THE TRUE SOCIAL COST OF CARBON: A SYSTEMATIC AND COMPREHENSIVE REVIEW

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Starting in 1880, the rise in global temperatures has aggravated the well-being of populations and the resilience of national economies (NASA, 2023). Governments and societies cannot ignore the financial costs that have emerged because of climate change. Central authorities have devoted a growing number of financial resources to offset the damages caused by natural disasters. However, the climate crisis represents a greater burden for societies, if one weighs the substantial impact that it has been having on human well-being as well as on the disappearance of entire ecosystems. While ecosystems have not been given enough time to adapt to the new external conditions, and they are therefore progressively dying out, global warming has also significantly increased mortality rates around the world (Zhao, et al., 2021). Although it is challenging, it is possible to determine the economic value of such damages.

Therefore, the goal of this paper is to set a framework to enable the proper quantification of the environmental, social, and economic externalities originated by climate change through the estimation of the Social Cost of Carbon (SCC). In practice, the SCC quantify the monetary damages associated to the release of an extra ton of carbon dioxide (CO_2) (Griffiths, et al., 2012). In the context of decision-making, the SCC has become a widely used tool, employed by institutions, such as the Environmental Protection Agency (EPA) and the European Union (EU), as well as by national governments to assess the benefits of reducing carbon emissions across different sectors and regions. Furthermore, numerous businesses have implemented thanks to the SCC internal carbon pricing systems to account for the climate externalities associated to their activities. By placing a carbon price, both businesses and individuals are compelled to adjust their behavior, and this, in turn, exerts a significant influence on the main dynamics governing national and international markets. Finally, academic establishments, like Harvard Business School (Serafeim & Trinh, 2020), have incorporated the SCC within their publications, aiming to systematically appraise the efficacy of climate-related policies, strategies, and regulatory measures, while recognizing that this objective is part of a broader agenda, which intends to increase the scientific advancement and identify the most cost-effective measures to mitigate climate change.

Given that SCC statistics are created using long-term scenario-based analyses, that rely on rigorous assumptions, they can fluctuate significantly and even exceed market values. As a result, many experts call for an accurate estimation of the real SCC to fully account for the externalities generated by the release of CO_2 into the atmosphere. The necessity to enhance the approaches used for the primary computations is stressed by Rennert et al. (2022), Aldy et al. (2021), and Stern et al. (2021) given that, as shown in Table 1, the academic community has not yet been able to agree on a single valuation.

Despite the widespread and still diverging adoption of the SCC, researchers tend to focus primarily on the financial costs related to the release of CO_2, ignoring other social and environmental impacts. To address the above-mentioned issue, this study carries out a holistic review of the environmental and social impacts of climate change.

The first step required to set up a proper estimation technique consist in applying a forward-looking perspective, that considers the long-term evolution of the current climate crisis. To this end, the present study examines several greenhouse gas (GHG) concentration trajectories that outline potential changes in future anthropogenic GHGs emissions. This is particularly important given that the costs triggered by global warming depend directly on the specific emission scenario that is being considered.

Among the several Representative Concentration Pathways (RCP) presented and adopted by the Intergovernmental Panel on Climate Change (IPCC), this study takes into consideration the following three: (i) RCP2.6, (ii) RCP4.5, and (iii) RCP8.5. These pathways outline distinct climate prospects with varying GHG emission levels from now until 2100. These pathways are selected for their intrinsic potential to embody the optimistic, the business as usual (BAU) and the pessimistic climate scenario. First, the RCP2.6, or the optimistic scenario, predicts that by 2100, the temperature increase will probably be held below 2°C. Second, according to the RCP4.5, or BAU scenario, by 2100 the average global temperature will increase by 2°C to 3°C. Finally, the projections of the pessimistic scenario RCP8.5 reveal that by the end of the century global temperatures will have risen by more than 4°C (IPCC, 2022).

While CO_2 is the primary GHG emitted into the atmosphere, it is important to remember that other gases, such as methane, nitrous oxide, and fluorinated gases also contribute to climate change and represent more than 26% of all GHG emissions (Rivera, et al., 2023). However, all other GHGs can be converted to carbon dioxide equivalents (Brander & Davis, 2012). This is the reason why total GHG emissions are often expressed in "CO_2 equivalent" terms. As a result, the SCC can serve as a decision tool that can be extended to GHGs in general.

TABLE 1
SOCIAL COST OF CARBON ESTIMATES

Publication	SCC proposed (USD or £ per ton of CO_2)	Reference Year	Adjusted SCC (USD 2023 per ton of CO_2)
Watkiss (2008)	£70	2000	$101
Nordhaus (2017)	$31	2010	$43
Aldy et al. (2021)	$135-5500	2010	$189-7684
Sarafeim et al. (2021)	$114	2019	$136
Rennert et al. (2022)	$185	2020	$218

NOTE: The prices from the articles cited above have been inflated to account for changes in the general price level, thus adjusting them first according to the price level prevailing in 2023 and then in conformity with the respective exchange rates (World Bank, 2023; FRB, 2023; IMF, 2023).

Source: author

Without neglecting the long-term dimension mentioned previously, the next section presents the methodology required to calculate the true SCC. To do so, certain academic proxies have been chosen to measure the damages imposed by the climate crisis on societies, the environment, and the economy. Thereafter, these methods will be applied to a specific case study, carried out in the United States, to clarify how to perform such analysis with empirical data. The United States represents an ideal case study for the scope of this examination. First off, among the various nations, the United States has been one of the biggest producers of carbon dioxide, both in absolute and per capita terms. Since 1751, the United States ranks as the main historical contributor to the cumulative global CO_2 emissions (Hannah, 2019). Second, there is a wealth of reliable data and research analyzing the amount of GHGs emitted in the United States and their effects. Finally, new environmental initiatives and regulations are being developed in the United States, making it more crucial than ever for the public debate to consider the environmental, social, and economic damages caused by the emissions of CO_2.

This work reveals that the SCC in the United States for the year 2023 amounts at least to $287. Researchers and organizations risk underestimating the true costs of global warming if they ignore the environmental and socioeconomic damages resulting from each additional metric ton of CO_2 released into the atmosphere. Consequently, societies all over the world would be unable to counteract the terrible effects of climate change and internalize the adverse impacts brought on by a significant temperature increase.

After this introduction, section 2 reviews the approaches that researchers have published, and which will be necessary for the estimation and ensuing monetization of the SCC. To demonstrate how the various computational techniques should be employed, section 3 presents a case study that has been conducted within the borders of the United States. Finally, section 4 concludes by discussing potential policy recommendations for national governments and research institutions.

METHODS

This section outlines the techniques employed by eminent economists to quantify the diverse impacts of climate change.

