained" development pathways that prevent responses to future crises[91,92]. In India, for example, extreme heat waves that nearly exceed the capacity for human survival[93] have already begun to weaken its progress towards the Sustainable Development Goals[94]. Even if the capacity for adaptation is not physically destroyed by an extreme event, international crises tend to distract resources and attention away from climate adaptation to situations that are perceived to be more urgent, as demonstrated by the COVID-19 pandemic and Russia-Ukraine war[7].

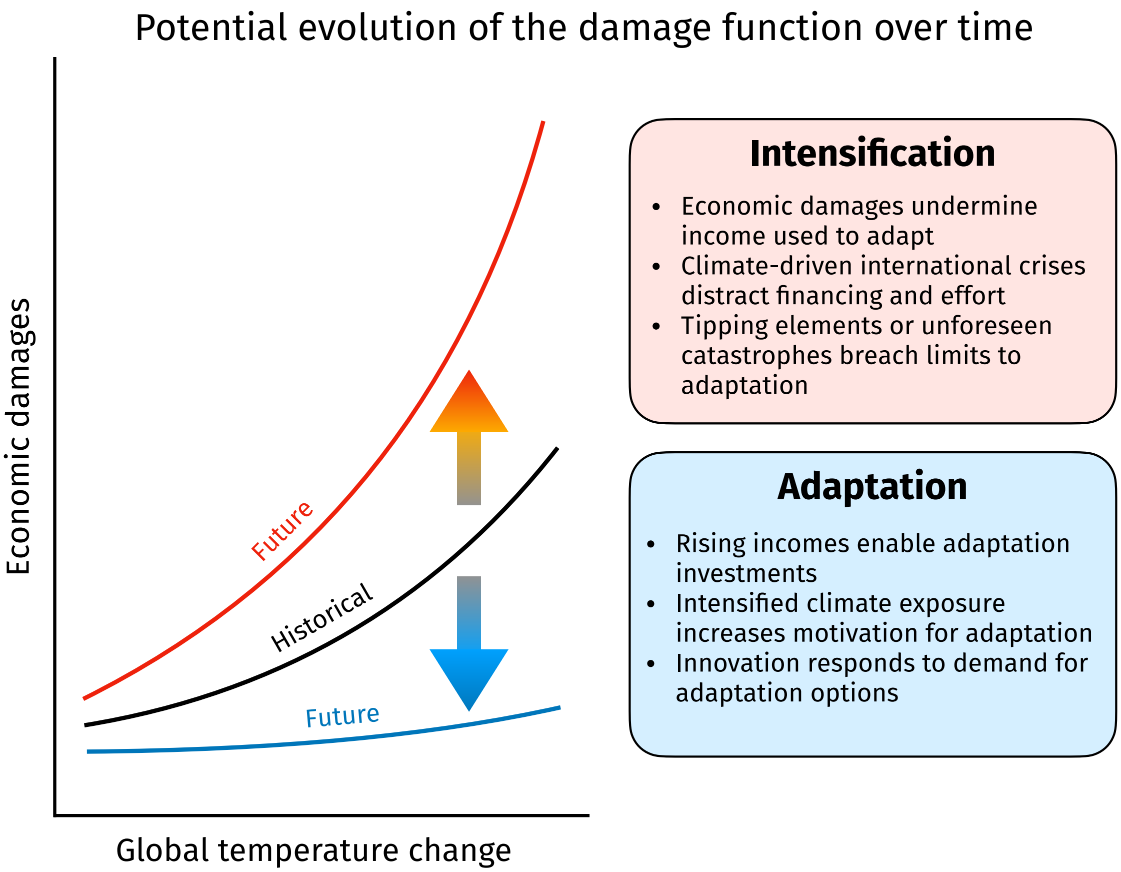

Figure 2: Shifts in the damage function over time. Schematized change in climate damages over time. Black line shows a hypothetical historical damage function, red lines show the damage function under the intensification hypothesis, and blue line shows the damage function under the adaptation hypothesis. Text boxes outline arguments for each hypothesis.

