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The legacy of the U.S. Clean Air Act at a crossroads

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Chronic and acute exposure to elevated concentrations of ambient fine particulate matter represents a significant health risk. Here, we evaluate the avoided air pollution due to the U.S. Clean Air Act and the potential of the 2016 Paris Agreement to improve air quality in the contiguous U.S. The current weakening of federal agencies in the U.S. will degrade environmental quality, induce sickness and death, and incur costs.

Globally, chronic and acute exposures to elevated concentrations of ambient fine particulate matter ($PM_{2.5}$) represent a significant risk factor for non-communicable diseases and increased premature mortality. Typical morbidities include chronic rhinosinusitis, respiratory diseases, and worsening cardiovascular health due to oxidative stress and systematic inflammation[1]. $PM_{2.5}$ mass is associated with cognitive decline as well as neurological dysfunction, such as Alzheimer's, Parkinson's, and autism spectrum disorder[2,3]. The U.S. Environmental Protection Agency (EPA) presently sets health-based National Ambient Air Quality Standards (NAAQS) for $PM_{2.5}$ at values of 9 $\mu g\ m^{-3}$ for the annual average, and 35 $\mu g\ m^{-3}$ for the daily 24-hour average. World Health Organization (WHO) guidelines for $PM_{2.5}$ are more stringent. The WHO recommends that the ambient annual average mass concentration not exceed 5 $\mu g\ m^{-3}$ and the 24-hour average not exceed 15 $\mu g\ m^{-3}$. In reality, there is no documented safe level for $PM_{2.5}$ exposure.

Most $PM_{2.5}$ mass forms in the atmosphere from reaction products of precursor gases that condense and change phase. Predominant inorganic gaseous species that contribute to $PM_{2.5}$ are nitrogen oxides ($NO_2 + NO = NO_x$), sulfur dioxide (SO_2), and ammonia (NH_3). Acute exposure during severe air pollution events in the U.S. associated with $PM_{2.5}$ formation resulted in premature deaths (e.g., Donora, PA in 1948) similar to other catastrophes such as the great London smog in 1952[4]. Such events helped spur the creation of the EPA, passage of the 1970 Clean Air Act (CAA), and later its amendments. Under the CAA, EPA regulates air pollution through airshed-based approaches with health- and ecosystem-based NAAQS, and with emission limits and performance standards for most controllable source sectors. Early EPA rules reduced NO_x and SO_2 emissions to avoid exceedances of the ozone NAAQS and to ameliorate the deleterious impacts of acid rain, respectively. Ancillary benefits include dramatic reductions in domestic surface level $PM_{2.5}$ mass concentrations, primarily a consequence of reduced particulate sulfate in the Eastern U.S. Here, we estimate the annual mortality from chronic exposure to air pollution for a counterfactual scenario where the EPA did not enforce the 1970 CAA relative to present-day air quality conditions. We explore ancillary health benefits from improved air quality should the U.S. achieve net-zero electricity production and complete electrification of the transport sector, roughly equal to a 50% emission reduction outlined in the international treaty on climate change, the 2016 "Paris Agreement". We specifically consider rural areas where air quality for $PM_{2.5}$ is not improved to the same degree as for high population areas[5], the NH_3 burden continues to rise, and the agricultural source sector is largely unregulated federally.

