Present and future limits to climate change adaptation

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Sustainable economic development and resilience to climate change impacts require human adaptation to a warming climate. It is possible that rising costs of climate change will provide incentives to increase adaptation actions in the future. This Perspective argues, by contrast, that adaptation to the costs of global warming is likely to be ineffective. Empirical evidence suggests that current adaptations are generally limited, and climate change is likely to undermine adaptive capacity, making intensification of the costs of warming as likely as adaptation to them. Climate adaptation will require difficult political action and is not an inevitable consequence of climate damages.

Despite economic growth over the last century or more, environmental stress remains a critical determinant of peoples' well-being globally[1]. Achieving sustainable development requires increasing the resilience of people and societies to natural disasters, biodiversity loss, and other stressors[2]. This goal would be important even in a stationary climate, but anthropogenic climate change is intensifying these stressors globally. As such, human adaptation to both today's climate and the effects of a changing climate will be necessary to achieve equitable and sustainable economic growth.

Adaptation, as defined by the Intergovernmental Panel on Climate Change[3], 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[4,5], 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 as the adoption of air conditioning or the building of a seawall, or migration from more vulnerable to less vulnerable areas.

The local and unobserved nature of many of these choices means that adaptation poses a challenge for empirically grounded climate impact projections. These projections seek to use observed relationships between climate stress and human outcomes to project the human costs of future warming. 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[6,7]. Econometric methods have been used to quantify, for example, the effects of extreme temperatures on human mortality[8,9], agricultural yields[10], and overall economic growth[11], as well as the impacts of more complex classes of climate extremes[12–14]. One of the key applications of this "new climate-economy literature"[6] is to develop damage functions that parameterize the total welfare loss in response to changes in global temperature. While attempts to empirically ground these damage functions using regression-based estimates are now numerous[9,15,16,17], 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" that historically based damage function estimates are biased high because of unforeseen future adaptations[18]. The argument that humanity will inevitably adapt to climate damages due to economic development was raised as early as 1984[19], and, this premise has been used to argue that economic growth is a more effective solution to the climate crisis than greenhouse gas mitigation, since rising incomes insulate societies from environmental stress[20]. Additionally, whether and how adaptation is incorporated into climate-economy models used for benefit-cost analysis can strongly affect their output[9,16,21], and other economic models of climate change assume that adaptation via international migration is able to reduce climate damages, with some fixed migration cost[22].

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[23]. That being said, this Perspective argues 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 suggests that climate adaptation is likely to be limited and broadly ineffective. This Perspective articulates 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, 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 and should instead understand adaptation as a risky, endogenous process.

The literature on climate adaptation is extensive and may be examined from many angles[4,24]. This Perspective focuses on adaptation in the context of the empirical climate-economy literature to make the subject contained and tractable. However, understanding the relationship between climate change and global economic well-being is central to understanding the broader prospects for sustainable development in the 21st century. If adaptation to climate change is more limited than previously understood, broader progress on sustainability could be threatened.

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[1] (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. These adaptations may take the form of short-run actions such as turning on an air conditioning unit that a person already owns or taking breaks from outdoor labor in the hottest part of the day. They may also be longer-run changes such as purchasing a new air conditioning unit or migrating to live and work in an entirely different location. The strategy of using heterogeneity in response functions to identify adaptation (Fig. 1) generally conflates these timescales, though particular empirical strategies such as "long differences" may allow researchers to assess adaptation on specifically chosen timescales[25].

Empirically, mortality is one of the clearest large-scale adaptation success stories. Mortality from extreme climate events, both heat and other disasters, has fallen dramatically over time. In the United States, the effect of extreme heat on mortality has steadily declined, especially in warm areas[8]. 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[9]. 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[26]. These reductions are strongest in areas with high incomes and strong political institutions[27], as such areas have the resources and political will to safeguard their populations from natural disasters.

More broadly, adaptive capacity is observed to be lowest in low-income areas that may begin from pre-existing positions of vulnerability, and correspondingly highest in high-income areas[28]. This pattern admittedly presumes an "assets"-based approach to adaptive capacity, focusing on the economic or physical resources available to people and societies, and neglects social organization, hierarchies, and other factors that may restrict peoples' agencies regardless of their assets[29,30].

