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Quantified, Localized Health Benefits of Accelerated Carbon Dioxide Emissions Reductions

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Abstract

Societal risks increase as Earth warms, but also for emissions trajectories accepting relatively high levels of near-term emissions while assuming future negative emissions will compensate even if they lead to identical warming [1]. Accelerating carbon dioxide (CO_2) emissions reductions, including as a substitute for negative emissions, hence reduces long-term risks but requires dramatic near-term societal transformations [2]. A major barrier to emissions reductions is the difficulty of reconciling immediate, localized costs with global, long-term benefits [3, 4]. However, 2°C trajectories not relying on negative emissions or 1.5°C trajectories require elimination of most fossil fuel related emissions. This generally reduces co-emissions that cause ambient air pollution, resulting in near-term, localized health benefits. We therefore examine the human health benefits of increasing ambition of 21st century CO_2 reductions by 180 GtC; an amount that would shift a 'standard' 2°C scenario to 1.5°C or could achieve 2°C without negative emissions. The decreased air pollution leads to 153±43 million fewer premature deaths worldwide, with ~40% occurring during the next 40 years, and minimal climate disbenefits. More than a million premature deaths would be prevented in many metropolitan areas in Asia and Africa, and >200,000 in individual urban areas on every inhabited continent except Australia.

The world's nations have agreed to limit the global mean temperature rise to well below 2°C. Cumulative CO_2 emissions need to remain below ~820 GtC to maintain a 50% chance of meeting the 2°C temperature goal accounting for non-CO_2 emissions [5, 6]. Though the share of the world's energy produced by low- or zero-carbon sources continues to grow, the

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Author contributions
D.S. conceived the project; G.F. performed the simulations and health impact calculations, K.S. assembled ozone datasets for use in model evaluation and helped develop ozone impact analyses, C.S. mapped the health outcomes onto metropolitan areas. D.S. wrote the paper, with all authors providing input.

Additional information
Supplementary information is available in the online version of the paper.

pace of change is too slow to have put the world on an emissions trajectory consistent with this carbon budget.

Societies do not seem to place enough value on climate change mitigation to overcome the many socio-economic barriers to transformation to a zero-carbon society [2]. Though studies have suggested that a complete transformation to renewables in the near-term is practical (e.g. [7, 8]), most scenarios that stabilize warming at or below 2°C, and virtually all scenarios that achieve the 1.5°C target, do so by relying heavily on negative emissions technologies and practices [9]. The bulk of these negative emissions come from technologies that have not been demonstrated at commercial scales and may not materialize (e.g. [1, 9]). The primary negative emissions technology in these scenarios is biofuel energy with carbon capture and sequestration (BECCS). This faces biophysical, logistical and social constraints, and if it were to be deployed at the scales envisioned would require a substantial fraction of the world's arable land and water resources, with potentially severe consequences for biodiversity and food security [1, 9, 10]. Assuming that negative emissions technologies will be widely deployed is attractive, however, in that it allows slower reductions in near-term emissions while still maintaining the 2°C or 1.5°C targets. Indeed, the Paris Climate Agreement's language specifically calls for the world to achieve a balance between anthropogenic emissions and sinks of greenhouse gases rather than to eliminate positive emissions. Yet even if net zero emissions achieved identical temperature goals to zero positive emissions (with no negative emissions), this would not imply all other impacts of the emissions would be the same. In particular, public health impacts have not previously been evaluated, but should be included in consideration of risks and benefits.

The 'co-benefits' associated with low carbon trajectories are important from a sociological perspective as well as a physical one. The collective, long-term nature of climate change makes it an especially challenging problem. Many risks are difficult to quantify reliably, and psychological research has shown that most people greatly discount uncertain future events when considering costs and benefits that occur over multiple timescales (e.g. [3]). People also discount risks that occur remotely and tend to believe climate change will largely influence people in far away places [4], which has led to suggestions to highlight local risks (see Supplemental Information section 2; SI.2).

Hence it becomes important that, in addition to reducing long-term risks, the transition to low- or zero-carbon emissions would also provide near-term, localized benefits, primarily via improved human health due to reduced co-emissions that lead to ambient air pollution. Using a metric that monetizes both climate and air quality impacts [11], we evaluated the portion of emissions-reduction benefits accruing within the first decade and at the level of a large nation (see SI.2). The majority of damages attributable to coal fired power generation and surface transportation are near-term and national, 51–78% depending on national conditions and discounting rate. Owing to the relatively well-quantified relationship between pollution exposure and health impacts combined with the very large population sample size in metropolitan areas, this means that an important, tangible impact of the transition to carbon neutrality can be quantified and localized with comparatively low uncertainty.