Prior to the measurement and monetization of such impacts, one must identify with precision the most relevant externalities associated exclusively to the onset of global warming. To accomplish that, the recommendations provided by the IPCC, and displayed in the following Figures (IPCC, 2022), are followed. This helps prevent data gaps and instances of double counting.

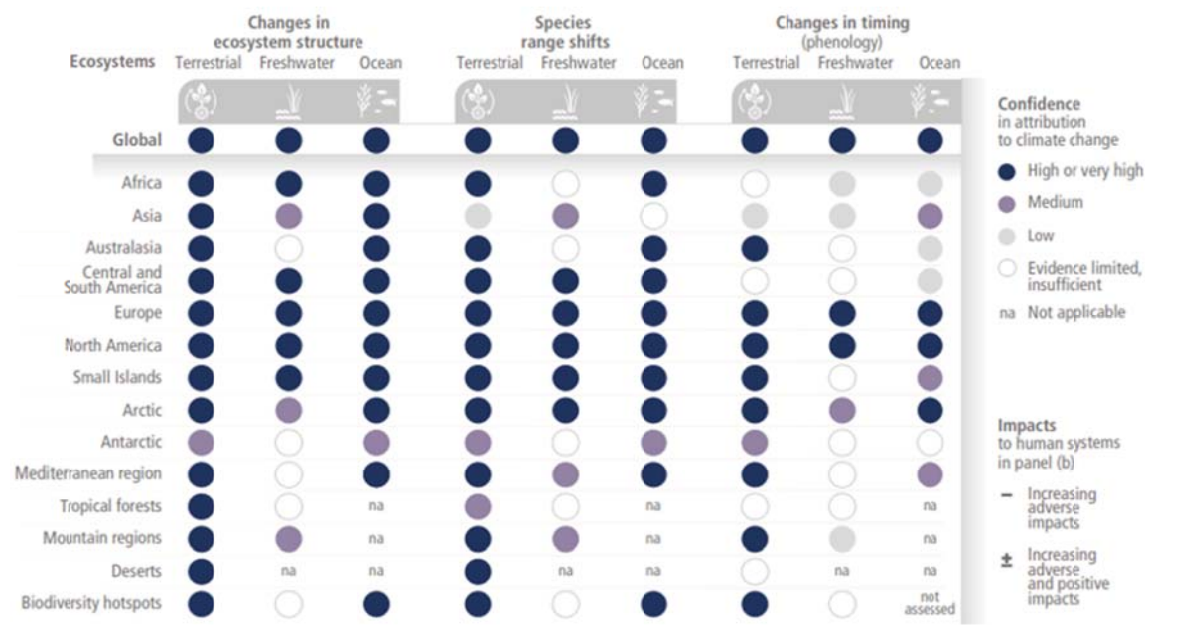
Firstly, it can be asserted that global warming prompts significant changes in the structure of various ecosystems as well as in the well-being of the species thriving in these habitats. Secondly, Figure 2 reveals that an increase in the concentration of CO_2 in the atmosphere might have a non-negligible impact on the health and wealth of human beings. Finally, with the objective of presenting a comprehensive approach, the IPCC underlines the importance of contemplating the pure financial damages caused by climate change on cities, settlements, and infrastructures.

Thanks to the evidence exhibited above, it was possible to identify the main environmental, social, and economic impacts related to a rise in global temperatures. The following subsections showcase a range of studies stemming from different regions of the world. These investigations enable the monetization of the consequences of climate change with a certain degree of robustness and precision.

Environmental Costs

The effects of climate change have an enormous impact on natural ecosystems and the various animal species inhabiting them (United Nations, 2023). The methodological analyses needed to identify the primary connections between global warming and the environment are showcased following the guidelines of Figure 1.

FIGURE 1
IMPACT OF GLOBAL WARMING ON ECOSYSTEMS



Source: IPCC (2022)

Terrestrial Ecosystem

The health of the biosphere is closely linked to the rapid worsening of the climate crisis. Some of the most relevant climate change-induced stressors on ecosystems are increased levels of atmospheric carbon dioxide, degradation, defaunation, and fragmentation (Malhi, et al., 2020). Furthermore, climate change gives rise to several natural disturbances that endanger the health of forests. These include insect outbreaks, invasive species, wildfires, and storms.

Thanks to the IPCC report on climate change, published in 2022 by the Working Group III, it was possible to obtain important statistics on how the terrestrial ecosystem will be altered by the escalation of the climate crisis (IPCC, 2022). According to the considered scenario, the relative change in forest land area from 2019 to 2050, or 2100, could take on positive or negative values. Data for a total of eight climate prospects and three different time periods can be extrapolated by analyzing Figure 3.28 of the above-mentioned IPCC report (IPCC, 2022). The preferred choice will be based on the study's specific framework.

Once the long-term relationship between climate change and the balance of the terrestrial ecosystem has been established, it is necessary to quantify the potential damages through monetary proxies. Thereby, researchers can derive the total costs of CO_2. On this matter, Krieger (2001) conducted a literature review to determine the economic value of forest ecosystem services in the United States. In practice, trees are believed to embody an economic value for the entire society, because they provide a service, which improves air quality by trapping airborne particulate matter. If there were no trees providing such service, governments would have to invest in substitute technologies to maintain or improve the level of air quality. Following this reasoning, the air quality value of each tree in a representative forest was estimated to be equal to $4.16[1].

1 The monetary values mentioned in this examination match the results published in the respective research papers. Consequently, the reference year of the dollar aligns with the specific year considered in each article.

Freshwater and Ocean Ecosystem

Climate change and water are deeply interconnected. As temperature rises, changes in precipitation patterns and water cycles reduce water availability and increase water-related hazards (Trenberth, 2005). Furthermore, over the last decades, the ocean ecosystem has been significantly affected by the aftermath of global warming. Due to the warming of the ocean, a series of concomitant cascading effects can be observed, such as ice-melting, sea-level rise, marine heatwaves (Frölicher, Fischer, & Gruber, 2018), and ocean acidification (Burger, John, & Frölicher, 2020). Finally, climate change is predicted to worsen water quality and decrease the supply of fresh water (Arnell, 1999).

In this regard, the World Resources Institute has conducted a study that examines potential changes in the amount of renewable surface water around the world (World Resources Institute, 2023). This analysis considers the optimistic, business as usual (BAU), and pessimistic climate scenarios identified under specific Shared Socio-economic Pathways (SSP). On one hand, the optimistic scenario (SSP1 RCP2.6), envisions a world in which emissions are stabilized at 420 parts per millions (ppm) of CO_2 and temperatures are limited to an increase of 1.3-2.4°C by 2100. The business as usual (SSP3 RCP7) and pessimistic (SSP5 RCP8.5) scenarios, on the other hand, depict a future in which CO_2 concentrations will reach 935 and 936 ppm by 2100 and global mean temperatures will rise by 2.8–4.6°C and 3.3–5.7°C, respectively. Simultaneously, the impact of global warming on the balance of water ecosystems can be analyzed from another perspective, as illustrated in the article published by Hanasaki et al. (2013). In their investigation, the authors identify the regions of the world affected by water scarcity under a series of SSPs, including the ones previously mentioned.

