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Health and economic cost estimates of short-term total and wildfire $PM_{2.5}$ exposure on work loss: using the consecutive California Health Interview Survey (CHIS) data 2015–2018

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ABSTRACT

Instruction To help determine the health protectiveness of government regulations and policies for air pollutant control for Americans, our study aimed to investigate the health and economic impacts of work loss due to sickness associated with daily all-source and wildfire-specific $PM_{2.5}$ (particulate matter with an aerodynamic diameter smaller than 2.5 µm) exposures in California.
Methods We linked the 2015–2018 California Health Interview Survey respondents' geocoded home addresses to daily $PM_{2.5}$ estimated by satellites and atmospheric modelling simulations and wildfire-related $PM_{2.5}$ from Community Multiscale Air Quality models. We calculated and applied the coefficient for the association between daily $PM_{2.5}$ exposure and work loss from regression analyses to the Environmental Benefits Mapping and Analysis Program—Community Edition (BenMAP-CE) platform to assess the health and economic impacts of $PM_{2.5}$ exposure on work loss due to sickness.
Results We observed that each 1 µg/m^3 increase in daily total $PM_{2.5}$ exposure will lead to about 1 million days of work loss per year ranging from 1.1 to 1.6 million person-days, and the related economic loss was \$310–390 million. Wildfire smoke alone could contribute to 0.7–2.6 million work-loss days with a related economic loss of \$129–521 million per year in 2015–2018. Using the function coefficient in the current BenMAP, the excess work-loss days due to sickness was about 250 000 days and the estimated economic loss was about \$45–50 million for each 1 µg/m^3 increase in daily total $PM_{2.5}$ exposure, and wildfire smoke alone would lead to 0.17–0.67 million work-loss days with related economic loss of \$31–128 million per year during the same period.
Conclusions Both conventional and wildfire-specific sources of $PM_{2.5}$ produced substantial work loss and cost in California. Updating the current BenMAP-CE calculations for work-loss days will be essential in quantifying the current health impacts of $PM_{2.5}$ to help inform the policies and regulations to protect public health.

WHAT IS ALREADY KNOWN ON THIS TOPIC

⇒ Many studies have investigated the association between various health outcomes from $PM_{2.5}$ (particulate matter with an aerodynamic diameter smaller than 2.5 µm) exposure, but there are still uncertainties on the full extent of the acute health impact of short-term PM exposure such as work loss due to sickness (ie, headache) that was not severe enough to warrant admission to an emergency or hospital; thus, it could not be fully incorporated into the calculation of air pollution exposure-associated health and economic cost.

WHAT THIS STUDY ADDS

⇒ We evaluated the health and economic impacts related to short-term $PM_{2.5}$ exposure (both all-source and wildfire-specific) on work loss due to sickness in California and developed better estimates for work-loss days due to $PM_{2.5}$ exposures for Californians than the current estimates used in the Environmental Benefits Mapping and Analysis Program—Community Edition platform.

HOW THIS STUDY MIGHT AFFECT RESEARCH, PRACTICE OR POLICY

⇒ It could update the health benefit calculations for work-loss days and will be crucial in quantifying more complete health impacts of $PM_{2.5}$ exposures to help inform the full impact of policy decisions to protect public health.

INTRODUCTION

Air pollution has become a global concern due to its association with public health impact with increased morbidity and mortality.[1–6] The US Environmental Protection Agency (USEPA) and California Air Resources Board have developed regulations and policies to help reduce the risk of air pollution impacts in the nation and California, as well as adopting 'standards for ambient air quality… in consideration of public health, safety, and welfare'. To help determine and demonstrate the health protectiveness of these regulations and policies for Americans, including the ambient air quality standards, empirical evidence is needed to guide regulations. The evidence can also help estimate the potential health and economic benefits of regulations by calculating the impact on health endpoints, such as cardiovascular mortality and cardiovascular hospitalisation, as well as respiratory hospitalisation and respiratory emergency room visits.