We construct scenarios designed to explore two questions: (1) if negative emissions technologies consistent with a 'standard' 2°C scenario were to indeed be achieved, what would be the additional health and climate impacts of accelerating carbon emissions reductions via greater reliance on renewables (i.e. non-polluting energy rather than a source such as biomass) so as to enable a high likelihood of achieving the 1.5°C target?, and (2) if we were to follow a 2°C trajectory via such accelerated carbon emissions reductions rather than reliance on future negative emissions, what would be the additional health and climate impacts? Despite air pollution being the largest environmental source of premature deaths [12], studies that have noted the link between carbon trajectories and air pollution [13, 14] have utilized simple metrics for the latter (such as SO_2 emissions), meaning the fuller health impacts have not yet been examined. These air quality-related health impacts would be complemented by additional health benefits of climate change mitigation (e.g. [15, 16]) in the first case (but not in the second).

We develop three scenarios to compare with the widely used Representative Concentration Pathway 2.6 (RCP2.6) (Figure 1; and Methods). The first includes accelerated reductions in positive carbon emissions and almost no negative carbon emissions to produce the same cumulative net emissions over the remainder of the 21st century (hereafter NoNegRCP2.6). The difference between RCP2.6 and NoNegRCP2.6 can be visualized by considering on the one hand a coal-fired power plant and a BECCS facility that removes as much CO_2 as the coal plant emits, so that the net CO_2 output is zero, and on the other hand a set of renewables such as wind and solar generating the same electricity output and again zero CO_2; obviously the coal-fired power plant's co-emitted air pollution (and any from the BECCS plant) is only present in the first case. The second scenario is an alternative 'reference' with slightly greater carbon emissions than in RCP2.6, consistent with 2°C warming (hereafter 2°C). The final scenario applies the accelerated emissions reductions of the NoNegRCP2.6 scenario to this reference, leading to ~1.5°C warming (hereafter 1.5°C). Comparison between these last two yields the effects of accelerating carbon emissions reductions to achieve a lower target (with no change in assumptions regarding negative emissions) (see SI.5).

Simulations were performed using the global composition-climate model GISS-E2 (see Methods). We use a newly developed method enabling simulation of $PM_{2.5}$ at substantially higher resolution than in the underlying climate model. We calculate human health impacts of pollution exposure changes using established methodologies based on epidemiological studies characterizing both median estimates and uncertainty ranges, and also calculate impacts without assuming low exposure thresholds (see Methods).

Accelerating CO_2 reductions, either in addition to or instead of negative emissions, leads to substantial decreases in adverse health impacts (Figure 2). Premature deaths due to $PM_{2.5}$ exposure decline greatly in both scenarios, but markedly earlier and by considerably more in the accelerated CO_2 reduction scenarios, which have less than half as many cumulative deaths. In contrast, total deaths due to ozone exposure only decrease in the last decades of the 21st century in the standard scenarios, whereas they decline greatly under the accelerated CO_2 reductions. Ozone-related premature deaths drop to near-zero around 2080 under the accelerated scenario due to the assumption of a lower threshold for impacts (see SI.4). Under the standard scenario, premature deaths from ozone remain high despite emissions decreases due to population growth, as in prior studies [17], and as ozone decreases more slowly than $PM_{2.5}$ they account for more than one-third of all air quality-related premature deaths from the 2050s onward, suggesting increased focus on ozone reductions may be warranted.

Integrated over 2020 through 2100, the accelerated CO_2 reduction scenarios would prevent 153±43 million premature deaths worldwide, with 93±41 million attributable to reduced $PM_{2.5}$ and 60±18 million to ozone (uncertainties represent exposure-response relationships and modeled biases; the former is typically greater [18]). Without including low exposure thresholds (see SI.4), values are modestly greater at 99±27 million for $PM_{2.5}$ and 75±22 million for ozone.

Unsurprisingly, benefits are especially large in regions with high current levels of pollution, such as South Asia, Indonesia, China, and Nigeria (Figure 3). Individual urban centers are visible around the world (Figure 4). Given the importance of local scale information to the public, illustrative avoided premature deaths for major metropolitan areas are presented in Table 1. Values over 900,000 occur around many large cities in South and East Asia, but also in Nigeria and in Cairo. Metropolitan area values are less certain than global totals, however, and are also quite sensitive to the choice of whether or not to include low exposure thresholds (see SI.4).