Based on the selected SSP, the projected change in water supply and water scarcity in the future must be calculated and then multiplied by a monetary proxy. Estimates of the value of water quantity, according to Krieger (2001), range from $0.26 per acre-foot for the generation of electricity to as much as $50 per acre-foot for irrigation and municipal use. Similarly, the average financial worth per acre-foot of water used for recreational purposes equates to $10 or less. Finally, Krieger (2001) asserted that maintaining water quality has a yearly economic value of $64.16 per household. For the purposes of this analysis, Henderson et al. (2015) have already provided specific statistics on the monetary damages incurred by each water-using sector of the American economy due to climate change by 2100.

Terrestrial, Freshwater and Ocean Species

The second category shown in Figure 1 —species range shifts— becomes the focus of the inquiry in the paragraphs that follow.

As sea levels and global temperatures rise, more heat waves, droughts, floods, cyclones, and wildfires occur. These conditions reduce the availability of food and water while prompting structural changes in the local flora. Thereby, a broad range of animal species' survival is threatened. Consequently, this subsection explores the potential contributions of climate change to the extinction of various animal species. Afterwards, robust evidence for the monetization of such externality is presented.

Rather than classifying the distinct species according to whether they live in terrestrial, freshwater, or oceanic ecosystems, as outlined in Figure 1, an alternative clustering method is employed. The animals at risk of extinction are grouped into four categories: mammals, birds, turtles, and insects. This approach is implemented due to the current data availability.

The percentage of animal species that are thought to be in danger of extinction under the various climate scenarios is shown on the right side of Figure 2.8 of the IPCC report drafted by the Working Group II in 2022 (IPCC, 2022b). After a meticulous analysis, it was possible to infer that 11.7% of mammals, 10.9% of birds, 4.1% of turtles, and 24.2% of insects face a very high risk of extinction[2] if global warming is contained below 2°C (RCP 2.6). If the rise in world temperatures is limited to 3°C (RCP 4.5) a greater proportion of each species is at very high risk of extinction: 36.5% of mammals, 35.4% of birds, 24.3% of turtles, and 53.5% of insects. Finally, if global temperatures increase by more than 4°C, 56.3% of mammals, 57% of birds, 41.3% of turtles, and 70.7% of insects would be at very high risk of extinction. The focus of this study is placed arbitrarily on these four animal categories. This decision was primarily driven by the necessity for monetary proxies in the subsequent stages of the analysis, and unfortunately economic scholars have not yet established economic values for all living species. Nevertheless, the entire set of information and methodology is provided, which can be adapted to meet the requirements of researchers.

The studies of Richardson et al. (2009) and Losey et al. (2006) managed to link the above-mentioned animal categories to their economic values. Through a meta-analysis, Richardson et al. (2009) investigated a vast number of research articles which used the willingness-to-pay (WTP) methodology to measure the financial worth of several animal species that are in danger of extinction. In turn, in Losey et al.'s (2006) investigation, the authors attempted to estimate the economic worth of insects using a technique comparable to the one employed by Krieger (2001). In practice, the authors argued that the annual value of the ecological services provided by insects in the United States is equivalent to $57 billion.

Societal Cost

Global warming is having catastrophic repercussions on the health and the livelihood security of millions of people (World Health Organization, 2023).

The methodological analyses required for the detection of the principal associations between climate change and human societies are showcased following the guidelines of Figure 2.

Diseases and Deaths

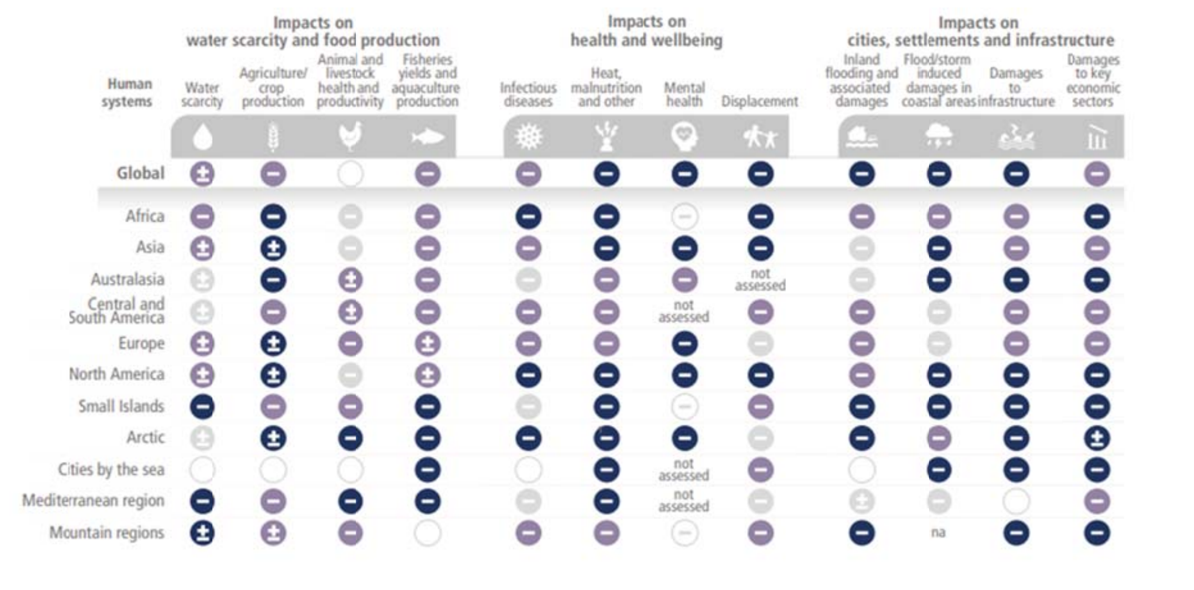
Climate change has a variety of effects on human health. Due to rising temperatures, new health threats are anticipated to emerge (Shope, 1991), while certain existing diseases may become more severe (World Health Organization, 2023). Increased respiratory and cardiovascular diseases, injuries and early deaths from extreme weather events, food- and water-borne illnesses, infectious diseases, and threats to mental health are some of the health effects of global warming (World Health Organization, 2023).