Current air quality

Routine surface $PM_{2.5}$ network monitors have recorded dramatic reductions in mass concentrations since 1999, most notably in the eastern U.S.[5] Yet, despite decades of successful air quality rules, only a handful of monitoring locations record annual averages below the 5 $\mu g\ m^{-3}$ WHO annual guideline. Several monitors routinely record concentrations above 9 $\mu g\ m^{-3}$, which exceed the EPA's current $PM_{2.5}$ annual NAAQS value. EPA's atmospheric photochemical model, the Community Multiscale Air Quality (CMAQ) model, also employed by National Oceanic and Atmospheric Administration (NOAA) for forecasting air quality, improves upon the spatial limitations of monitoring networks and provides $PM_{2.5}$ mass concentration estimates for all locations in the contiguous U.S. (CONUS) as applied here. CMAQ exhibits high predictive skill when compared to surface $PM_{2.5}$ mass recorded by routine monitoring networks (Fig. 1a). CMAQ indicates widespread non-attainment of WHO recommendations in densely populated regions, such as southern California, and East Coast metropolitan areas, in addition to more sparsely populated agricultural regions in the Central U.S. and California's San Joaquin Valley. This suggests widespread adverse health endpoints for urban and rural U.S. populations alike. EPA's Environmental Benefits Mapping and Analysis Program (BenMAP) model predicts that the present-day air quality in the 'current' CMAQ simulation is associated with approximately 186,000 premature U.S. deaths each year due to the annual burden of $PM_{2.5}$. This fatality rate constitutes nearly one-third of all heart disease-related deaths, the leading cause of death in the U.S., and exceeds the number of all unintentional accidental deaths combined[6]. Detailed discussion regarding uncertainties in these estimates is provided in the supplemental information (Table S1).

Air avoided – a success story

Air quality and the associated health impacts in the contiguous U.S. would be significantly worse had the 1970 CAA and its amendments not been implemented, especially the $PM_{2.5}$ NAAQS (Fig. 1b). In such a scenario, the WHO-recommended annual average $PM_{2.5}$ mass would be exceeded everywhere in the Eastern U.S., as well as in many densely populated locations such as California, Oregon, Washington. The 24-hour average ambient $PM_{2.5}$ mass concentrations would frequently exceed 100 $\mu g\ m^{-3}$ across the CONUS (Fig. S1). Exceedances of the daily WHO recommendation of 15 $\mu g\ m^{-3}$ would be the norm rather than the exception (Fig. S2). The air avoided is associated with 298,000 additional excess deaths each year relative to current U.S. air quality. This air quality-induced mortality rate (484,000 deaths per year) is approximately half of the yearly U.S. cancer-related deaths and about twice as many respiratory system cancer deaths[6].