We also considered the climate implications of NoNegRCP2.6 relative to RCP2.6. As the cumulative CO_2 emissions were by design the same, the only impact of CO_2 itself is from the slightly earlier net emissions reductions (required due to the absence of net negative emissions towards the end of the century), leading to negative radiative forcing relative to 2010 peaking at −0.13 W m^{-2} in the 2040s, turning to weak positive forcing (~0.04 W m^{-2}) during the 2090s. Co-emissions of course changed substantially, causing positive aerosol forcing throughout the 21^{st} century of at most +0.23 W m^{-2} (direct plus indirect effects on clouds), negative forcing due to ozone decreases (primarily tropospheric) of at most −0.09 W m^{-2}, and a forcing due to methane of up to +0.06 W m^{-2} attributable largely to reduced oxidation (methane's residence time increases by ~10%, and this effect outweighs reduced emissions). Net non-CO_2 forcing is at most +0.21 W m^{-2} (see SI.6).

CO_2 and non-CO_2 forcings offset one another during the coming decades, so total forcing is less than 0.03 W m^{-2} through 2060. Total forcing is weakly positive, from 0.1 to 0.25 W m^{-2}, from 2075 to 2100 however, which would mostly have an impact in the 22^{nd} century, leading to an additional warming of ~0.1–0.2°C. Factors such as potentially reduced fertilizer production and albedo decrease associated with the lack of BECCS merit further study, and the positive aerosol forcing may lead to larger changes at regional scales, but at present we conclude that there appears to be little 'climate penalty' due to co-emissions under an accelerated CO_2 mitigation scenario.

As there is great socio-economic resistance to reducing positive emissions to near zero [2], it is extremely important to have a full picture of the opportunities and challenges of such trajectories. Much information is already available, e.g. the costs of 1.5°C relative to 2°C scenarios are estimated to be roughly 1 to 2% of world GDP [19]. To put our results in perspective, the OECD estimated losses of 0.55% of world GDP (market costs due to labor,

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capital, heath care expenditures, and agriculture) due to a projected increase of 2.4 million annual premature deaths related to air quality from 2030 to 2060 [20]. Hence our estimated reductions of 2060 premature deaths yr^{-1} of ~2.4 million (Figure 2) might be expected to avert market losses of ~0.5–0.6% of world GDP, a substantial portion of the mitigation costs (with benefits persisting into the future). Accompanying these benefits would be non-market health benefits and reduced climate change impacts (e.g. [21, 22]), including additional human health benefits associated with decreased climate change [15]. Our results contribute new knowledge by showing that ~150 million air quality-related premature deaths could be prevented by increasing ambition in carbon emissions reductions and hence quantify the human costs of reliance on negative emissions to achieve 2°C (or reliance upon geoengineering to compensate for inadequate carbon reductions). They further suggest such impacts are not simply proportional to SO_2 emissions (see SI.5).

Results are dependent upon assumptions regarding technological development and population trends, and the presumed offset between projected population aging and improved baseline health (see Methods). They are also sensitive to physical uncertainties such as how climate change affects pollutant lifetimes and how population exposures relate to large-area ambient concentrations, and on biological uncertainties associated with exposure-response functions. Hence results should not be regarded as predictions, particularly at local scales. Growing urban populations would certainly reap large air quality-related health benefits from decreased use of fossil fuels over the century, however, with indicative magnitudes presented here.

Near-term public health information resonates more strongly with most people than many more widely known impacts of a transition to a low-carbon economy. That is, most people can relate more directly to preventing millions of premature deaths during the next few decades than to preventing a half a degree of warming in 80 years. Furthermore, information about local consequences such as the number of potential lives saved in one's own city is easier to understand than remote or global change such as the consequences of melting of polar ice sheets or biodiversity loss in remote regions. Even though public health impacts are also statistical, given the large populations in metropolitan regions we can quantify the number of premature deaths prevented in a particular decade in a way that is generally not possible for many climate change impacts. Thus this information may help both the public and policy makers to better grasp the benefits of accelerating carbon reductions in the near-term, alongside the well-documented costs, the tradeoffs associated with reliance on negative emissions, and to incorporate these alongside climate information in decision-making regarding the transition to a low carbon economy.