Several studies have managed to uncover the relationship between increasing temperatures and the deterioration of one's physical health. Firstly, a study of the IPCC states that a 1°C warming can increase in Asia and Africa the number of people with diarrhea and E. Coli by 7% and 8%, respectively (IPCC, 2022b). Secondly, compared to the 1980s mortality rates from cardiovascular diseases might rise by 18.4%, 47.8%, and 69% in the 2020s, 2050s and 2080s, respectively, under the RCP4.5, and by 16.6%, 73.8%, and 134% under the RCP8.5. Thirdly, the Swiss RE Institute's analysis published in 2023 found that a moderate climate change pathway (RCP 4.5) could result in global excess mortality of 1% annually by 2100 (Swiss RE Institute, 2023). According to this examination, if efforts are made to keep global warming below 2°C (RCP 2.6) the annual change in global excess mortality by 2100 could decrease to 0.75%. However, a pessimistic scenario of unmitigated climate change (RCP 8.5) could result in 5.2% annual excess mortality by 2100.

One could consider using the Value of Statistical Life (VSL), a well-known instrument in the field of economics, to measure the financial worth that each lost life has for the economy and society. According to a report released by the Australian government, a plausible estimate of the VSL equates to $5.3 million, whereas the value of a statis-

2 According to the UCN (2019), a species is anticipated to be at a "very high risk" of extinction if quantitative analyses demonstrate a likelihood of more than a 50% decline in the next 10 to 100 years. Conversely, a species is categorized as being at "high risk" when the probability of extinction within the next 10 to 100 years is greater than 20%.

FIGURE 2
IMPACT OF GLOBAL WARMING ON HUMAN SYSTEMS



Source: IPCC (2022)

tical life year amounts to $227,000 (Australian Government, 2022).

Malnutrition and Hunger

The occurrence of extreme weather events destabilizes the productivity of the agricultural sector (Cline, 2007). This poses a serious risk to the survival of entire communities residing in the world's most underdeveloped areas. If local societies are highly dependent on agricultural yields, then the worsening of the climate crisis could result in a growing number of people suffering from malnutrition and hunger.

On one hand, according to the IPCC, by 2030 570,000 additional children under the age of five will be suffering from malnutrition due to a moderate but significant rise in temperatures (RCP2.6) (IPCC, 2022b). This number will rapidly increase under the pessimistic scenario (RCP8.5). If the temperatures were to increase by more than 4°C in comparison to pre-industrial levels, then the statistics regarding the number of children suffering from malnutrition will increase by one million. Similarly, the report published in 2020 by the Center for Development Research (ZEF) and the Food and Agriculture Organization of the United Nations (FAO) asserted that by 2030, under the Toward Sustainability Scenario (TSS), the BAU scenario, and the Stratified Society Scenario (SSS), 3%, 7% and 12% of the world's population, respectively, will be undernourished (Von Braun et al., 2020). Even though there is no direct link between these climate prospects and the previously mentioned RCPs, it can be assumed that the TSS represents an optimistic climate scenario, while the SSS can be regarded as the pessimistic scenario. Additional estimates for the impact of global warming on the number of people at risk of undernourishment according to different climate scenarios are provided by Dawson, Perryman, and Osborne (2016), Mirzabaev et al. (2023) and Richards, Gauch, and Allwood (2023).

On the other hand, depending on the climate scenario under consideration, the effect of global warming on hunger could significantly differ. The IPCC predicted that due to climate change between 8 million (SSP1-6.0) and 80 million people (SSP3-6.0), predominantly in sub-Saharan Africa, South Asia, and Central America, will experience hunger by 2050 (IPCC, 2022b). Furthermore, Schmidhuber and Tubiello (2007) argued that, depending on the considered climate scenario, projected estimates suggest varying levels of hunger by 2050: approximately

210 to 219 million people under the A1 scenario, around 722 to 730 million under the A2 scenario, 242 million under the B1 scenario, and an estimated 336 to 358 million people under the B2 scenario. These scenarios are not directly correlated with specific degrees of global warming; however, they depict a future where the severity of climate change could vary based on different assumptions regarding economic and population growth, emissions, technological advancement, and energy consumption (IPCC, 2000). While the B1 scenario can be associated to an optimistic climate scenario, due to its emphasis on global sustainability and environmental conservation, the A1 scenario is often considered as the business as usual scenario, because it depicts a world with rapid economic growth and a diverse utilization of energy sources. In contrast, the A2 scenario leans toward a more pessimistic outlook, foreseeing fragmented development, slower economic growth, and a heavier reliance on fossil fuels. It is clear that the number of people at risk of hunger in the future will change depending on the RCP or SSP scenario taken into consideration, as highlighted by the Hasegawa et al. (2018).

To calculate the economic damages caused by the rise in malnutrition and hunger cases across the globe, two different techniques are proposed. Firstly, the VSL approach is recommended to estimate the costs related to malnutrition, given that robust statistics on global and regional mortality rates are provided by reliable sources, as Our World in Data (Our World in Data, n.d.). Secondly, for hunger-related economic estimations, beside using information on the regional mortality rates, it is advisable to reference the publications of prominent researchers who have tried to estimate the financial worth of the investments needed to eradicate this disease. The report published by (Von Braun et al., 2020), argued that the yearly investments needed to lift 500 million people out of hunger by 2030 should be equal by 2030 should be equal to $11-14 billion.

Mental Health

Climate change can cause individuals to relocate (Warner, Hamza, Oliver-Smith, Renaud, & Julca, 2010), disrupt the job market (International Labour Organization, 2018) and eventually damage community resources and social cohesiveness (World Health Organization, 2023), all of which have an impact on mental health.

The relationship between global warming and mental health can be approached from different angles. This investigation focuses on two of the most problematic psychological disorders that current societies are facing: anxiety and depression (World Health Organization, 2022).

On one hand, according to the World Bank, in Bangladesh, individuals who encountered a 1°C rise in external temperatures before the survey rounds were 21% more likely to report an anxiety disorder and had a 24% higher likelihood of simultaneously suffering from both anxiety and depression (World Bank Blogs, 2015). On the other hand, Charlson et al. (2021) reported that prolonged exposure to high temperatures in Taiwan resulted in a 7% increase in the occurrence of major depressive disorders for every 1°C rise in regions where the average yearly temperature exceeded the median of 23°C. These analyses offer a preliminary understanding of the deterioration of mental health disorders due to an increase in temperature, even though the robustness and external validity of these results remain relatively limited.

Eventually, it is possible to monetize this externality by employing statistics regarding the average costs borne by societies to treat these mental disorders.

Displacement

The ultimate way to evaluate the aftermath of global warming on the well-being of citizens can be performed by accounting for climate-induced displacements. In response to natural disasters and the negative effects of climate change, millions of people worldwide are forced to move or in the process of relocation (McAdam, 2010). As the intensity and frequency of extreme weather events rise, this situation is only expected to get worse.

The United Nation (UN) Migration Agency reveals that there could be as many as 1 billion people living in uninhabitable areas by 2100 because of climate change (RCP8.5), even without accounting for the projected global population growth. This estimation would fall to 133 million and 16 million people if national governments manage to limit global temperatures to reach the RCP4.5 and RCP2.6 scenarios by 2100, respectively (United Nation Migration Agency, 2017).