Alongside the benefits of income for adaptation, we might 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 United States. 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[31]. 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. 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[32]. But the sensitivity of U.S. crop yields does not appear to have meaningfully declined over the last several decades[10], 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[25]. 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[33].

There is suggestive evidence of adaptation in response to climate exposure in other contexts. Countries that are more frequently exposed to tropical cyclones experience reduced economic damage from those cyclones[12,34], 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[35], suggesting that such adaptations are highly costly or only partially effective[12,34]. 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[36], while other studies argue that high-income countries simply lie in a different location on a single underlying response function[15].

But regardless of the equivocal evidence for adaptation in the context of average temperature, income does not appear to moderate the effects of some 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[37] as well as rainfall[38], *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[18].

Globally, the macroeconomic effects of extreme rainfall[14] and El Niño[13] 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[13]. Additionally, while higher average temperatures appear to moderate the effects of extreme heat on mortality[9] and crop yields[31], higher average temperatures appear to *intensify* the effect of extreme heat on overall economic growth globally[11].

Thus, across contexts and sectors, 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[24,39]. Humans[40] and crops[41] 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[42].

Even where adaptation is possible, misaligned incentives may contribute to a lack of adaptation progress. For example, crop insurance in the U.S. allows farmers to recoup climate-driven losses, which creates a moral hazard to forego costly forward-looking adaptations in favor of receiving indemnity payments after losses[43,44]. Recent extreme events, such as the summer 2012 drought and heat across the contiguous U.S., have therefore led to large and costly crop indemnity payouts due to yield losses[37]. A similar misalignment occurs in the context of the National Flood Insurance Program (NFIP), which subsidizes flood insurance premiums across the U.S. Because the NFIP historically did not incorporate updated location-specific flood risk estimates into pricing, the availability of risk-agnostic flood insurance in high-risk floodplains may have contributed to a systematic overvaluation of residential properties in the U.S.[45]. At the time of this writing, flooding due to Hurricane Helene has devastated western North Carolina, a place that simultaneously has been referred to as a “climate haven”[46] and has been identified a hotspot of property overvaluation due to underestimated flood risk[45]. Unfortunately, updated flood risk information that might enable homebuyers to consider climate impacts is often produced by private climate services firms who aim to profit from this information and therefore provide it primarily to other firms[47]. Aligning adaptation incentives in an equitable way would likely require the public provision of climate risk information so that individuals and local governments could make informed decisions about housing, infrastructure, and other investments[48].

It is also possible that the costs of adaptation are simply too high, especially for nations in the global South. 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 transformative adaptations[49]. Low institutional capacity and local power imbalances in low-income regions also mean that adaptation funds do not reach the people who need them[50]. That is, even in places where the resources or financial capacity may exist, social hierarchies organized around characteristics such as race, class, ethnicity, or gender identity may undermine the agency of the most vulnerable to adapt to environmental stress[51].

Warming may undermine adaptive capacity

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[4,23]. Additionally, as secular trends in technology and productivity enable greater economic output, resilience to climate stress may similarly increase (e.g., [9]).

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[49,52] (Fig. 2). Here, again, this Perspective focuses on a capability-based definition of adaptive capacity, which emphasizes that financial resources and other assets enable actors to undertake adaptations such as installing air conditioning[53]. Resources are only one component of an agent's adaptive capacity, which also depends on factors such their social position, willingness to undertake transformative actions, and risk perceptions[29,30]. However, a resources-based focus is consistent with other treatments of adaptation in the climate economics field, and provides a tractable way to understand the relationship between climate damages and adaptation[52].

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[8]. Air conditioning depends on consistent electricity access, and as climate change increases extreme heat incidence, demand for electricity is likely to increase substantially[54]. Rising energy demand means additional costs and potential financial stress for households who cannot afford those costs. Extreme heat events have already led utilities to disconnect the electricity of some low-income households, and future heat waves might result in additional disconnections that further undermine access to air conditioning[55]. 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[56]. Loss of power generation during heat waves could amplify the effects of such heat waves and greatly increase morbidity and mortality risk[57]. This threat becomes more significant when compounding hazards are considered, such as tropical cyclones followed by heat waves; if a cyclone disrupts energy infrastructure and causes a blackout[58], 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[59]. 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[60]. But globally synchronized production shocks compromise such trade networks by damaging crops worldwide[61], 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, simultaneous "breadbasket failure" may challenge trade networks and jeopardize global food security[62].