Methods

Emission Scenarios

The most widely studied scenario consistent with 2°C is the Representative Concentration Pathway 2.6 (RCP2.6) [23]. This scenario is the only one of the marker scenarios used in the Intergovernmental Panel on Climate Change's Fifth Assessment Report (IPCC AR5) that had a substantial probability of achieving the 2°C target. As cumulative CO_2 emissions were already ~560 GtC by 2016, only ~260 additional GtC can be emitted on a 2°C path. Net CO_2

emissions under the RCP2.6 scenario are ~220 GtC for the remainder of the century (2017–2100), and consistent with those emissions being somewhat below the allowable budget the mean temperature response projected by climate models is likewise ~0.1–0.2°C below 2°C. Negative emissions are assumed to begin in the 2030s in this scenario. Their magnitude is assumed to increase rapidly while the magnitude of positive emissions declines so that net CO_2 emissions become negative during the 2070s.

To create the emissions associated with the NoNegRCP2.6 scenario, we first derived the amount of positive CO_2 emissions embodied in the RCP2.6 scenario, then phased in a reduction in those emissions that compensates for the absence of massive deployment of negative emissions technologies. We assume the reduction of positive emissions is ramped up rapidly beginning in the 2020s with emissions decreasing by 25% in 2030 and by 90% in 2100 (relative to the positive emissions in the RCP2.6 scenario; see Figure 1). Achieving such deep reductions in CO_2 emissions would require cuts in emissions from all major sectors, so we apply these reductions to energy, industry, transportation, residential and shipping emissions. We do not alter emissions from solvents, aviation, agriculture, agricultural waste burning, waste management or wildfires as these sectors either are not major emitters of CO_2 (e.g. solvents, agricultural waste burning) or it remains unclear how deep reductions such as those envisioned here could be achieved while still providing the needed services (e.g. aviation providing long-distance transportation, agriculture providing adequate food for an increasing population). Our scenario is qualitatively consistent with modeling showing that 1.5°C scenarios require large increases in the pace and amount of decarbonization of energy sectors [19]. We assume that emissions are reduced by greater reliance on renewable energy along with end-use electrification and hence the CO_2 emissions reductions are accompanied by reductions in co-emitted pollutants (Figure S4). We include a minimal amount of negative CO_2 emissions (8 GtC, e.g. via improved land-management) along with accelerated carbon emissions reductions to produce 220 GtC cumulative 21st century emissions as in RCP2.6, and hence approximately the same temperature change as RCP2.6. The comparison between RCP2.6 and NoNegRCP2.6 therefore yields the impact of accelerating cuts in carbon emissions rather than relying upon negative emissions or carbon offsets to achieve the same warming. Emissions of all pollutants are based on the RCP2.6 scenario that projected emissions across world regions by sector and then provided gridded estimates at 0.5 × 0.5 degree resolution.

In our alternative 'reference' 2°C scenario, 75% of the negative emissions assumed under RCP2.6 are achieved, leading to ~265 GtC additional cumulative emissions and 2°C warming. As the only difference between these scenarios is the smaller assumed negative CO_2 emissions, we therefore maintain all other pollutant emissions at identical levels (e.g. there is less C removal via land management, or less deployment of BECCS is substituted for by C-neutral renewables, either way with minimal effect on any other emissions).

The 1.5°C scenario maintains the 75% of assumed negative emissions as in 2°C which, along with the accelerated positive carbon emissions reductions from the NoNegRCP2.6 scenario, yields ~85 GtC additional cumulative 21st century emissions. Hence the only difference between these scenarios is the assumption regarding negative emissions, and we therefore again keep emissions of all other pollutants constant (both have much lower emissions of non-CO_2 co-pollutants than the RCP2.6 and 2°C scenarios). Thus, comparisons of either the scenarios with changing temperature outcome but both with substantial negative CO_2 emissions (2°C versus 1.5°C) or the accelerated reductions replacing negative emissions (NoNegRCP2.6 versus RCP2.6) have the same impacts on co-emissions and hence on human health due to air pollution.

Our scenarios eliminate 180 GtC cumulative positive emissions, reducing warming by ~0.5°C, and we note that the results are thus generally applicable to other low carbon scenarios with equivalent carbon reductions. That is, our comparisons reveal the health impacts of eliminating the lowest 180 GtC from energy systems that would be imposed upon whatever similar baseline other policies brought us to (e.g. 2°C versus 2.5°C, or 1.5°C without negative emissions versus 1.5°C with negative emissions). These results hold for the multiple cases discussed here because strengthening reduction of positive CO_2 emissions beyond RCP2.6 essentially must also greatly reduce co-emitted pollutants, as virtually all remaining combustion-related emissions are eliminated. Mitigation strategies applied to higher baseline scenarios have a different mix of available mitigation options, but would likely give qualitatively similar results. The relationship between emissions of CO_2 and traditional air pollutants is less clear for higher CO_2 trajectories due to differing socio-economic and technological assumptions among the underlying integrated assessment models (IAMs) generating the scenarios. For example, RCP4.5 leads to fewer air pollution-related premature deaths than RCP2.6 whereas RCP6.0 has only a modestly larger amount [17] despite their CO_2 emissions following the target forcing reasonably closely. The differences between the higher and lower scenarios explored here, however, are robust to these types of assumptions as they all assume low carbon baselines.