The reallocation costs depend directly on the regional level of wealth and technological advancement. In practice, to get an accurate assessment of the costs linked to relocating entire cities, researchers must consider the type of private and social infrastructures that need to be replaced. According to the data presented by Hauer et al. (2020) the most conservative estimate related to the potential costs of reallocating a person within the U.S. borders would ascend to $200,000.

Economic Cost

Extreme weather events are predicted to occur more frequently and severely, resulting in damages to infrastructures and loss of properties (Mirza, 2003). Given that economic scholars have widely investigated the financial damages caused by climate change on cities, settlements, and infrastructures, this aspect is not overly emphasized in the current study. The annual percentage change in national GDP levels due to a rise in temperatures ranging from 1°C to 4°C is summarized in detail in Table 2 of Kompas et al. (2018).

CASE STUDY: UNITED STATES

In this framework the environmental, social, and economic costs of CO_2 are discussed. Following the guidelines of Griffiths et al. (2012), these costs are defined as the net

TABLE 2
SOCIAL, ENVIRONMENTAL, AND ECONOMIC IMPACTS OF CO_2

UNITED STATES			
Potential Impact	Optimistic Scenario	BAU Scenario	Pessimistic Scenario
Terrestrial Ecosystem	1,717 billion	978 billion	-683 billion
Freshwater and Ocean Ecosystem	-156 billion	-184 billion	-200 billion
Animal Welfare - Mammals	-312 billion	-969 billion	-1,494 billion
Animal Welfare - Birds	-150 billion	-489 billion	-787 billion
Animal Welfare - Turtles	-692 thousand	-4.1 million	-6.9 million
Animal Welfare - Insects	-186 billion	-410 billion	-542 billion
Diseases	-291 billion	-594 billion	-32,578 billion
Malnutrition	-1.8 million	-2.5 million*	-3.2 million
Hunger	Not Applicable	Not Applicable	Not Applicable
Mental Health	-404 billion	-809 billion	-1,213 billion
Displacement	-266 billion	-2,215 billion	-22,199 billion
GDP	-23,996 billion	-45,832 billion	-66,114 billion

NOTE: The monetary impact presented above have been integrated and subjected to temporal discounting within the specified time frames, by assuming a linear growth trajectory supported by the application of a 3% discount rate.

Source: author

present value (NPV)[3] of projected financial damages that the United States will incur between 2023 and 2100, due to a significant rise in temperature. This analysis relied on the methods outlined in the previous sections.

Terrestrial Ecosystem

The calculation of the percentage change in forest land from 2019 to 2100 under the various climate scenarios began with an analysis of the information provided by the IPCC in Figure 3.28 of the 2022 report drafted by the Working Group III (IPCC, 2022). Thereafter, the absolute change in the population of trees within the United States territory was predicted by leveraging data sourced from the FAO (2020, 2020b) and Our World in Data (2020). Their databases and reports contain statistics concerning the national afforestation rate, measured by the number of trees planted per hectare.

The monetary value of a tree was set at $4.16[4] after analyzing the services provided by forests in the southwest region of the United States, which served as a representative sample of the entire nation (Krieger, 2001). Thereby, it was possible to ascertain the economic value of the forest area which will form, or disappear, by 2100 due to global warming. Finally, by assuming a linear growth of the impact across the considered period, the cumulative effect of climate change on the expansion of forest land from 2023 until 2100 was estimated.

Freshwater and Ocean Ecosystem

The calculation required to obtain the social costs of CO_2 arisen solely via the impact of climate change on the level of water availability can be performed on the bases of the information published by the World Resources Institute concerning the projected evolution of water supply by 2080 (World Resources Institute, 2022). However, as the present study aims to assess the impact of global warming by considering potential damages occurring within a time frame extending until 2100, this part of the analysis relies on the evidence published by Henderson et al. (2015) and Hanasaki et al. (2013). These publications provided insights into the economic damages resulting from an increase in temperature in the United States, for the optimistic, BAU and pessimistic climate change scenarios. Finally, as before, a linear growth assumption across the considered time horizon was employed to estimate the total impact of climate change on the reduction of water supply from 2023 until 2100.

Animal Welfare

The data presented by the Working Group II, in the 2022 IPCC report, was fundamental to evaluate the influence of global warming on the well-being of diverse animal species (IPCC, 2022b). In its disclosure regarding the projected reduction in animal species due to elevated temperatures, the IPCC omitted the temporal dimension, not specifying the time frame within which this phenomenon would occur. Nonetheless, since the RCP scenarios chosen in this framework assume that a certain temperature increase will be reached by 2100, the above-mentioned impacts of climate change were presumed to materialize in their entirety by 2100.

Mammals

Knowing the number of mammals living in the United States is crucial for the calculation of the financial costs associated with the extinction of these animal species. This information is nearly impossible to acquire due to the shifting migration trends of wildlife. Nevertheless, a preliminary estimate of the total population of mammals in the U.S. was derived by employing a proportional relationship between the count of mammal species inhabiting the U.S. and the global count of mammal species (The

3 A 3% discount rate is applied in all NPV calculations, as indicated in the Energy Performance of Buildings Directive of the European Commission (European Commission, 2018). This decision is in line with the guidelines offered by economic scholars (Quiggin, 1997).
4 Whilst performing the main calculations, adjustments were applied to all monetary proxies in accordance with their respective inflation rates. (World Bank, 2023; International Monetary Fund, 2023).

national wildlife federation, 2023; Tomasik, 2019; IUCN, 2012).

Thereafter, the total number of mammals which are expected to become extinct within the U.S. borders was multiplied by the mean economic value of endangered mammals (Richardson & Loomis, 2009). This process allowed to assess the financial damages associated with climate-induced mammalian extinction, which were assumed to grow linearly over the considered time span of 77 years.

Birds, Turtles, and Insects

The same technique presented in the previous subsection was employed to estimate the impact of global warming on the potential extinction of the other animal species taken into consideration during this investigation: birds, turtles, and insects.

As before, data regarding the total number of birds, turtles, and insects worldwide was gathered to estimate the animal population residing within the U.S. borders (Oliver Ridley Project, 2021; Oliver Ridley Project, 2023; American Ornithological Society, 2023; Xplore Our Planet, 2023; Avibase, 2023; Callaghan, Shinichi, & William, 2021; The Cornell Lab of Ornithology, 2023; National Oceanic and Atmospheric Administration, 2023; Smithsonian, n.d.). Afterwards, the impact was monetized through the average economic value of each species (Richardson & Loomis, 2009; Losey & Vaughan, 2006) and the assumption of a linear growth over the analyzed period.