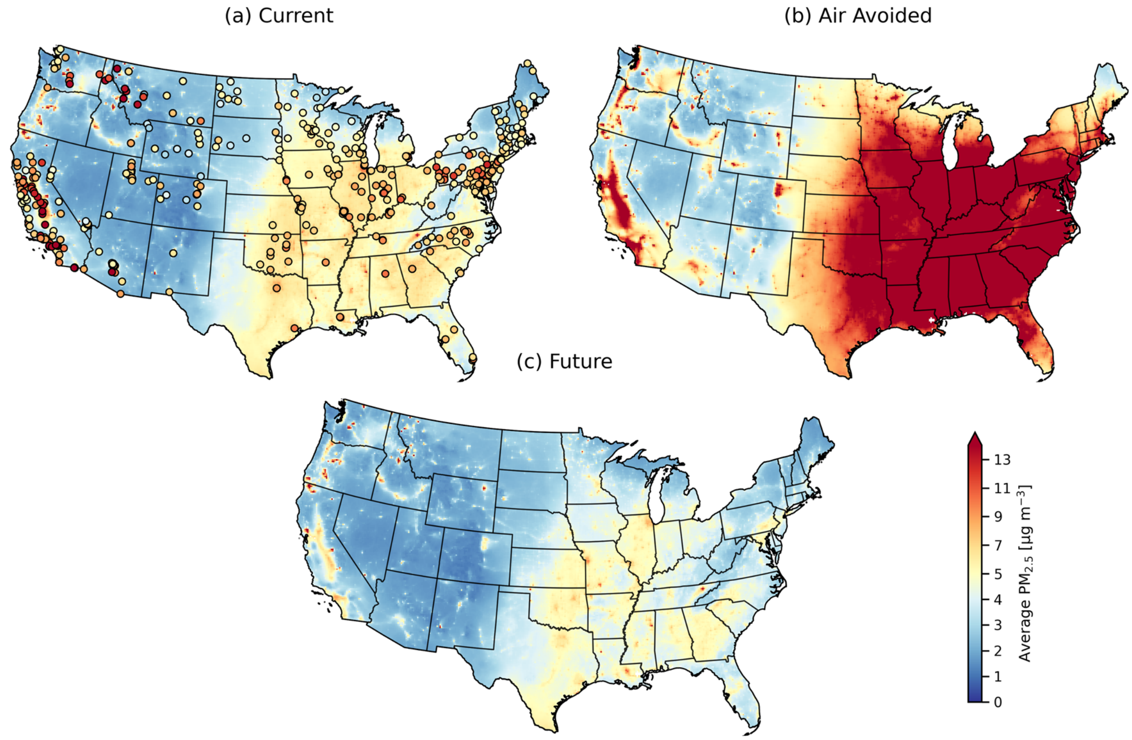

Fig. 1 | Annual average $PM_{2.5}$ mass concentration for three emission scenarios. The emission scenarios are: **a** current air quality including CAA policies, **b** no adaptation of any CAA policy, and **c** CAA implemented with net-zero emissions from transport and energy production. The colormap is centered around the annual WHO exposure recommendations of 5 µg m^{-3}, where blue and red colors indicate regions below and above 5 µg m^{-3}, respectively. For the current air quality (**a**), the annual average of $PM_{2.5}$ mass concentration reported by the Air Quality System is displayed, which contains data collected by EPA, state, local, and tribal air pollution control agencies. We display all observation stations that have reported data for at least 10 months.

The number of avoided deaths is highest in densely populated counties, with the greatest number occurring in Chicago, IL (Cook County), New York City, NY (e.g., Queens), and Los Angeles, CA (Fig. 2). The highest number of additional annual deaths by state occur in Pennsylvania, New York, and Ohio at a rate of more than 18,000 each year (Table S2). In addition to avoided deaths, hospitalization rates, Medicare, and Medicaid costs would also be substantially greater[7]. Precise extrapolation of subsequent socio-economic impacts is difficult to explicitly quantify, but continued substantial acidic deposition (Fig. S3) would have further contributed to acidification of soil and surface waters, a decline in forest and vegetation cover, and damage to buildings, infrastructure, and agriculture[8,9]. Other societal impacts, such as the frequency and duration of school closures that occur during severe air pollution events today, incur costs that are not calculated here.

Future – The power of the 2016 Paris Agreement

The emission sources that contribute to global warming are the same that lead to poor air quality. In light of the ongoing climate emergency, the U.S. pledged to reduce greenhouse gas emissions by 50% of the 2005 (base year) level by 2030 to prevent a global average temperature increase above 2 °C compared to pre-industrial levels[10] in accordance with the Paris Agreement of 2016, signed on April 22, 2016. The U.S. recently reversed course on its commitment for a second time. A significant decrease in anthropogenic emissions for a climate impetus can also improve air quality. In the U.S., the electricity, transportation, and agriculture sectors are the dominant sources of greenhouse gases (GHG), collectively accounting for more than 60% of all domestic GHG emissions[11]. In an ambitious scenario, where the U.S. attains net-zero emissions for both the electricity generation and transportation sectors, substantial improvement in ambient $PM_{2.5}$ mass concentration is predicted, most dramatically in urban locations (Fig. 1c). We estimate that the U.S. withdrawal from the Paris Agreement will cost nearly 65,000 premature deaths each year in the U.S. Counties with high population densities will bear much of the excess mortality (Fig. 2).