This two-way interaction between climate damages and adaptation is additionally significant in the context of migration. Migration has been framed at times as an important adaptation strategy, allowing people to move from highly vulnerable areas to less vulnerable ones[22,63]. Spatial economic models incorporating migration find that it reduces climate damages relative to a world in which people do not move[22]. Critically, however, climate change is not merely a potential driver of the aspiration to migrate; it may also reduce the capability to migrate by undermining economic resources available to the poorest populations[64]. And even when people do migrate, they may face greater danger along their route, such as escalating heat and water stress due to climate change along the U.S.-Mexico border[65].

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[17], more intense tropical cyclones[12], or more frequent El Niño events[13], societies may not have the resources or democratic stability to access the international funds that enable adaptation[50]. 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. The negative impacts of climate change on economic activity may additionally reduce tax revenue for governments, undermining their ability to provide services to their citizens. As a result, nations or regions may be locked-in to vicious cycles of "adaptation-constrained" development pathways that prevent responses to future crises[66], especially if developing countries are unable to increase tax revenue to support social services, strong state capacity, and broader development[67].

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 increased disease risk[68] and and civil conflict[69], the result may be political instability and the rise of right-wing populist leaders[70]. Such leaders may be resistant to coordinated action on climate resilience and instead embrace a "fortress mentality" that undermines adaptation finance and international trade, jeopardizing the safety of migrants, food security, and potentially other risks[71].

Like underlying constraints on adaptation, these effects of climate damages on adaptive capacity will likely be structured not only by income or assets but also by existing social hierarchies and inequalities. If climate damages widen global income inequality, income-based constraints are likely to be most severely felt in the lowest-income countries that have contributed least to warming[72]. Such constraints also manifest in the lived experience of an individual. For example, in rural areas, women are often tasked with the arduous and often dangerous task of gathering water. Water gathering is likely to become more difficult and time-consuming as warming reduces surface water availability in some regions[73], further constraining the time and independence of women relative to men[74]. This example illustrates that even given a certain level of assets or material resources, the lived adaptive capacity of an individual may be shaped by how characteristics such as their gender identity intersect with existing social structures. Finally, each of these effects may be exacerbated by potential negative externalities from private adaptation actions. For example, several recent studies have highlighted that a common adaptation strategy in response to water scarcity is for privileged individuals or firms to intensify extraction of groundwater, harming access to water for nearby areas[75] and increasing prices for water sold by the public utility[76].

This risks make *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, 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.

Approaching adaptation differently

None of these risks are guaranteed. There are many changes humanity could make in order to blunt their impacts. But if humanity does adapt to climate change, it will not be an autonomous, smooth process wherein people optimally adjust to their environmental conditions. Adaptation to the catastrophic risks of climate change will require transformational changes that radically alter our social and economic structures, rather than simply intensifying existing adaptations[77]. Unfortunately, observed adaptations to date have been overwhelmingly marginal changes that do not provide confidence in the possibility of such transformational change[4,5].

Consider the previous example of migration as adaptation. While it may be physically possible for people to move to cooler climates as their home locations warm, thus reducing direct impacts such as heat stress, this adaptation strategy depends on political choices made by governments regarding border enforcement and immigration policy. At the same time that climate-related migration pressures increase, governments are hardening their borders against new migrants[63]. For example, India has increasingly militarized its 4,000-km border with Bangladesh, becoming more willing to turn away and even kill Bangladeshi migrants fleeing flooding and sea level rise in their home country[78]. Similarly, the southern border of the U.S. has become increasingly hardened—and "border security" increasingly politicized—at the same time that the U.S. military has begun to treat climate change as a security threat that might yield an unwanted surge of migrants[78]. This example highlights 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, and some of the most severe consequences of climate change might themselves undermine the capacity or willingness to make such a choice.

What does such a conclusion imply for researchers moving forward? The possibility for climate damages to undermine adaptation progress 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[9,16]. Yet these scenarios explicitly do not include climate damages in their long-run projections[79], meaning they almost certainly overestimate adaptive capacity by not considering the possibility that climate change could reduce economic output or growth[80]. More sophisticated analytical treatment of adaptation will be necessary to understand how adaptive capacity evolves in the SSP trajectories[79].