Total particulate matter with an aerodynamic diameter smaller than 2.5 µm ($PM_{2.5}$), either from conventional sources such as traffic, industrial or agricultural emissions, or wildfire smoke, is among the most damaging air pollutants and has been documented to cause both acute and chronic diseases and their exacerbation.[7] Many studies have investigated the association between various health outcomes from $PM_{2.5}$ exposure[1–6]; however, there are still uncertainties on the full extent of the acute health impact of short-term PM exposure.[8] Researchers generally use emergency room visits and hospital admissions as the health endpoints,[8] while outcomes such as work loss due to sickness (ie, headache) that were not severe enough to warrant admission to an emergency or hospital were not fully incorporated into the health-related costs of air pollution exposure nor were the primary effects of $PM_{2.5}$ differentiated and captured,[9] which is critical for informing the policy decisions to protect public health.[8] There were only two papers published in the 1980s that reported that PM exposure was associated with increased days of work loss and days with reduced activity[10 11]; however, the estimated coefficient was the only one used in Environmental Benefits Mapping and Analysis Program (BenMAP) platform for work loss-related health and economic impact calculation, and these two papers used limited fine particle exposure information from airport visibility rather than actual PM measurements, thus restricting the conclusions drawn from the results. Previous studies[12] that attempted to identify knowledge gaps in the current academic understanding of the effect of wildfire smoke on minor adverse health outcomes also reported a lack of research on the impact of wildfire smoke on acute health outcomes, such as coughs and headaches that are not represented by emergency room visits or hospital admissions data.

Therefore, given the increasing wildfire episodes which can elevate total ambient PM and related acute health outcomes,[13 14] it would be particularly relevant and crucial to investigate both the conventional and wildfire-related $PM_{2.5}$ impacts on some condition exacerbation that may not be fully captured in medical records but might lead to work loss due to sickness. Thus, this study aims to investigate the health and economic impacts of work loss due to sickness related to daily total $PM_{2.5}$ and wildfire smoke exposures, respectively, using data from California from 2015 to 2018, and assess differences in current BenMAP estimates and results based on our study.

MATERIALS AND METHODS

Study population

The study population was drawn from the California Health Interview Survey (CHIS) 2015–2018 data (84 419 adults in total). Starting from 2001, CHIS is a continuous state-wide telephone survey with an annual target of 20 000 households, employing a geographically stratified sample design to include households from all California counties. The survey is conducted in English, Spanish, Cantonese, Mandarin, Korean, Tagalog or Vietnamese, to capture the diversity of California populations. Adjustment factors for the selection mechanisms are incorporated into the data's sample weights. The interview date was recorded and the CHIS respondents' reported home addresses were geocoded. In this study, we used 44 544 adults in total who were in the workforce for the logistic regression analysis (online supplemental figure 1). More information has been detailed elsewhere.[15]

No study participants were involved in setting the research question or the outcome measures, nor were they involved in developing plans for the design or implementation of the study. No participants were asked to advise on interpretation or writing up of results. There are no plans to disseminate the results of the research to study patients or the relevant patient community.

Exposure assessment

Details of how we generated daily total $PM_{2.5}$ and wildfire exposure estimates have been described elsewhere.[15]

The daily total $PM_{2.5}$ exposure estimation was generated from continuous spatial surfaces of daily $PM_{2.5}$ on a 3 km grid for the entire state of California from the year 2015–2018 using the geostatistical surfacing algorithm,[16–22] with the input of environmental data from the USEPA ground observation Air Quality System database and National Aeronautics and Space Administration Moderate Resolution Imaging Spectroradiometer (MODIS) remotely sensed data.[16 17] This spatial surfacing algorithm first used linear regression models to estimate $PM_{2.5}$ from MODIS Aerosol Optical Depth (AOD) observations on a monthly basis, followed by two spatial surface-fitting techniques—B-spline and inverse distance-weighted smoothing models—to generate daily $PM_{2.5}$ surfaces and compared the results, as well as a bias adjustment procedure for MODIS/AOD-derived $PM_{2.5}$ data. The daily total $PM_{2.5}$ estimates generated were assigned to each CHIS respondent by linking the respondents' geocoded home addresses and interview dates.

Wildfire exposures were generated based on the daily wildfire smoke-related $PM_{2.5}$ concentration for 2015–2018 at a spatial resolution of 12 km from the Community Multiscale Air Quality (CMAQ) modelling system V.5.0.1-5.2.[23–26] The CMAQ models used year-specific daily fire emission estimates from SMARTFIRE[27] emissions to simulate changes in air pollution concentrations with and without fires across the contiguous USA.[26] Fuel consumption was calculated using the US Forest Service's CONSUME V.3.0 fuel consumption model and the Fuel Characteristic Classification System fuel-loading database in the BlueSky Framework.[28] Wildland fire emission estimates incorporate multiple sources of fire activity such as Earth observations, and federal, state, local and tribal databases. Emission factors and non-fire emission sources were taken from the Fire Emission Production Simulator model and the National Emissions Inventory, respectively. The models were run with both fire and non-fire source emissions and again without fires, and the difference between the two simulations isolates the wildfire-specific $PM_{2.5}$ contribution.