Diseases

Khatana et al.'s (2022) investigation found that for every extra day of high heat between 2008 and 2017, there was a rise of 0.07 deaths per 100,000 adults. These figures emphasize the importance of considering the impact of global warming on the health of American citizens.

The Swiss RE Institute's report provided information about the annual percentage change in global mortality rates until 2100, across various climate scenarios (Swiss RE Institute, 2023). Upon estimating the cumulative mortality rate across the entire time frame, it became important to calculate the level of heat-induced mortality at the baseline. The evidence provided by Khatana et al. (2022) enabled the computation of the absolute change in deaths caused by extreme temperatures in the U.S. by 2100. However, to avoid assuming that in the future there will be only one day per year with extreme heat, comprehensive evidence was gathered regarding the anticipated increase in the number of extreme heat days in the U.S. under the RCP2.6, RCP4.5 and RCP 8.5 scenarios (Center for Climate and Energy Solutions, 2023; Climate Service Center Germany, 2018).

Afterwards, an attempt was made to correlate the rise in fatalities to its economic value by employing the VSL. After multiplying this figure by the number of additional casualties induced by the climate crisis, it was possible to obtain the monetized impact of CO_2 on the decline of people's physical health. The financial losses displayed in Table 2, were obtained by assuming a linear growth of the impact during the period under consideration.

Malnutrition

According to the definition offered by the WHO (2023b), malnutrition is characterized by an inadequate or excessive consumption of vital nutrients, which can result in cases of both under-nutrition and obesity. According to Bowen et al. (2018) the dual burden of malnutrition affects a vast portion of the American population. Hence, this analysis quantified the economic costs resulting from an increase in malnutrition cases within the U.S. borders.

Thanks to the dataset provided by the IPCC (2022b) it was possible to estimate how climate change will contribute to malnutrition among children under the age of five. The IPCC (2022b) does not provide any statistic for the RCP4.5 scenario. Deriving this figure involved assuming a linear relationship between external temperatures and the number of undernourished children. Given that this calculation relied on stronger assumptions, which reduced the explanatory power of the consequent financial impact, the result associated with the increase in malnutrition cases was signaled with an asterisk in Table 2. For the purpose of correctly distributing the impact across the globe, it needs to be specified that while the United States is home to 4,19% of the global population, only 0.53% of the children affected by stunting worldwide are residing in this nation (Global Nutrition Report, 2023; Childstats, 2023; World Health Organization, 2021; World Bank, 2023b).

The mortality rate from malnutrition in the country is equal to 0.9 per 100,000 people (Our World in Data, n.d.). Therefore, it can be stated that the actual rise in deaths due to malnutrition in the United States is minimal. A conservative assumption was made that the years lost because of this sickness amount to 74,11 since the projections estimated by the IPCC referred to a specific group of children aged 0 to 5, and the life expectancy in the U.S. is currently equal to 79,11 years (Macrotrends, 2023). This data was then multiplied by the Value of Statistical Year (VSY) and, eventually, by the total number of excess deaths brought on by malnutrition. To assess the overall impact up to 2100, this calculation relied on the evidence published by Richards, Gauch, and Allwood (2023) concerning regional starvation deaths per decade, spanning from 2000 to 2100 in an accelerated global warming scenario. The impact was calculated for the year 2100 and had therefore to be discounted over a period of 77 years, assuming a linear growth of the impact.

Hunger

Hunger does not significantly affect U.S. citizens today, nor it is expected to in the short-term. In practice, the Global Hunger Index (GHI) does not exist for developed countries such as the U.S., Canada, Australia, Spain, Sweden, Italy, and so on (Global Hunger Index, 2023). This result may be attributed to an internal food distribution system designed to address regional shortages. Therefore, even though hunger is an important consequence of climate change, it does not apply for the specific case study presented here.

Mental Health

With the aim of calculating the projected increase in the prevalence of anxiety disorders due to global warming, the proxy provided by the World Bank was multiplied by the total number of individuals currently experiencing anxiety in the United States (World Bank Blogs, 2015; Anxiety & Depression Association of America, 2023). Based on Marciniak et al.'s (2005) argument that the average costs of treating anxiety amount to $6,475, the climate change-induced financial damages linked to this specific mental health disorder were estimated. Also in this framework, the assumption was made that the impact would increase linearly from 2023 to 2100.

Similarly, when taking depression into consideration the costs bore by the American society rise significantly for each additional 1°C. The methodology is similar to the one used previously. However, in this context the proxy estimated by Greenberg et al. (2021) was used to quantify the average costs of treating depression in the United States. Finally, after having gathered statistics regarding the number of people suffering from depression in the United States (Mental Health America, 2023), it was possible to quantify the impact of climate change on the spread of this mental health illness (Charlson, et al., 2021). The monetized value was discounted over a 77-year period assuming a linear growth of the impact during the analyzed time horizon.

Displacement

To estimate the cost associated to the projected climate-induced displacement of the American population, the calculation involved multiplying the data provided by the UN Migration Agency by the proportion of the global population affected by this event within the United States (Climate Impact Lab, 2023; United Nation Migration Agency, 2017).

The net cost of relocating the American population to habitable areas by 2100 was calculated using estimates provided by Hauer et al. (2020). After discounting the integrated impact over a time horizon of 77 years, the results displayed in Table 2 were obtained.

GDP

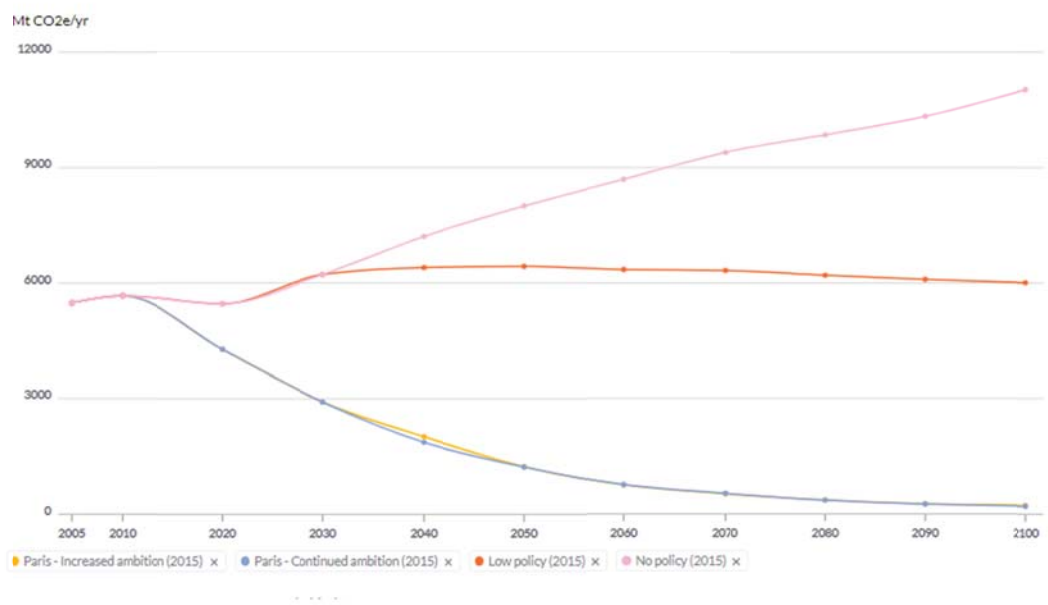
Given that Kompas et al. (2018) provided data on the annual percentage change of the American GDP owing to a rise in temperatures ranging from 1°C to 4°C, the calculation needed to estimate the pure economic damages caused by climate change was rather direct. Following a set of robust mathematical regressions, it can be remarked that if by 2100 global temperatures increase by 2° (RCP2.6), 3° (RCP4.5), and 4° (RCP8.5) degrees, the American GDP will decrease annually by 0.392%, 0.622%, and 0.885%, respectively. The damages were calculated in comparison to the baseline scenario of 1°C of global warming, where the GDP was assumed to decrease annually by 0.182%.