More broadly, it is worth reconsidering damage functions that do not include adaptation. Adaptation is often used to explain why empirically estimated damage functions cannot be extrapolated into the future. This argument applies equally 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[43]. As a result, damage functions that do not account for adaptation should not be framed as "worst-case" no-adaptation baselines[23], but instead as approximate estimates that might be modified in either direction by the advancement or retreat of adaptation efforts.

This framing admittedly introduces greater uncertainty into damage functions, but it may be more productive to confront this uncertainty and analyze its implications rather than reduce it by treating adaptation as an inevitability. Welfare-economic analyses of climate impacts have historically accounted for decision-makers' risk aversion by quantifying and valuing multiple dimensions of uncertainty, such as uncertainty in baseline socioeconomic trajectories and parametric uncertainty in the climate response to emissions. In the future, it may be productive to conduct structured uncertainty analyses for adaptation projections that explore multiple pathways by which climate damages might alter adaptive capacity[79]. These analyses could then form inputs into the risk valuation techniques used to assess the costs of climate change in the presence of uncertainty, alongside the other dimensions of uncertainty typically considered. The key conceptual innovation in this approach would be to treat adaptation as an endogenous and risky process with an uncertain sign, rather than an exogenous process that modifies other climate damage estimates.

The focus of this paper has been on adaptation in the context of large-scale climate-economy models. However, the fundamental argument that adaptation is currently limited and may be hindered by additional climate change has implications in other settings as well. First, considering the endogeneity of human and climate systems, rather than treating adaptation as exogenous, could be a useful complement to other recent efforts to model human-climate feedbacks in the Earth system[81]. Second, the idea that high-income areas are often not less vulnerable than low-income areas suggests that interventions aimed at local economic development will not necessarily deliver climate adaptation co-benefits. This point does not suggest that adaptation finance is not useful, just that development as such is not a panacea for climate vulnerability. Finally, my argument suggests that climate loss and damage—often defined as climate impacts which cannot be mitigated or adapted to—may be greater than models may currently assess. As a result, additional international financing may be required through the fund established by the 2022 Conference of the Parties. Research attempting to quantify the magnitude of required loss and damage funds is in its infancy[82], but would benefit from consideration of the limits to adaptation such as those discussed here.

Climate change threatens global sustainable development. The economic and social risks of warming have the potential to undermine equitable economic growth and welfare for the most disadvantaged people globally. As a result, managing present and future environmental stress and ensuring human well-being requires adaptation actions that ensure societal resilience and social justice. Unfortunately, while the insufficiency of current climate mitigation efforts makes such adaptation necessary, there is no guarantee that it will become easier with practice.

Figure Captions

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.

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.

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Acknowledgements
I thank J. S. Mankin and C. E. Kernan for helpful discussions. This work was supported by National Science Foundation Graduate Research Fellowship #1840344.

Competing interests
The author declares no competing interests.

Author contributions
C.W.C. conceived the argument and wrote the manuscript.