Health and economic impact calculations

The USEPA estimates, the number of events and economic value of the health impact of national-scale air quality policies via the BenMAP—Community Edition (BenMAP-CE) program. BenMAP is an open-source program that uses the incorporated database including air quality, demographic and economic data as well as concentration–response relationships to quantify the number and economic value of health impacts resulting from changes in air pollution concentrations (https://www.epa.gov/benmap). For the work-loss days, the current BenMAP-CE applied Ostro's[10] estimate of the impact of fine particles on the incidence of work-loss days in a national sample of the adult working population living in metropolitan areas.

The steps of the health and economic impact calculation are displayed in figure 1.

Statistical analysis

The outcome variable for the adult respondents experiencing work loss due to sickness in the previous week was developed according to two questions: (1) 'Which of the following were you doing last week?' and (2) 'What is the main reason you did not work last week?'. If the respondent selected the answers 'with a job or business but not at work' for question 1 and 'sick' for question 2, the respondent was defined as having work loss due to sickness in the previous week.[15]

To facilitate the comparison of the results with Ostro's study, when evaluating the health and economic impact of daily total $PM_{2.5}$ exposure on work loss due to sickness, we used logistic regression models[15] by treating the continuous exposure variable as per 1 $\mu g/m^3$ increase in 2-week average $PM_{2.5}$ exposure prior to the interview date (from week 2 and week 3 prior to the interview date; more details were described in the online supplemental appendix). Then, we received the coefficient ($\beta PM_{2.5}$) of the daily total $PM_{2.5}$ effect estimate (where exp ($\beta PM_{2.5}$) represents the OR for work loss corresponding to per 1 $\mu g/m^3$ increase in 2-week average $PM_{2.5}$ exposure prior to the interview). More details are described in the online supplemental appendix.

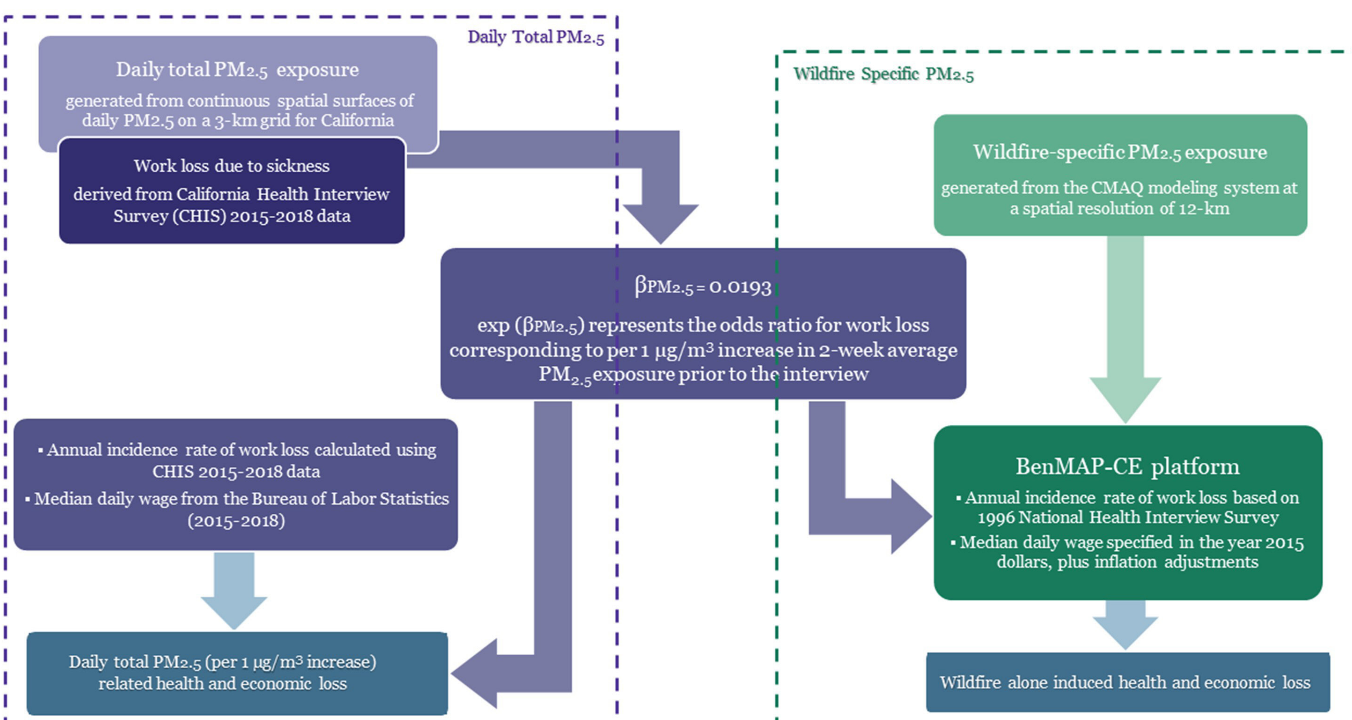

Figure 1 Flow chart of the health and economic impact calculation for short-term $PM_{2.5}$ exposure on work-loss days. BenMAP-CE, Environmental Benefits Mapping and Analysis Program—Community Edition; CMAQ, Community Multiscale Air Quality; $PM_{2.5}$, particulate matter with an aerodynamic diameter smaller than 2.5 µm.

