# Critique of "Comprehensive evidence implies a higher social cost of $CO_2$"

The recent *Nature* article by Rennert et. al.[1] attempts to estimate the social cost of $CO_2$, summing costs through 2300. They find a total cost of $185 per ton of $CO_2$, more than three times the value currently being used by the U.S. government. Of the cost they find, $90 is the cost of increased mortality due to higher temperatures, $84 the cost of reduced agricultural output, $2 from sea level rise. It is our claim that the first two figures are substantial exaggerations due to unrealistic assumptions implicit in the calculations.

## Mortality

The mortality calculation is based on regional figures from Cromar et. al. for increased mortality per degree of temperature rise. It is well known[2] that temperature-related mortality depends, among other things, on income, since richer people can afford better insulated homes and have less need to go out in unfavorable weather. The economic model in Rennert et. al. implies per capita GNP roughly tripling by 2100, increasing about eleven-fold by 2300.[3] The calculations in Cromar et. al. ignore the effect of that increased income on mortality. The implicit assumption is that temperature-related mortality will remain at the level of the recent past, from where their data are derived.

Correcting this error would require redoing the analysis in Cromar et. al. to include the effect of per capita GNP and then redoing the calculation in Rennert to replace a single mortality increase per degree with the increase as a function of per capita GNP, and integrating over the period. Bressler et. al.[4] calculated the effect of redoing the calculation in Gasparrini et. al.[5] of the change in mortality by 2090-2099 due to climate change, including the effect of income. They found that doing so reduced the increase in mortality, under four different climate scenarios, to about two-thirds of the value found without taking account of income. Their calculations were based on national figures so ignored the effect of differing incomes within nations, hence probably underestimated the effect. It follows that the best guess at the effect of including income in the calculations, an improvement suggested in Cromar et. al. for future work,[6] is that it would reduce temperature-related mortality to less than two-thirds of the result they calculated.

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[1] Rennert et. al., "Comprehensive evidence implies a higher social cost of $CO_2$" *Nature* 610, 27 October, 2022.

[2] For example: "Work examining the United States has shown large declines in heat-related mortality due to the adoption of air conditioning (Barreca et al. 2016) and declines in cold-related mortality due to migration to warmer regions (Deschênes and Moretti 2009). Both adaptation strategies can be effective but require resources, again highlighting the role of wealth and the adaptative capacity it enables." Daniel Raimi, "Effects of Climate Change on Heat- and Cold-Related Mortality: A Literature Review to Inform Updated Estimates of the Social Cost of Carbon," Resources for the Future working paper 2021.

[3] Calculated from Figure 2b in Rennert et. al. Note that even an eleven-fold increase in income would still leave countries such as India, Nigeria, and Indonesia with incomes substantially lower than current U.S. incomes.

[4] R. Daniel Bressler, Frances C. Moore, Kevin Rennert & David Anthoff, "Estimates of country level temperature-related mortality damage functions," www.nature.com/scientificreports

[5] Gasparrini, A. *et al.* Projections of temperature-related excess mortality under climate change scenarios. *Lancet Planet. Health* **1**, e360–e367 (2017).

[6] "Effects of temperature may vary across socioeconomic conditions, a critical consideration for a wide range of adverse health outcomes highlighted explicitly by the respiratory, cardiovascular, and infectious disease subgroups. A small sample of important variables to consider as modifiers may include air conditioning prevalence (70), level of infrastructure and greenspace coverage, population density, poverty and education levels, and health care access."

Temperature-related mortality also depends on technology, most obviously medical technology and heating, cooling, and insulating technologies. It is impossible to predict what the changes in those technologies will be over the next three centuries, but that there will be no change is the least plausible assumption. That is the assumption implicit in Rennert et. al., since it applies the increase in temperature-related mortality per degree of warming calculated by Cromar from past data to project the increase from now to 2300.

Since technological progress over long periods of time cannot be predicted, we do not know by how much dropping that assumption would modify the conclusion of Rennert et. al. One can, however, use changes in mortality over recent history to get some idea of the order of magnitude of the effect. Thus, for example, Sidney et. al.[7] find an annual decline in cardiovascular mortality in the United States from 2000 to 2011 of 3.79%. If that rate were continued for the rest of the century it would reduce CVD, one of the sources of temperature-related mortality, about twenty-fold by 2100.