The physical risks of climate change are also likely to generate political crises that may undermine coordinated action. When potential economic stagnation or decline are combined with stressors such as climate-driven refugee crises[95–97], increased disease risk[98], and civil conflict[99], the result may be political instability and the rise of strongman populist leaders[100]. Such leaders may be resistant to coordinated action on climate resilience and instead embrace a “fortress mentality”[101] that undermines adaptation finance and international trade, jeopardizing food security among other risks[102].

In more extreme cases, catastrophic climate outcomes or unexpectedly high climate sensitivities (which should not be ruled out[103]) may result in irreversible losses. From the perspective of economic damages, such catastrophic outcomes could reverse global economic development and induce global economic decline, exceeding more subtle slowdowns in growth[104]. These catastrophic scenarios have been hypothesized in the climate-economy literature and problematize classical optimization approaches to climate benefit-cost analysis[105], but are under-examined in climate impacts analyses[106]. The potential to trigger tipping elements in the climate system[107], especially at lower warming levels than previously appreciated[108], could also challenge global risk management and lead to irreversible costs[109,110]. Adaptations to such catastrophic risks would require transformational changes that radically alter our social and economic structures, rather than simply intensifying existing adaptations[111]. Such transformational adaptations could include completely revamping the legal structure for water rights in the American West or altering land use from irrigated crops to grazing land in the Great Plains[111]. Unfortunately, such transformational adaptations are difficult, costly, and constrained by historical legal and political structures such as the Colorado River Compact in the United States[111]. Furthermore, observed adaptations to date have been overwhelmingly marginal changes that do not provide confidence in the possibility of such transformational change[9,10].

Given these risks, I argue that the *intensification* of the damage function is just as likely or more likely than *adaptation* to it (Fig. 2). That is, while it is often argued that damage functions will shift over time as adaptations come online, I argue that such shifts may be just as likely to occur in the opposite direction. The accumulating risks of climate change may undermine the precise adaptations that we appreciate at present and expose our economies to even greater climate risk than is currently projected.

Adaptation is a choice

If humanity does adapt to climate change, it will not be an autonomous, smooth process wherein people optimally adjust to their environmental conditions. Successful adaptation will require coordinated and transformative political action, involving, for example, substantial financial transfers from high-income regions to highly vulnerable ones[7]. These political choices may need to challenge aspects of the existing economic and social order, such as the World Bank's proposal to suspend future sovereign debt payments for countries in the wake of climate disasters—a move that has still been called too little, too late by nations burdened with historical debt and climate vulnerability[112]. In the context of managed retreat from areas facing inundation, for example, attention must be paid to racist legacies of housing discrimination and the historical displacement of Indigenous peoples; without such attention, adaptation risks worsening inequities and increasing vulnerability[113].

These issues imply that successful climate adaptation will be a difficult political choice, not an inevitable feature of humanity's relationship with the climate. There is no guarantee that this choice will be made, or made correctly. What does such a conclusion imply for researchers moving forward? The possibility of climate damages undermining adaptation progress (Fig. 2) has not been broadly appreciated in approaches to quantifying damage functions. For example, researchers have used economic scenarios such as the Shared Socioeconomic Pathways to project future adaptive capacity with rising incomes[17,29–31]. Yet these scenarios explicitly do not include climate damages in their long-run projections[114], meaning they almost certainly overestimate adaptive capacity by not considering the possibility that climate change could reduce economic output or growth[115].

More broadly, I argue for a reconsideration of damage functions that do not include adaptation. Adaptation is often used to explain why empirically estimated damage functions cannot be extrapolated into the future, since people will respond to climate change differently than climate stress at present. I propose that this argument applies equally, but in the opposite direction, to empirically observed adaptations. Given increases in systemic climate risk, it is inappropriate to assume that current climate adaptations will continue or accelerate in the future[64]. As a result, damage functions that do not account for adaptation should not be seen as "worst-case" no-adaptation baselines[36], but instead as approximate estimates that might be modified in either direction by the advancement or retreat of adaptation efforts.

Climate change is a wicked problem whose consequences stretch across all human and natural systems. It is likely to have a variety of systemic and interconnected effects that will stress human well-being, the built environment, and the biosphere. Given the insufficiency of mitigation efforts, some degree of adaptation to this challenge will be necessary, but it will not be easy or straightforward. It may well be the hardest thing our world has ever done.

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Competing interests

The author declares no competing interests.

Author contributions

C.W.C. conceived the study and wrote the paper.

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