Health and economic impacts of work loss associated with daily total $PM_{2.5}$

We first calculated the weekly incidence rate of the work-loss days per person per year by dividing the number of respondents who reported work-loss events by the total number of respondents who were in the workforce using CHIS data. We then applied the mean annual number of workdays lost due to injury or illness (3.26 days) in California from pooled 2001–2016 Medical Expenditure Panel Survey (MEPS)[29] to the weekly incidence rate and then multiplied the number by 52 weeks to derive the annual rate of work-loss days per person in California (annual rate of work-loss days per person=weekly incidence rate (0.017 cases per week)×3.26 days per case×52 weeks per year). The average daily salary ($249.04 per day in 2015–2018 from the Bureau of Labor Statistics (https://www.statista.com/statistics/305761/california-annual-pay/)) was used to calculate the related economic cost.

Using the coefficient ($\beta PM_{2.5}$) of the daily total $PM_{2.5}$ effect estimate received from the logistic analyses, we derived the change in the incidence of work-loss days due to sickness between exposed versus unexposed populations based on the following equations adopted from the BenMAP-CE platform:

$$\Delta\text{Incidence} = \Delta y \times \text{Population} = (y_1 - y_0) \times \text{Population}$$

Where y_0 and y_1 are the incidence rates of work-loss days in the unexposed and exposed groups, respectively; while Δy as well as the lower and upper bounds can be calculated using the estimated coefficients that we received from regression analyses:

$$\Delta y = [y_0 \times (e^{\beta \times \Delta PM} - 1)]$$

Second, we repeated the health and economic impact calculations of daily total $PM_{2.5}$-related work loss using the incidence rate of work loss, estimate coefficient and salary rate from the current BenMAP-CE platform. The current BenMAP-CE applied Ostro's study coefficient ($\beta PM_{2.5}$=0.0046, SE=0.00036) of the impact of fine particles on the incidence of work-loss days in a national sample of the adult working population, aged 18–64 years, living in metropolitan areas.[10] In BenMAP, the yearly work-loss day incidence rate per 100 people was based on estimates from the 1996 National Health Interview Survey (NHIS).[30] They reported total annual work-loss days of 352 million for individuals aged 18–64 years. The total population of individuals in this age group in 1996 (162 million) was obtained from the US Bureau of the Census. They used these numbers to calculate the average annual incidence rate of work-loss days per person and weekly work-loss day incidence rate per person aged 18–64 years.[30] BenMAP calculates county-specific median daily wages from county-specific annual wages by dividing by (52×5), on the theory that a worker's vacation days are valued at the same daily rate as work-days. In valuing work-loss days, the BenMAP setup uses a function like the following: daily wage×wage index, where the daily wage is specified in the year 2015 dollars. In the inflation dataset, the wage index scales the daily wage value up or down depending on the year of interest.

Wildfire-specific $PM_{2.5}$ exposure-related health and economic impact analyses

To estimate the health impacts on work-loss days attributed to the wildfire-specific $PM_{2.5}$ exposure and the related economic costs, we used the BenMAP-CE tool with the wildfire-specific $PM_{2.5}$ emission from the CMAQ model simulations. As previously mentioned, the CMAQ models are run with all emissions (fire and non-fire sources) and again without fires; the difference between the two simulations isolates the wildfire-specific $PM_{2.5}$ contributions. Both CMAQ models with fire and without fire source emissions run for each year between 2015 and 2018 were included as inputs into the BenMAP-CE platform, and wildfire-specific $PM_{2.5}$ concentrations were isolated by subtracting the daily averages of the control from the daily average baseline CMAQ concentrations.

RESULTS

Associations for short-term daily total $PM_{2.5}$ exposure and work loss due to sickness

There were 905 (weighted percentage=1.69%) respondents who reported to have work loss due to sickness in the week before the interview among 44 544 CHIS respondents in the workforce with the demographic characteristics of the participants detailed in our previous paper.[15] We observed that the OR of work loss due to sickness was 1.02 (95% CI: 0.99, 1.05, β=0.0193) per 1 µg/m^3 increase in the 2-week average $PM_{2.5}$ exposure, after adjusting for age, sex, race/ethnicity, income/poverty level, smoking status, comorbidity and interview year (online supplemental table 1). After adjusting for other demographic, socioeconomic and meteorological factors, the results remained similar (online supplemental table 1). Repeating the analyses using the Firth regression models, propensity score weighting method and Poisson model with repeated 1000 bootstrap samples also generated similar effect estimates for each 1 µg/m^3 increase in 2-week average $PM_{2.5}$ exposure prior to the interview date, respectively (online supplemental table 2).