Atmospheric Modeling

Simulations were performed using the global composition-climate model GISS-E2 [24, 25] to evaluate radiative forcing and surface concentration of air pollutants. The model was run for two years once per decade with results linearly interpolated between the second simulated year in each period. Climate change over the 21st century was incorporated. Fixed meteorology was used in each pair of reference and reduced-emissions simulations, eliminating meteorological noise but restricting aerosol-cloud (indirect) forcings to cloud-albedo effects and excluding cloud-lifetime changes. This has been shown to be a reasonable approximation of the full aerosol-cloud forcing in our model [26].

We utilize high-resolution emissions data so that emissions alter not only constituent masses but also the first- and second-order horizontal gradients used to allow realistic transport of constituents (as well as heat and momentum) [27], and we incorporate chemical transformation from sulfur dioxide into sulfate aerosol into those gradients. We then calculate surface $PM_{2.5}$ distributions incorporating the first- and second-order horizontal gradients of all aerosol constituents. This allows us to simulate $PM_{2.5}$ distributions at 0.5 × 0.5 degree resolution despite the climate model's native resolution being only 2 × 2.5 degrees, allowing us to better resolve urban centers and thereby map population exposures (see SI.1). Ozone is simulated only at 2 × 2.5 degrees, and we perform bias corrections to account for the model's tendency to overpredict surface concentrations. Model biases are shown to nearly always play a smaller role than uncertainties related to health effects (see SI. 1, SI.3).

Health Impact Methodology

Premature deaths are calculated as $M_i = M_b \times P \times AF_i$, where M is the number of premature deaths due to ozone or $PM_{2.5}$, M_b is the cause-specific baseline mortality rate, P is population, and AF_i is the cause-specific attributable fraction of deaths due to $PM_{2.5}$ or ozone, all for simulation *i*. AF can be expressed in terms of relative risk (RR) as AF=(RR-1)/RR. For $PM_{2.5}$, we incorporate the substantial range in reported relative risk functions by using 1000 variants within an integrated exposure-response model that includes impacts of $PM_{2.5}$ on ischemic heart disease, cerebrovascular disease (stroke), chronic obstructive pulmonary disease, lung cancer, and acute lower respiratory infection [28]. This model provides median estimates as well as uncertainty ranges, for which we use the 95% confidence interval based on the variation across the 1000 functions specified for each cause. Among the causes, ischemic heart disease is the largest. We calculate impacts both including and excluding a low exposure threshold (see SI.4).

For ozone, we rely on a recent analysis of the association of long-term ozone exposure with premature death from circulatory and respiratory diseases as this study included more than double the number of participant deaths than in prior studies [29]. The circulatory (including diabetes) RR has a value of 1.03 (95% CI, 1.01–1.05), whereas the respiratory RR has a value of 1.12 (95% CI, 1.08–1.16) per 10 ppb increase in the mean annual daily 8-hr maximum concentration. These 95% confidence intervals are used to characterize uncertainties. The lowest exposures in the study were 26.7 ppb, which was hence used as a threshold. Since the RR for respiratory disease is much larger than in prior studies, we also analyzed ozone-health impacts using ‘legacy’ methods for context, and as for $PM_{2.5}$ we also calculated impacts without low exposure thresholds (see SI.4). As with prior ozone exposure-response relationships, epidemiological data comes from developed countries and additional studies covering the higher exposures in many developing nations would be valuable.

To put our results into context, we performed 2010 simulations and evaluated the health impacts of air pollution. Ambient pollution leads to 4.2±1.0 million premature deaths (3.6±1.0 million from $PM_{2.5}$ including thresholds, 0.6±0.1 from ozone using ‘legacy’ methods) based on our model results, within the range of 3.0 million per year estimated by the World Health Organization [30] and 4.3 million (average of 2005 and 2015 values) estimated by the Global Burden of Disease [12] using comparable ‘legacy’ methods for ozone. With the increased relative risk functions based on the newer, larger sample, unsurprisingly total ozone-related premature deaths are greater at 1.0±0.3 million (using a threshold). Our value for respiratory-related premature deaths due to ozone using this updated methodology [29] is 0.6±0.2 million for 2010, and 1.0±0.3 million without bias adjustment, the latter consistent with the value of 1.0–1.2 million reported by a recent study using the same epidemiology and ozone from a different model without any bias-adjustments (see SI.4). Without thresholds, 2010 deaths due to $PM_{2.5}$ and ozone are 5.0±1.2

and 2.8±0.9 million, respectively, which are 2.9±0.8 and 1.5±0.6 million more than 2010 values based on preindustrial concentrations.