Social Costs of CO_2 in the United States

With the purpose of ascertaining the true SCC for the U.S., it is necessary to quantify the amount of anthropogenic CO_2 emissions produced by the American economy under the distinct climate scenarios and during the time period considered throughout the study, which in this case spans from 2023 to 2100. This information, displayed in Figure 3, was provided by the Climate Watch website, which compiled data from a vast collection of models stemming from the IPCC, the private sector, and country-specific sources (Climate Watch, 2023). The estimations are based on the Global Change Assessment Model (GCAM). The GCAM is a dynamic, recursive model that can be used to investigate different climate change mitigation strategies, such as carbon taxes and carbon trading.

In this framework, the Paris-Continued Ambition (2015), Low Policy (2015), and No Policy (2015) scenarios were designated as

FIGURE 3
MEGATON OF CARBON DIOXIDE EQUIVALENT PRODUCED YEARLY BY THE AMERICAN ECONOMY



Source: Climate Watch (2023)

the optimistic, BAU, and pessimistic climate scenarios, respectively.

In practice, the total financial damages originated by climate change were divided by the amount of CO_2 produced during the same period. Given that the optimistic scenario is the only one in which emissions are reduced to account for the negative externalities generated by global warming, the process of cost internalization was carried out by considering this specific climate prospect.

After considering solely the negative externalities, it can be argued that each additional metric ton of CO_2 produced in the United States should be taxed by national authorities with an amount corresponding to $287. By focusing only on the economic damages associated to global warming, one would underestimate the actual losses brought on by an extra metric ton of CO_2 by about $20. The distinction becomes more pronounced when looking at the total amount of CO_2 produced by the American economic system over the course of a year.

Limitations

While this study provides an intriguing angle to examine the societal costs associated with the escalating climate problem, it only serves as a starting point for future studies that should attempt to address as many of its shortcomings as feasible.

In the first place, this analysis is constrained to the territory of the United States, but the SCC estimate will highly vary based on the region taken into consideration. However, the primary goal of this study is to provide a collection of academically accepted and robust methodologies that will enable academics and institutions all around the world to calculate their own national SCC.

In the second place, the analysis relied on a series of assumptions to allow carrying out the main computations, which, in turn, resulted in a certain level of abstraction from the reality of the modern world. Unfortunately, this represents the best estimate at this moment due to the limited data availability and the practical impossibility to accurately predict future climate developments. On this matter, future scholars could focus on addressing some of the major limitations outlined in this framework, given that they will most likely have access to updated and more precise information.

In the third place, it is important to clarify that this investigation did not account for the tipping points which would results from future rises in global temperatures (Armstrong McKay, et al., 2022).

Finally, one might consider focusing on additional effects stemming from global warming on both society and the environment. The estimate provided in this analysis constitutes a lower bound, since the current information is insufficient to comprehensively encompass the myriad potential long-term consequences originated by climate change. Nevertheless, to enhance the external validity of this research, it adhered to the IPCC's framework, depicted in Figures 1 and 2.

DISCUSSION

Through a comprehensive literature review, this study aims at identifying and employing a set of statistically robust methodologies for the computation of the true SCC. Upon conducting a case study within the U.S. territory, it was determined that the minimum estimate for the SCC in 2023 amounts to $287.

The goal of the SCC is to internalize, and therefore reduce, the negative externalities stemming from the release of harmful substances into the atmosphere, which might otherwise exacerbate the climate crisis. This approach allows regulatory bodies to integrate the true cost of products into the global market. However, an effective implementation of this pricing mechanism requires international collaboration among sovereign governments, as the ramifications of global warming transcend national boundaries. International societies possess the capacity to restructure market dynamics while also modifying production and consumption patterns, all in the pursuit of effectively mitigating climate change.

While this article modestly represents a further step in the right direction, it is essential for academic researchers to continue evaluating the wide-ranging effects of climate change on the diverse ecosystems and their inhabitants. Novel methodologies and additional analyses must be developed with the utmost precision to enable policymakers to formulate and enforce science-driven adaptation and mitigation strategies.

REFERENCES

Aldy, J. E., Kotchen, M. J., Stavins, R. N., & Stock, J. H. (2021). Keep climate policy focused on the social cost of carbon. Science, 850-852. doi:10.1126/science.abi7813

Armstrong McKay, D. I., Staal, A., Abrams, J. F., Winkelmann, R., Sakschewski, B., Loriani, S., ... Lenton, M. T. (2022). Exceeding 1.5°C global warming could trigger multiple climate tipping points. Science. doi:10.1126/science.abn7950

Australian Government. (2022). Best Practice Regulation Guidance Note. Department of the Prime Minister and Cabinet Office of Best Practice Regulation.

Bowers, K. S., Francis, E., & Kraschnewski, L. J. (2018). The dual burden of malnutrition in the United States and the role of non-profit organizations. Preventive medicine reports, 294-297. doi:https://doi.org/10.1016/j.pmedr.2018.10.002

Brander, M., & Davis, G. (2012). Greenhouse Gases, CO2, CO2e, and Carbon: What Do All These Terms Mean. Econometrica, White Papers.

Center for Climate and Energy Solutions. (2023). Heat waves and climate change.

Charlson, F., Ali, S., Benmarhnia, T., Pearl, M., Massazza, A., Augustinavicius, J., & Scott, J. G. (2021). Climate Change and Mental Health: A Scoping Review. International journal of environmental research and public health. doi:https://doi.org/10.3390/ijerph18094486

Climate Service Center Germany. (2018). Regional Climate Projections for Europe.

Climate Watch. (2023). Pathways.