Health and economic impact estimates of work loss associated with daily total $PM_{2.5}$

According to the CHIS weighted data, the estimated incidence rate of work loss per week (the number of cases per person per week) among the adult Californian population in the workforce (18–64 years) was 0.017 from 2015 to 2018. Using the mean annual number of workdays lost due to injury or illness—3.26 days from MEPS to the weekly incidence rate and then multiplying the number by 52 weeks—the annual rate of work-loss days we derived was 2.86 days per person in California (=weekly incidence rate (0.017 cases per week)×3.26 days per case×52 weeks per year) (table 1).

Using the coefficient of daily total $PM_{2.5}$ effects from our study (exp ($\beta PM_{2.5}$)=0.0193), we observed that for each 1

Table 1 Estimated number and cost of work-loss days associated with $PM_{2.5}$ exposure (per 1 μg/m^3 increase) in California, using the incidence rate calculated by CHIS weighted data and updated salary rate, 2015–2018

Year	Weekly work-loss day incidence rate per person (CHIS)	Average work-loss days per year in California (Cawley *et al*[29])	Annual incidence rate of work-loss days per person	β (CHIS)*	Delta $\Delta PM_{2.5}$ (μg/m^3)	$\Delta y=[y_o \times (e^{\beta \times \Delta PM} -1)]$	Population in California (BenMAP listed)	Work-loss days (Δ incidence=Δ incidence rate×population)	Median daily wage ($)†	Economic cost due to work loss per year ($)
2015–2018	0.017	3.26	2.863	0.0193	1	0.0557829	24 932 520	1 390 808	249.04	346 366 706
2015	0.017	3.26	2.948	0.0193	1	0.0574502	24 707 640	1 419 460	237.30	336 837 867
2016	0.020	3.26	3.316	0.0193	1	0.0646245	24 868 644	1 607 124	242.17	389 197 239
2017	0.016	3.26	2.777	0.0193	1	0.0541160	25 013 056	1 353 606	253.30	342 868 331
2018	0.014	3.26	2.422	0.0193	1	0.0471999	25 140 738	1 186 641	263.38	312 537 479

*According to our study, for each 1 μg/m^3 increase in 2-week average $PM_{2.5}$ level, the odds of work loss were 1.02 (95% CI: 0.99, 1.05); β=0.0193, SE=0.0143.
†The median daily wage rate referred here was from the state-wide average daily salary in California in 2015–2018 from the Bureau of Labor Statistics (https://www.statista.com/statistics/305761/california-annual-pay/).
BenMAP, Environmental Benefits Mapping and Analysis Program; CHIS, California Health Interview Survey; $PM_{2.5}$, particulate matter with an aerodynamic diameter smaller than 2.5 μm.

μg/m^3 increase in $PM_{2.5}$ exposure, it will lead to more than a million days of sick leave per year ranging from 1.1 to 1.6 million person-days in 2015–2018 (table 1). The average economic cost per 1 μg/m^3 increase in $PM_{2.5}$ exposure was even bigger and reached $346 million per year from 2015 to 2018 using the California state-wide average daily salary from the Bureau of Labor Statistics (table 1 and figure 2). Using the BenMAP-CE tool to calculate the health and economic impacts of work loss associated with daily total $PM_{2.5}$ exposure, for each 1 μg/m^3 increase in daily total $PM_{2.5}$ exposure, the excess incidence of work-loss days due to sickness was about 250 000 person-days and the related economic cost was $45–50 million (online supplemental table 3). Nationwide, we found that for each 1 μg/m^3 increase in $PM_{2.5}$ exposure, there would be more than 11 million days of sick leave per year ranging from 9.5 to 12.8 million person-days in the USA, and the average economic cost was around $2.7 billion per year in 2015–2018 using the nationwide average daily salary from the Bureau of Labor Statistics (online supplemental table 4); while it could lead to about 2 million work-loss days with the related yearly economic cost of $377 million using the existing BenMAP-CE tool (online supplemental table 5).