For future cases, projected changes in population are included based on country-level data for a medium fertility scenario [31]. Changes in baseline mortality rates were not included here as these are poorly constrained, are not available for scenarios fully consistent with the underlying emissions, and appear less important than demographic changes in the case of $PM_{2.5}$ [17, 32]. Population aging, which is estimated to affect IHD and stroke modestly [28], was also excluded as this appears to roughly offset changes in baseline mortality in another study [33]. Furthermore, as the burden of disease shifts from infectious to chronic in developing countries while health care spending and technology advance, baseline changes can be of either sign: e.g., they increase ozone-related mortalities but decrease $PM_{2.5}$-related deaths in one analysis [17].

Data Availability

Emissions are available from: http://tntcat.iiasa.ac.at:8787/RcpDb/. Baseline health and population data are available from the World Health Organization [30] and the United Nations [31], respectively. The NASA GISS ModelE2 is available at: https://www.giss.nasa.gov/tools/modelE/. Data from composition-climate modeling that support the findings of this study are available from the corresponding author upon request.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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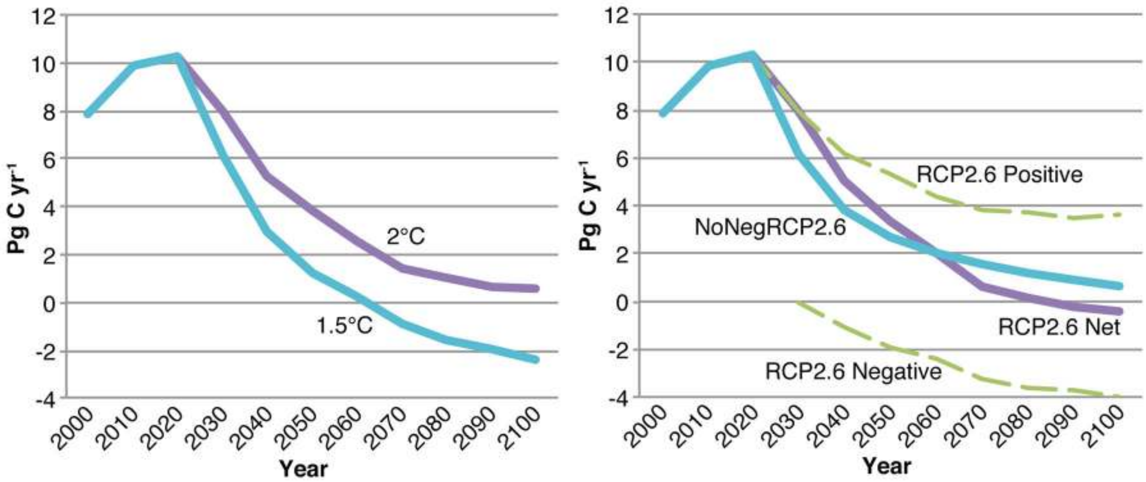

Figure 1.

CO_2 emissions in the four scenarios used here. Net CO_2 emissions are shown for the 2°C, 1.5°C and NoNegRCP2.6 scenarios whereas both net and separate positive and negative values are shown for the original RCP2.6 scenario. Note that NoNegRCP2.6 net and NoNegRCP2.6 positive are nearly identical.