Interestingly, agricultural regions such as the Midwest, Southeast, and Central Valley of California, have the worst air quality in the future CMAQ scenario that considers climate goals. Agricultural NH_3 emissions are approximately 90% of the total U.S. NH_3 inventory[11] and occur largely in the absence of federal regulation. Emissions reductions for NH_3, a key ingredient of $PM_{2.5}$, and a toxic pollutant, may be warranted to safeguard human health in rural areas. European Union members have set a target to reduce agricultural NH_3 emissions by 19% by 2030 relative to 2005 emissions. A recent air quality modeling study finds that meeting the interim target for 2020, a 6% reduction in total European agricultural NH_3 emissions, reduces $PM_{2.5}$ mass concentrations in Central Europe substantially. The economic benefits from avoided premature deaths exceed the cost of compliance with the NH_3 regulations[12]. This is suggestive that air quality strategies for agriculture are cost-effective. Further, in the U.S., agriculture is the largest source of methane and nitrous oxide, potent greenhouse gases, but the sector is often exempt from international climate agreements. Effective policies to mitigate agricultural air pollution and the extent to which cost

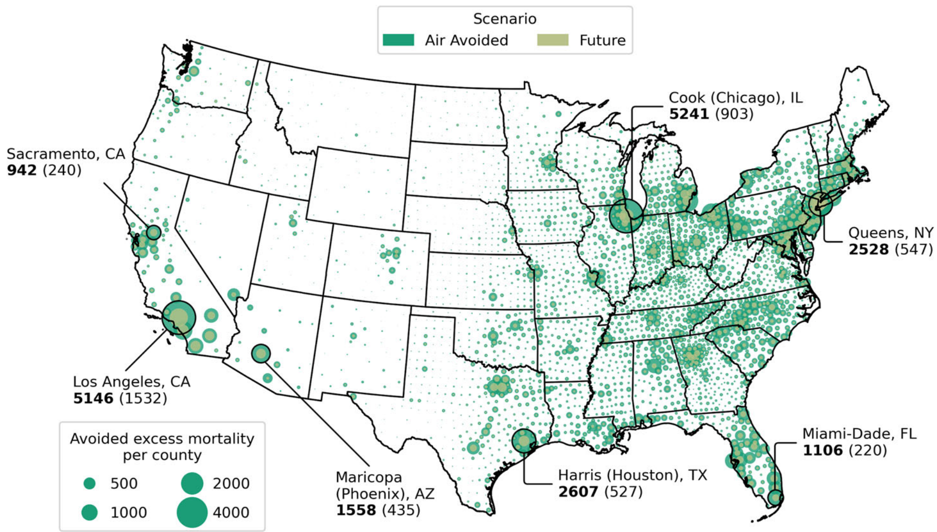

Fig. 2 | Annual avoided excess mortality for the Air Avoided and the Future emission scenario. Each county is represented by a green circle, for which the circle size is scaled to the number of annual avoided deaths. For a selection of counties, the actual number is displayed in bold and parentheses for the Air Avoided and Future scenario, respectively. Figures S4, S5 provide individual representations for each emission scenario.

considerations should play a role in policy development are important topics for future study.

Climate and air quality crossroads

Independent federal science, such as the tools and models used in this work, safeguards human health and the environment. A weakening of federal agencies will degrade environmental quality, increase sickness and death, and incur costs. Such burdens will add to rising environmental and climate-related stresses. For example, wildland and infrastructure fires continue to increase in frequency, duration, and severity[13]. U.S. regions subject to exceptional fire events frequently exceed the WHO 24-hour average guideline for acute exposure to $PM_{2.5}$ by almost an order of magnitude. It is anticipated that such exceptional events will become sufficiently more frequent in some regions to perturb annual average $PM_{2.5}$ mass concentrations[14]. Large-scale wildland and infrastructure fires are not a direct consequence of federal policy, and are challenging to control. Air quality and climate questions in a changing global context include: To what degree should the government limit controllable emissions from all sectors? Do we want to save lives at risk from poor environmental quality? And to what extent should cost be a factor?

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Author contributions

S.R. and A.M.C. conceptualized this study. S.R. performed the simulation and their analysis. S.R. and A.M.C. wrote the manuscript.

Competing interests

The authors declare no competing interests.

Additional information

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