Health and economic impact estimates of work loss associated with wildfire-specific $PM_{2.5}$

According to the BenMAP calculation with the application of the effect coefficient that we estimated (exp ($\beta PM_{2.5}$)=0.0193), due to the wildfire-specific $PM_{2.5}$ concentrations generated in 2015–2018, respectively, the total increased number of work-loss days in the state ranged from 708 206 to 2 659 312 days. Consequently, the work loss-related economic loss was estimated to be US$130 to more than US$500 million from 2015 to 2018 (table 2 and figure 2). We also repeated the wildfire impact calculations using the effect coefficients calculated by Ostro; the results showed there were 170 562–673 870 days of work loss and $31–128 million economic loss (online supplemental table 6).

DISCUSSION

To our knowledge, this is one of the first few studies to characterise the health and economic impacts of $PM_{2.5}$, both conventional and wildfire-specific sources, on work loss in California across an extended time period from 2015 to 2018. The 2018 wildfire season was marked as the deadliest and most destructive in California history at that time but now third after the 2020 and 2021 California wildfire seasons. The overall economic value of $PM_{2.5}$ attributable to work loss is considerable. Generally, a one-unit total $PM_{2.5}$ concentration increase is associated with more than 1 million days of sick leave per year ranging from 1.1 to 1.6 million person-days with an average related economic loss of $346 million in 2015–2018, and the economic losses due to wildfire-specific $PM_{2.5}$-attributable work loss in 2017 and 2018 are estimated to

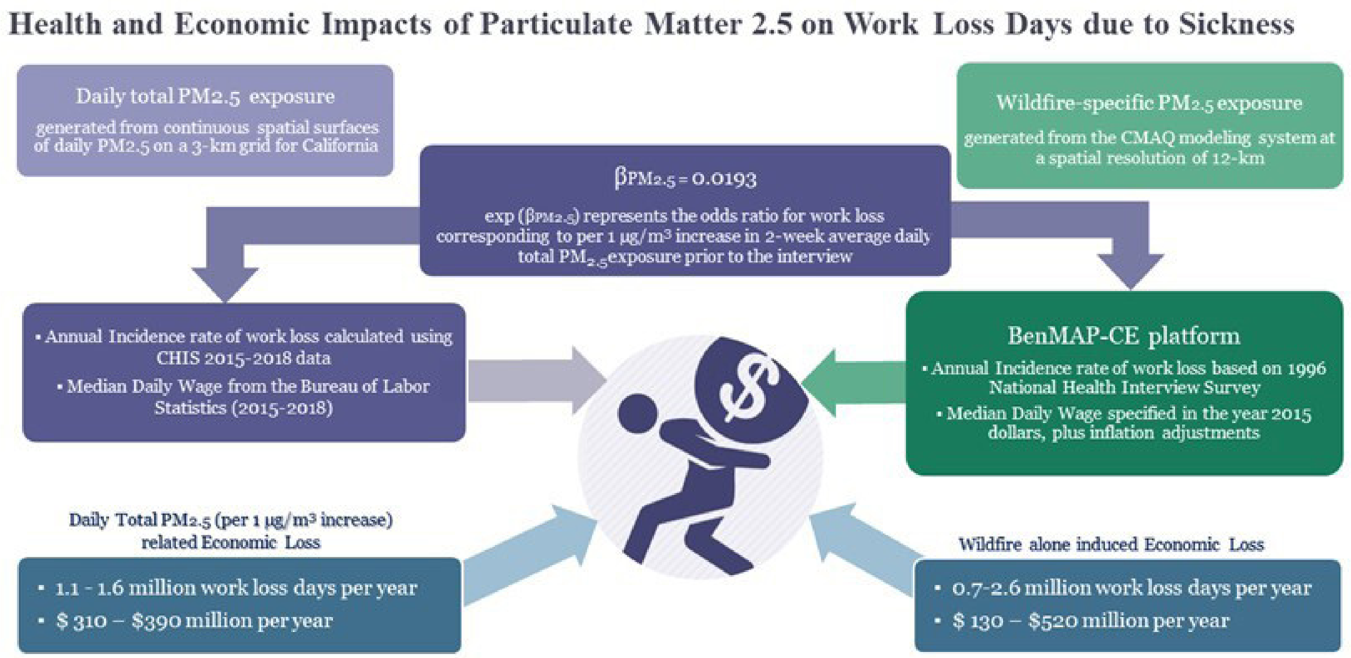

Figure 2 Health and economic impacts of short-term $PM_{2.5}$ exposure on work-loss days. BenMAP-CE, Environmental Benefits Mapping and Analysis Program—Community Edition; CHIS, California Health Interview Survey; CMAQ, Community Multiscale Air Quality; $PM_{2.5}$, particulate matter with an aerodynamic diameter smaller than 2.5 µm.

be more than $500 million. Our findings were consistent with the recently published studies which showed that the wildfire smoke produced substantial health costs.[31] The updated economic impact of short-term exposure to $PM_{2.5}$ total mass is important, but the understanding of the economic impact of wildfire smoke exposure is even more important and timely given global warming.