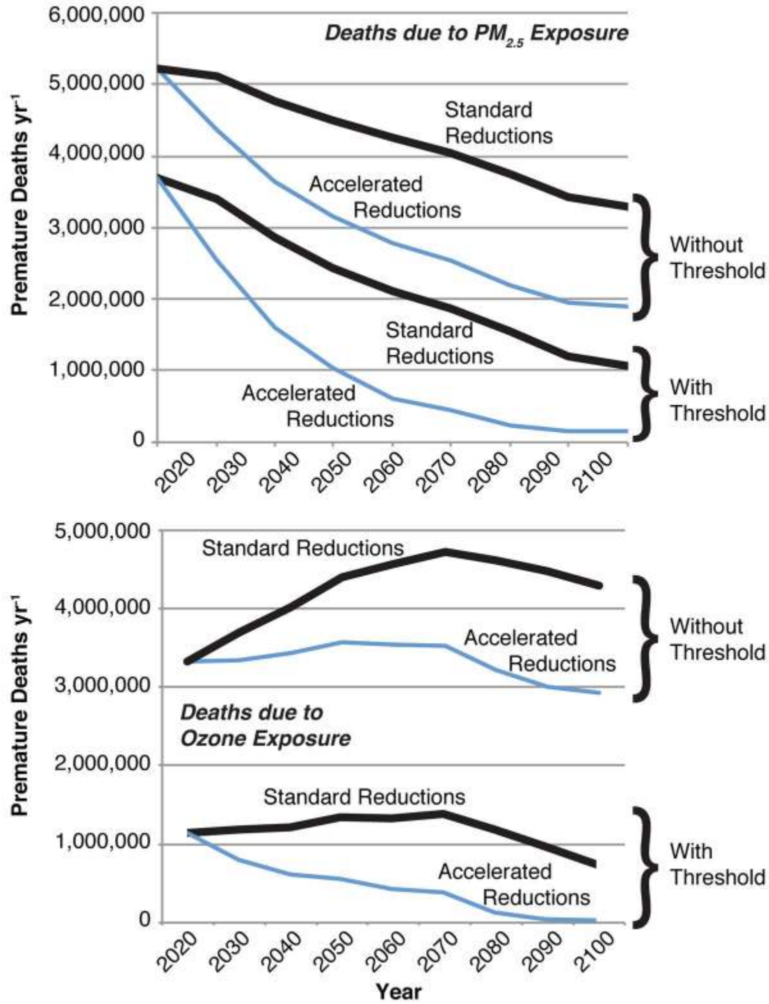

Figure 2.

Global total annual premature deaths (all-cause) due to $PM_{2.5}$ and ozone exposure. Values are given for the standard scenarios (RCP2.6 and 2°C) and under those with accelerated CO_2 emissions reductions (NoNegRCP2.6 and 1.5°C) both assuming low exposure thresholds below which there are no impacts and without such assumptions (in the latter case, comparisons to preindustrial levels would reduce values by 2.2 and 1.6 million in 2020 for $PM_{2.5}$ and ozone, respectively).

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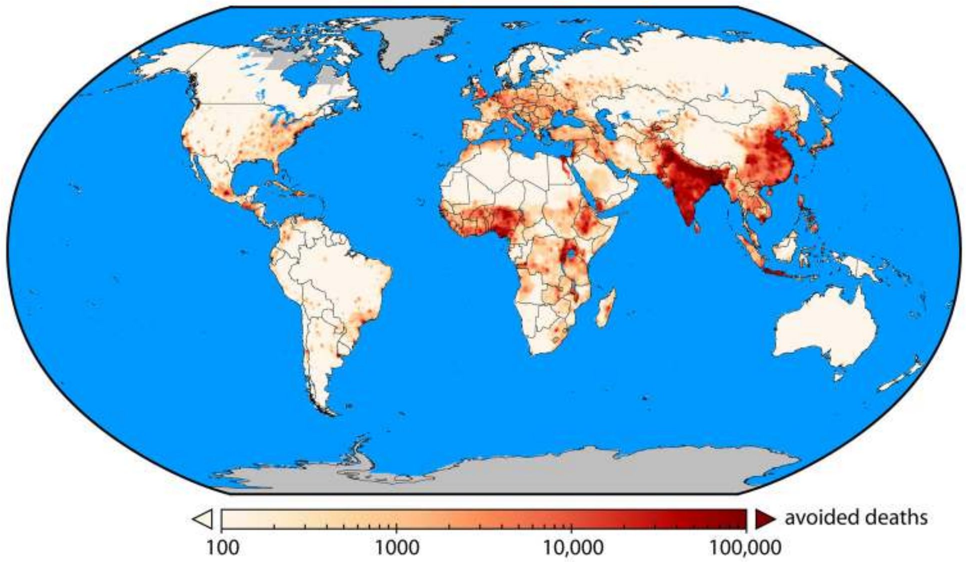

Figure 3.

Reduction in annual premature deaths due to $PM_{2.5}$ and ozone over 2020–2100 from co-emissions accompanying accelerated CO_2 emissions reductions. Values are all-cause per 0.5 × 0.5 degree area (~50 × 50 km at mid-latitudes) without low exposure thresholds.