For further evidence, from Lay et. al.[8]:

> … vulnerability to extreme heat has decreased over time, probably due to a combination of physiological, behavioural, infrastructural, and technological adaptations. We aimed to account for these changes in vulnerability and avoid overstated projections for temperature-related mortality. We used the historical observed decrease in vulnerability to improve future mortality estimates.
>
> We used historical mortality and temperature data from 208 US cities to quantify how observed changes in vulnerability from 1973 to 2013 affected projections of temperature-related mortality under various climate scenarios.
>
> … US mortalities projected from a 2°C increase in mean temperature decreased by more than 97% when using 2003–13 data compared with 1973–82 data. However, these benefits declined with increasing temperatures, with a 6°C increase showing only an 84% decline in projected mortality based on 2003–13 data.

So the change in temperature-related mortality in the U.S. for a 6°C increase fell by 84% due to changes in mortality rates over thirty years. Yet Rennert et. al. projects mortality rates on the assumption that temperature-related mortality will remain constant for almost three hundred years.

A third problem with the calculations in Cromar et. al. has to do with the assumed pattern of temperature increase, the relation between the amount by which winters become milder, reducing mortality, and the amount by which summers become hotter, increasing it. The article estimates the effect of increases in average temperature without specifying the distribution. An increase of

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Cromar et. al. under "Recommendations for Improving Health Modules in Economic-Climate Models."

[7] Sidney S, Quesenberry CP, Jaffe MG, et al. Recent Trends in Cardiovascular Mortality in the United States and Public Health Goals. *JAMA Cardiol.* 2016;1(5):594–599. doi:10.1001/jamacardio.2016.1326

[8] Lay et. al., "City-level vulnerability to temperature-related mortality in the USA and future projections: a geographically clustered meta-regression," The Lancet, Planetary Health.

2° in winter and 0° in summer would have a very different effect on mortality than an increase of 0° and 2°.

Increases due to anthropogenic climate change, as projected in the IPCC reports, are greater in winter than summer. The data in the articles used by Cromar et. al. to deduce temperature-related mortality is from temperature variation in recent years over either time or space, so has no reason to reproduce that pattern. If we assume that the increases in Cromar et. al. are uniform, with both minimum and maximum temperature rising by one degree, and further assume that the reductions in mortality reported in the article are proportional to the increase in minimum temperature, the increases in maximum, we can combine the information on the ratio of decrease to increase in Table 2 of Cromar et. al. with the information in Figure 11.A.1 (scaling of regional annual minimum temperature) and Figure 11.3 (scaling of regional annual maximum temperature)) from IPCC AR6 WGI to get a rough estimate of how much lower the net mortality effect would be if the calculation took into account the pattern of change projected by the IPCC.[9] The calculation is shown in Table 1.

| A<br>Region from Table 1 | B<br>Mortality Decrease | C<br>Mortality Increase | D<br>Scaling of Minimum | E<br>Scaling of Maximum | F<br>BxD | G<br>CxE | H<br>F/G |
|---|---|---|---|---|---|---|---|
| Europe | 0.007 | 0.012 | 2.167 | 1.533 | 0.014 | 0.018 | 0.78 |
| United States | 0.008 | 0.024 | 2.233 | 1.533 | 0.017 | 0.037 | 0.46 |
| East Asia | 0.010 | 0.034 | 1.875 | 1.375 | 0.019 | 0.047 | 0.40 |
| Eastern Europe | 0.007 | 0.022 | 2.800 | 1.600 | 0.020 | 0.035 | 0.56 |
| MENA | 0.029 | 0.120 | 1.550 | 1.550 | 0.045 | 0.186 | 0.24 |
| Average | | | | | | | 0.49 |

Table 1

Columns B and C show the decrease and increase of mortality from Table 1 of Cromar et. al. Columns D and E show the increase if minimum and maximum annual temperature per degree of warming, from Figures 11.A.1 and 11.3 of IPCC AR6 WGI. F and G show the change in mortality per degree of warming, assuming that decrease and increase are proportional to the change in minimum and maximum temperature. H shows the ratio of decreased to increased mortality risk. Its average value is .49. The corresponding figure in Cromar et. al. is .36. Net mortality is the increased risk minus the decreased risk, so equal to Increase x (1-Decrease/Increase). Replacing the average in Cromar et. al. with the average on Table 1 above, converts the parenthesis from .64 to .51, reducing net mortality by 20%.