While wildfires may result in a wide range of health outcomes, studies that estimated health-related economic costs of wildfire smoke exposure are limited. The researchers studying a community in Brunei, a Southeast Asian country, during the wildfire in Indonesia in 1997–1998, observed that 2% of the households had hospitalisation and 6% had self-treatment, but 57% reported at least one of the household members took leave of absence from work or school.[32] It was also suggested that the estimated cost of health effects related to wildfire smoke ranged from $0.26 to $1201 million, depending on the fire scale and health outcomes studied.[33] Among the mortality cost, work-loss days and restricted activity days (including minor restricted activity) accounted for 36–74% of the total morbidity-related cost, then followed by the cost related to hospitalisation and respiratory diseases.

The findings imply that the current health impact function for work-loss days (ie, Ostro's study) used in the BenMAP underestimates the health and economic burdens related to work loss due to sickness. Compared with Ostro's study, the current study used updated survey data, advanced exposure measurements, and a more stringent and robust statistical methodology. Our study improved the estimates in several ways. First, Ostro's study used airport visibility to derive the fine particle exposure level rather than using more accurate and updated PM monitoring data or estimates generated by exposure assessment models as we did. Second, Ostro used 1976 NHIS data with a smaller sample size and did not take into account survey weights. We used CHIS 2015–2018 data and applied both CHIS final and replicate weights to compensate for the probability of selection and a variety of other factors resulting from the design and administration of the survey. Additionally, the current BenMAP used annual work-loss day incidence rates of NHIS 1996 (2.17 per person), while we used updated ones from CHIS 2015–2018 (2.86 per person). Further, the current daily salary rates used by BenMAP for California were lower ($189 per day) compared with the estimates ($249 per day) from the Bureau of Labor Statistics in 2015–2018. We find this study provides more updated and useful contentration-response function (C-R function) estimates for work-loss days, and given the strength of our study, our updated estimates should be used with BenMAP calculations (table 3).

With state-of-the-art modelling estimates for both total $PM_{2.5}$ and wildfire exposures, plus the large sample size of representative Californian adults, CHIS respondents' geocoded address and various interview information, we conducted a first-of-its-kind study to evaluate the impact of short-term $PM_{2.5}$ exposure on work-loss days among Californians and developed much better estimates for work-loss days due to $PM_{2.5}$ exposures for Californians than the current estimates used in BenMAP. However, we need to point out that our point estimate of the $PM_{2.5}$ effect was based on an OR of 1.02 (95% CI: 0.99, 1.05)

 Meng Y-Y, et al. BMJ Public Health 2024;2:e000491. doi:10.1136/bmjph-2023-000491

Table 2 BenMAP-calculated number of work-loss days and economic cost associated with wildfire-specific $PM_{2.5}$ exposure in California, 2015–2018

Year	Endpoint	Author	Delta ($\Delta PM_{2.5}$ concentration)	Population	Work-loss days (95% CI)	Economic cost due to work loss (95% CI)
2015	Work-loss days	Meng	0.71	24 707 640	708 206 (−353 106, 169 256)	129 381 224 (−64 508 436, 309 156 064)
2016	Work-loss days	Meng	1.02	24 868 644	1 016 952 (−518 446, 2 396 338)	189 764 176 (−96 742 424, 447 158 656)
2017	Work-loss days	Meng	2.82	25 013 056	2 659 312 (−1 505 384, 5 973 173)	508 400 000 (−287 795 328, 1 141 935 104)
2018	Work-loss days	Meng	2.67	25 140 738	2 652 724 (−1 374 627, 6 127 832)	521 826 144 (−27 007 456, 1 205 426 048)

For each 1 $\mu g/m^3$ increase in 2-week average daily total $PM_{2.5}$ level, the odds of work loss were 1.02 (95% CI: 0.99, 1.05); β=0.0193, SE=0.0143.
BenMAP, Environmental Benefits Mapping and Analysis Program; $PM_{2.5}$, particulate matter with an aerodynamic diameter smaller than 2.5 µm.

per 1 $\mu g/m^3$ increase in daily total $PM_{2.5}$. We are confident that our point estimates are robust enough to indicate how much the risk of work loss increase related to the $PM_{2.5}$ exposure. We have repeated the analyses using multiple statistical models and all the statistical methods generated very similar point estimates, while this step was not done in Ostro's analysis. We used weighting to achieve more robust results; this step was also not part of the Ostro analysis. We also did sensitivity analyses without using replicate weights but with the final weight only. Using the Firth model, we observed the same point estimate and a much narrower 95% CI, which did not cross null. This confirms that we can get the same significant results as Ostro's study if we do not apply the survey replicate weights. In addition, there are increasing concerns regarding the misinterpretation and misuse of statistical significance based on an arbitrary 0.05 threshold of p values or 95% CI including the null value to make all-or-none categorical statements.[34 35] These concerns are relevant to our work, as a statistically significant effect refers to the rejection of a null hypothesis of zero air pollution effect, and it is difficult to imagine that air pollution exposure or intervention would have absolutely zero effect on health outcomes.