Dawson, T. P., Perryman, A. H., & Osborne, T. M. (2016). Modelling impacts of climate change on global food security. Climatic Change, 429-440. doi:https://doi.org/10.1007/s10584-014-1277-y

European Commission. (2018). Directive 2018/844 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL. Official Journal of the European Union.

Greenberg, P. E., Fournier, A. ,., Sisitsky, T., Simes, M., Berman, R., Koenigsberg, S. H., & Kessler, R. C. (2021). The economic burden of adults with major depressive disorder in the United States (2010 and 2018). Pharmacoeconomics, 653-665. doi:https://doi.org/10.1007/s40273-021-01019-4

Griffiths, C., Kopits, E., Marten, A., Moore, C., Newbold, S., & Wolverton, A. (2012). The social cost of carbon: Valuing carbon reductions in policy analysis. Fiscal policy to mitigate climate change. doi:https://doi.org/10.5089/9781616353933.071

Hanasaki, N., Fujimori, S., Yamamoto, T., Yoshikawa, S., Masaki, Y. H., Kainuma, M., ... Kanae, S. (2013). A global water scarcity assessment under Shared Socioeconomic Pathways–Part 2: Water availability and scarcity. Hydrology and Earth System Sciences. doi:https://doi.org/10.5194/hess-17-2393-2013

Hannah, R. (2019, October 1). Who has contributed most to global CO2 emissions?

Hasegawa, T., Fujimori, S., Havlík, P., Valin, H., Bodirsky, B. L., Doelman, J. C., ... Witzke, P. (2018). Risk of increased food insecurity under stringent global climate change mitigation policy. Nature climate change, 699-703. doi:https://doi.org/10.1038/s41558-018-0230-x

Hauer, E. M., Fussell, E., Mueller, V., Burkett, M., Call, M., Abel, K., ... Wrathall, D. (2020). Sea-level rise and human migration. Nature Reviews Earth & Environment. doi:https://doi.org/10.1038/s43017-019-0002-9

Henderson, J., Rodgers, C., Jones, R., Smith, J., Strzepek, K., & Martinich, J. (2015). Economic impacts of climate change on water resources in the coterminous United States. Mitigation and Adaptation Strategies for Global Change, 135-157. doi:https://doi.org/10.1007/s11027-013-9483-x

IPCC. (2022). Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press. doi:10.1017/9781009157926

IPCC. (2022b). Climate Change 2022: Impacts, Adaptation, and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press. doi:10.1017/9781009325844.

Khatana, S. A., Werner, R. M., & Groeneveld, P. W. (2022). Association of extreme heat with all-cause mortality in the contiguous US, 2008-2017. JAMA Network Open, e2212957-e2212957. doi:10.1001/jamanetworkopen.2022.12957

Kompas, T., Pham, V. H., & Che, T. N. (2018). The effects of climate change on GDP by country and the global economic gains from complying with the Paris climate accord. Earth's Future, 1153-1173. doi:https://doi.org/10.1029/2018EF000922

Krieger, J. D. (2001). Economic value of forest ecosystem services: a review.

Losey, E. J., & Vaughan, M. (2006). The economic value of ecological services provided by insects. Bioscience, 311-323. doi:https://doi.org/10.1641/0006-3568(2006)56[311:TEVOES]2.0.CO;2

Marciniak, M. D., Lage, M. ,., Dunayevich, E. R., Bowman, L., Landbloom, R. P., & Levine, L. R. (2005). The cost of treating anxiety: the medical and demographic correlates that impact total medical costs. Depression and anxiety, 178-84. doi:https://doi.org/10.1002/da.20074

Mirzabaev, A., Kerr, R. ,., Hasegawa, T., Pradhan, P., Wreford, A., von der Pahlen, M. ,., & Gurney-Smith, H. (2023). Severe climate change risks to food security and nutrition. Climate Risk Management. doi:https://doi.org/10.1016/j.crm.2022.100473

Nordhaus, W. D. (2017). Revisiting the social cost of carbon. Proceedings of the National Academy of Sciences, 1518-1523. doi:https://doi.org/10.1073/pnas.1609244114

Our World in Data. (n.d.). Death rate from malnutrition, 2019.

Quiggin, J. (1997). Discount rates and sustainability. International Journal of Social Economics, 65-90. doi:https://doi.org/10.1108/03068299710764305

Rennert, K., Errickson, F., Prest, B. C., Rennels, L., Newell, R. G., Pizer, W., … Anthoff, D. (2022). Comprehensive evidence implies a higher social cost of CO2. Nature, 687-692. doi:https://doi.org/10.1038/s41586-022-05224-9

Richards, C. E., Gauch, H. ,., & Allwood, J. ,. (2023). International risk of food insecurity and mass mortality in a runaway global warming scenario. Futures. doi:https://doi.org/10.1016/j.futures.2023.103173

Richardson, L., & Loomis, J. (2009). The total economic value of threatened, endangered and rare species: an updated meta-analysis. Ecological economics, 1535-1548. doi:https://doi.org/10.1016/j.ecolecon.2008.10.016

Rivera, A., Movalia, S., Rutkowski, E., Rangel, Y., Pitt, H., & Larsen, K. (2023, September 19). Global Greenhouse Gas Emissions: 1990-2021 and Preliminary 2022 Estimates.

Schmidhuber, J., & Tubiello, N. F. (2007). Global food security under climate change. Proceedings of the National Academy of Sciences, 19703-19708. doi:https://doi.org/10.1073/pnas.0701976104

Serafeim, G., & Trinh, K. (2020). A Framework for Product Impact Weighted Accounts. Harvard Business School Accounting & Management Unit Working Paper, 20-076. doi:http://dx.doi.org/10.2139/ssrn.3532472

Stern, N., & Stiglitz, J. E. (2021). The social cost of carbon, risk, distribution, market failures: An alternative approach. National Bureau of Economic Research.

Swiss RE Institute. (2023). The risk of a lifetime: mapping the impact of climate change on life and health risks.

The Cornell Lab of Ornithology. (2023). Birds of the World.

Von Braun, J., Chichaibelu, B. B., Torero Cullen, M., Laborde, D., & Smaller, C. (2021). Ending hunger by 2030–policy actions and costs.

World Bank Blogs. (2015, February 15). Stressed and depressed: Climate change and mental health in Bangladesh.

World Health Organization. (2022, June 8). Mental Disorders.

World Resources Institute. (2023). The Aqueduct Water Risk Atlas. Retrieved from

Zhao, Q., Guo, Y., Ye, T., Gasparrini, A., Tong, S., Overcenco, A., … Vicedo-Cabrera, A. (2021). Global, regional, and national burden of mortality associated with non-optimal ambient temperatures from 2000 to 2019: a three-stage modelling study. *The Lancet Planetary Health*. doi:https://doi.org/10.1016/S2542-5196(21)00081-4

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