A fourth factor ignored in Cromer et. al. is adaptation by migration. Currently, 280,000,000 people, about 3.5% of the world population, live in a different country than they were born in. If some parts of the world become less attractive due to climate change and some more, populations can be expected to shift in response, reducing temperature-related mortality. A recent article [I have to

[9] To convert the regions in the IPCC figures to regions in Table 2, I used Figure 11.4 from the IPCC report to figure out what regions were included in Europe, Eastern Europe, U.S., East Asia, and MENA, then used the average figure for the included regions.

find the cite] found that increased U.S. life expectancy was in part due to elderly people moving to more favorable, in that case warmer, climates. As discussed later in this article, one effect of climate change is a large increase in the amount of land in the northern hemisphere warm enough for human use, so there will be places for people, and crops, to move to.

In summary, we found four errors in the mortality calculation from Cromar et. al. as used in Rennert et. al:[10] neglecting the effect of income on temperature-related mortality, neglecting the effect of technological change, ignoring the pattern of temperature change implied by greenhouse warming, ignoring adaptation by migration. Correcting the first and third should reduce mortality by at least fifty percent. Correcting the second should further reduce it by a large, but unknown, amount, there being no way of predicting the scale of technological progress over the next three centuries.

## Effect of Climate Change on Agriculture

Rennert et. al. bases its estimate of the effect of climate change on agriculture on Moore et. al. 2017. We find three different problems with its calculations.

### Technological Change

The first is that, like the calculation of mortality, it ignores technological change. One way of adapting to a changed environment is by modifying crop varieties. Biotech is a rapidly progressing field at present, so we can expect that our ability to modify crop varieties to make them less vulnerable to increased temperature will improve over time, although there is no way of knowing by how much. We do know that a more primitive version of biotech, selective breeding, practiced by the inhabitants of Central America over a period of several thousand years, gradually adapted maize to the cooler climate of North America,[11] with the result that a once tropical crop is currently grown in both tropical and temperate regions. As our biotechnology improves we should be able to do it with other crops a little faster.

Improved technology is relevant to the effect of increased $CO_2$ in two ways. Most obviously, it reduces the reduction in yield due to warming. Less obviously, it increases the incentive to develop improved technologies, thus further reducing the reduction in yield.

### Crop Migration

One way in which a farmer can adjust to increased temperature, or other changes in climate, is by moving where he grows his crops. A shift towards the pole of a few miles a year in where a particular crop is grown is sufficient, on average, to entirely cancel the effect of increased temperature. Sloat et. al. 2020 observed the effect from warming from 1973 to 2012 and found that "the most damaging impacts of warming on rainfed maize, wheat, and rice have been substantially moderated by the migration of these crops over time and the expansion of irrigation. … We find that although average growing season temperatures over areas under cultivation have increased by 0.7–1.1 °C, there has been less or no increase (−1.6–0.5 °C) in the upper bound (95th percentile) of temperatures experienced by maize, wheat, and rice crops because crop areas have shifted over time."

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[10] These are mostly not errors in Cromar et. al. if viewed as an estimate of current effects of temperature change, only when incorporated into Rennert et. al. and used to project effects into the far future.

[11] https://en.wikipedia.org/wiki/Maize#Pre-Columbian_development.

As best we can tell, Moore et. al. entirely ignores that form of adaptation to climate change and so substantially exaggerates the effect of climate change on agricultural yield.

### CO2 Fertilization

Increases in $CO_2$ concentration in the atmosphere increase the yield of C3 crops and reduce water requirements for both C3 and C4 crops. Early estimates of the effect, done mostly with enclosed experiments, found about a 30% increase in yield from a doubling of $CO_2$ concentration. Those results were used in earlier estimates of the effect of climate change on agriculture, with the result that some such estimates found a net gain.

Later experiments, using open field plots and computer controlled $CO_2$ (FACE), found a considerably weaker effect. Moore et. al., citing Long et. al. 2006, use a figure of 11.3% increase in C3 yield with a doubling of $CO_2$ concentration. The use of that lower figure appears to be a large part of the reason that they get a much more negative result for the social cost of carbon than FUND, which found a net benefit, or AgMIP, which found a cost but a substantially smaller cost.[12]

A still more recent study, however, not available when Moore et. al. was written, reverses the conclusion. Taylor and Schlenker 2022[13] used random variation in $CO_2$ concentration observed by NASA's Orbiting Carbon Observatory-2 satellite, combined with county level crop yield data, to directly observe the effect of varying $CO_2$ concentration on crop yields in actual agricultural practice. They found that a 1 ppm increase in $CO_2$ equates to a 0.4%, 0.6%, 1% yield increase for corn, soybeans, and wheat, respectively. Their article includes a lengthy discussion of reasons why the FACE studies may have substantially underestimated the effect.