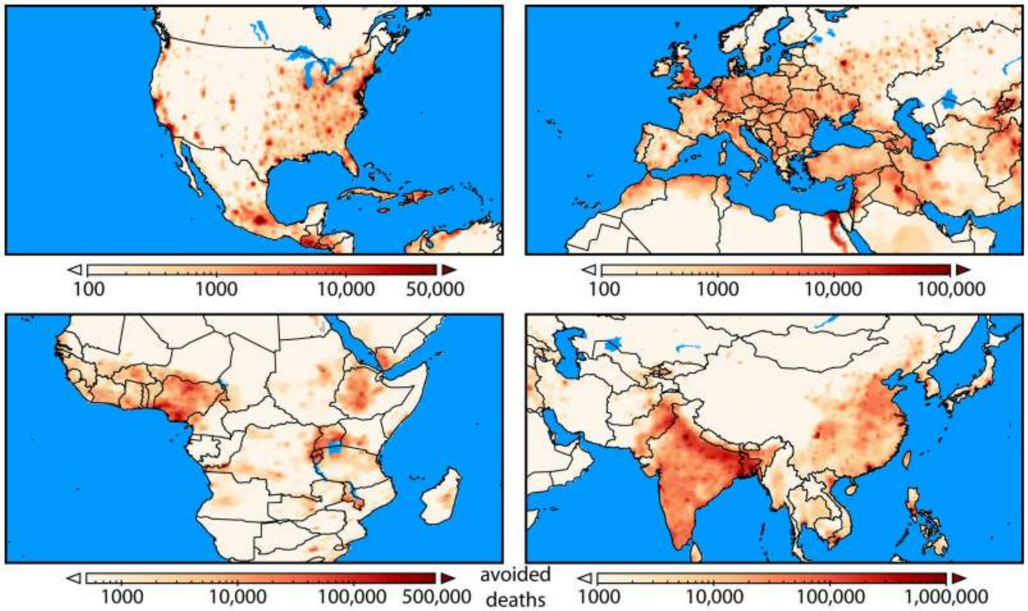

Figure 4.

Regional highlights of reduction in annual premature deaths due to $PM_{2.5}$ and ozone over 2020–2100 as shown in Figure 3. Note change in range between panels.

Table 1

Health benefits due to reduced $PM_{2.5}$ and ozone exposure over 2020–2100 attributable to co-emissions accompanying accelerated CO_2 emissions reductions for metropolitan areas with over 1.5 million current population. These are illustrative values from calculations including low exposure thresholds.

Metropolitan Area	Avoided premature deaths
Kolkata	4,400,000
Delhi	4,000,000
Dhaka	3,600,000
Patna	3,200,000
Lahore	2,600,000
Mumbai	2,000,000
Faisalabad	2,000,000
Lucknow	1,900,000
Ibadan	1,900,000
Agra	1,800,000
Jakarta	1,600,000
Kanpur	1,500,000
Lagos	1,400,000
Bandung	1,100,000
Dongguan	1,100,000
Guangzhou	930,000
Cairo	930,000
Ludhiana	870,000
Pune	850,000
Ahmedabad	830,000
Shanghai	800,000
Vadodara	800,000
Rawalpindi	750,000
Hanoi	690,000
Hyderabad	690,000
Chittagong	680,000
Shenzhen	670,000
Karachi	630,000
Saidu	620,000
Nagpur	590,000
Manila	590,000
Chennai	530,000
Zhengzhou	510,000
Ho Chi Minh City	490,000
Surat	490,000
Kinshasa	490,000
Hong Kong	490,000

Metropolitan Area	Avoided premature deaths
Jaipur	470,000
Indore	440,000
Xuzhou	440,000
Suzhou	430,000
Taian	400,000
Wuhan	390,000
Hangzhou	390,000
Tokyo	360,000
Bangalore	360,000
Beijing	360,000
Additional urban areas	See Table S1

Uncertainties are estimated at ±50–55% for metropolitan area values based on exposure-response relationship uncertainties and modeling uncertainty evaluated from the mean absolute bias relative to observations for a given health methodology (with or without low exposure thresholds). Note that model biases for $PM_{2.5}$ tend to be fractionally larger in more polluted areas, but the $PM_{2.5}$ exposure-response curve is less sensitive at high exposure levels so that overall uncertainty is fairly uniform across regions. City locations obtained from http://simplemaps.com/data/world-cities#anchor_updates (downloaded 20 April 2017). Metropolitan areas are defined here as 1.5 × 1.5 boxes incorporating the city located within the central 0.5 × 0.5 degree grid. Some neighboring cities have been combined but some areas shown here may overlap.