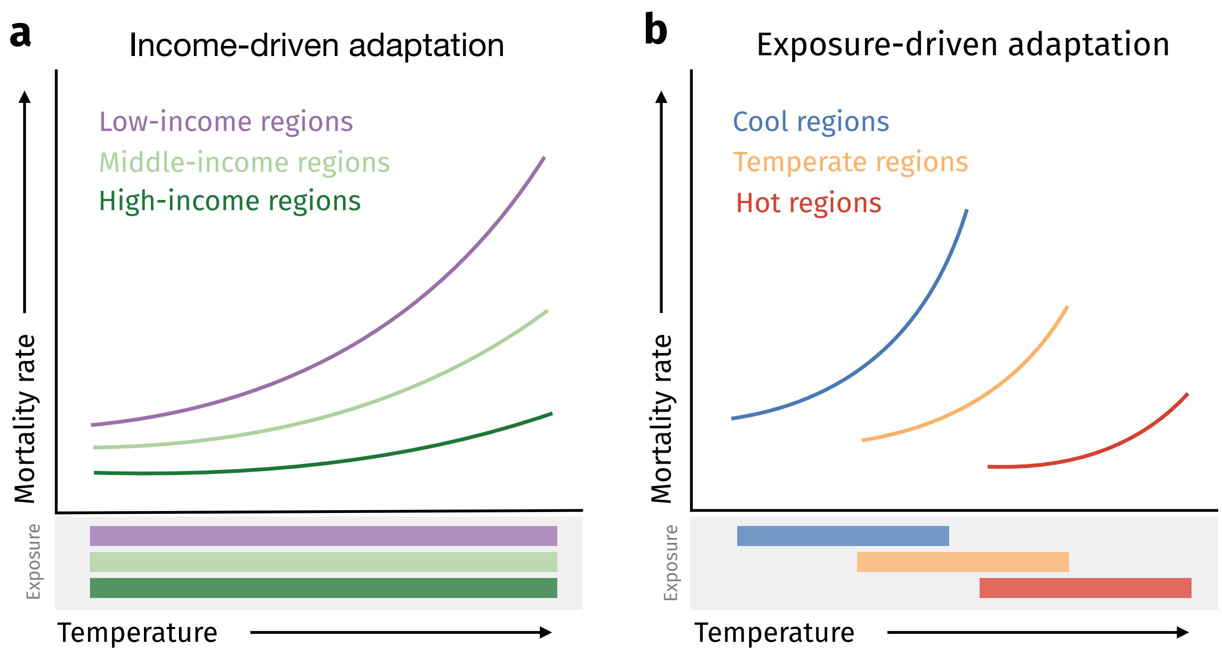

Figure 1.

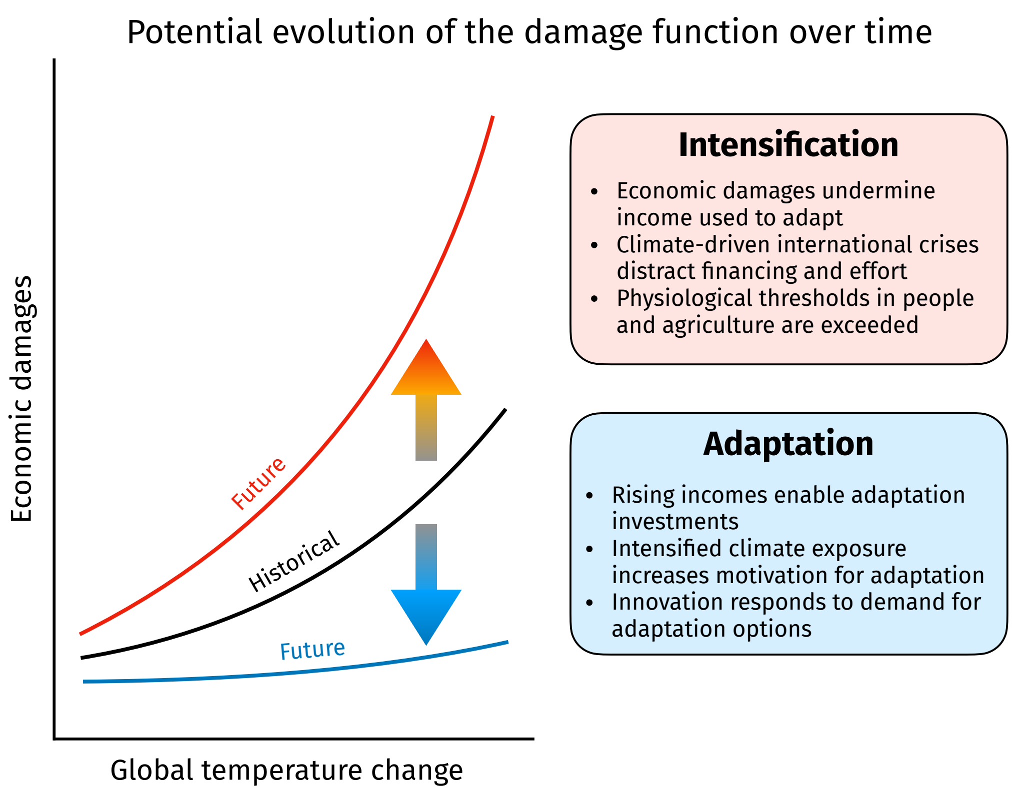

Figure 2.

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