There were no regions in the US with a doubled concentration of $CO_2$ — observed variation was only over a range of about 15 ppm — so their results do not tell us how large the effect would be for much greater increases in $CO_2$ concentration. But they are evidence that the FACE results, and so Moore et. al. that uses them, seriously underestimate the yield increases from $CO_2$ fertilization and so seriously overestimate the net reduction in agricultural output from climate change.

### Conclusion

We have pointed out three different problems with the calculation of the effect of climate change on agriculture. Correcting one of them, the low value used for $CO_2$ fertilization, may be sufficient by itself to flip the result, make the net effect of climate change positive rather than negative. Correcting the other two should at least substantially reduce the estimate of cost.

## Effect of Climate Change on Usable Land Area

As one can see by looking at population density maps, human land use is currently limited by cold, not heat — the polar regions are empty, the equator inhabited. Warming due to anthropogenic climate change will push temperature contours towards the poles. The result will be a large increase in the amount of land in the northern hemisphere warm enough for human use. One of us has estimated an increase of 10.8 million $km^2$ from an increase in global temperature of 3°C. Ramankutty et. al.,[14] considering additional constraints for cultivatable land, got an increase in

[12] Moore et. al. Fig. 4.

[13] Charles A. Taylor and Wolfram Schlenker, "Environmental Drivers of Agricultural Productivity Growth: CO 2 Fertilization of US Field Crops."

[14] Ramankutty, N. et al 2002, "The global distribution of cultivable lands: current patterns and sensitivity to possible climate change," *Global Ecol. Biogeogr*. 11 377–92

suitable cropland area of 6.6 million $km^2$. A less optimistic calculation by Xhang et. al.[15] finds a change in agricultural land availability ranging from -.8 million $km^2$ to +1.2 million $km^2$. The latter paper does not, and the former does, take account of the reduction in water requirements due to $CO_2$ fertilization.

In order to include this in the calculation of the Social Cost of Carbon one would have to price the additional land and calculate the marginal increase due to the warming produced by an additional ton of carbon dioxide. We have not done so. But a large benefit produced by increased $CO_2$ — ten million $km^2$ is a little more than the land area of the United States — should be included as a negative term in the calculation of the SCC.

## A General Problem

Over the past two centuries, technological change has replaced sailing ships with jet planes for long distance transportation. Over the past century, medicine has progressed from a point where almost no contagious diseases were curable to one where the appearance of an incurable disease is a rare event. Over the past fifty years, computer technology has progressed to the point where the typical member of a developed society carries in his pocket a computer more powerful than any that existed fifty years ago. There is no reason to believe that the process has stopped and no way of predicting its effects on the world beyond the very short term. Rennert et. al. attempt to sum costs over the next three centuries. Their solution to the problem of predicting technological change over that period is, with the sole exception of their estimates of $CO_2$ production, to ignore it, implicitly assume technological stasis. That is obviously the wrong solution, for reasons we have suggested, but it is not obvious that there is a right solution. As one of us wrote in a book published fifteen years ago:

> … with a few exceptions, I have limited my discussion of the future to the next thirty years or so. That is roughly the point at which both AI and nanotech begin to matter. It is also long enough to permit technologies that have not yet attracted my attention to start to play an important role. Beyond that my crystal ball, badly blurred at best, becomes useless; the further future dissolves into mist.[16]

In our view, calculating the cost of climate change three centuries into the future, as Rennert et. al. claims to do, is impossible. The results of such an exercise, even with the best possible projections of technological change, a wild guess. Any such calculation should be limited to at most this century while recognizing the uncertainty of both costs and benefits beyond that.

About two-thirds of the SCC in Rennert et. al. is from later than that, so truncating their results at the end of the century, without making any other changes, would reduce their figure for the SCC to about a third of the value they found.[17]

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[15] "Climate change impacts on global agricultural land availability" by Xiao Zhang and Ximing Cai 2011 *Environ. Res. Lett.* 6 014014.

[16] D. Friedman, *Future Imperfect: Technology and Freedom in an Uncertain World*, p. 11. My view of AI has turned out to be too conservative — it has already started to matter.

[17] Estimated from Extended Data Fig. 2 in Rennert et. al.