Some limitations also need to be noted. In this study, we only used the study population located in California, while CHIS provides a representative sample of Californians with a large sample size and the application of survey weights. Also, California has a very diverse population and pollutant levels which made the findings more generalisable to the nation. However, caution should be taken if an attempt is made to generalise the results to a particular population or community with different profiles. The exposure misclassification due to the limitations related to the exposure models cannot be ruled out. Daily total $PM_{2.5}$ exposure was generated using a spatial surfacing algorithm, but this surface-fitting model is difficult to incorporate the meteorological factors and thus might affect the size of hygroscopic particles and the light extinction efficiency; however, we adjusted multiple meteorological factors in the analyses and the results remained very similar. Additionally, similar to most models, the CMAQ model also contains some inherent biases[36]; while it has been evaluated and validated by many studies. Using the Atmospheric Model Evaluation Tool to compare various CMAQ simulations paired in space and time with observed data, the researchers have reported the typical Pearson correlations for the daily average $PM_{2.5}$ and observations with an R^2 of 0.4–0.6,[37 38] which could reduce the uncertainty of the CMAQ model estimates. Finally, we should mention that we used an estimated effect coefficient of a 2-week average of daily total $PM_{2.5}$ instead of wildfire-specific $PM_{2.5}$ exposure to estimate the health impacts and economic cost associated with wildfire smoke exposure; however, it should be noted that the compositions of wildfire-related $PM_{2.5}$ are different from that of conventional sourced $PM_{2.5}$; even the $PM_{2.5}$ compositions could be various due to the types

Table 3 Summary of the differences between Ostro's (1987)[10] and the current (2022) study

	Ostro's study (1987)	Current study (2022)
Data		
Data source	(National) Health Interview Survey (NHIS)	California Health Interview Survey (CHIS)
Study year(s)*	1976	2015–2018
Sample size*	n=7111	n=44 544
Outcome		
Related questions	'How many days in the past 2 weeks did illness or injury prevent one from working?'	(1) Which of the following were you doing last week? Answer: 'With a job or business but not at work'; (2) What is the main reason you did not work last week? Answer: 'Sick'
Endpoints	Days of work loss in the past 2 weeks	Events of work loss due to sickness in the previous week
Exposure assessment		
Air pollutant	Fine particles	$PM_{2.5}$
Exposure window	2-week average	2-week average
Assessment method*	Airport visibility data	Continuous spatial surfaces of daily $PM_{2.5}$ on a 3 km grid using the geostatistical surfacing algorithm with the input of environmental data from the USEPA ground observation AQS database and NASA MODIS remotely sensed data
Statistical method		
Outcome variable	Counts (# of work-loss days)	Dichotomised (1: yes vs 0: no)
Exposure variable character	Continuous	Continuous
Statistical model* (including sensitivity analyses)	Poisson model	(1) Logistic regression (logit function); (2) Firth model (to address rare event issue); (3) Poisson model (1000 bootstrap samples)
Survey weight included*	No	Yes, final weight+replicate weight
Covariates adjusted*	Age, sex, race, education, income, quarter of survey, marital status, existence of a chronic condition, minimum 2-week average temperature	Age, sex, race, income/poverty level, race/ethnicity, smoking status, chronic disease status, interview year, interview season, insurance, occupation, full/part-time job position, length of living at current address, rural or urban residential location, wildfire exposure, 2-week average temperature, precipitation, relative humidity, dew point, wind direction
PM effect estimate		
Effect estimates	β=0.0046, SE=0.0021	Logistic regression model: OR=1.02 (95% CI: 0.99, 1.05), using both final weight and replicate weight Firth model: OR=1.020 (95% CI: 1.019, 1.021), using final weight only Poisson model: OR=1.02 (95% CI: 0.99, 1.04), using final weight and 1000 bootstrap samples
Interpretation	A 1 $\mu g/m^3$ increase in 2-week average of fine particles would increase the expected number of work-loss days by 0.403%	Per 1 $\mu g/m^3$ increase in 2-week average of $PM_{2.5}$ exposure, the odds of work loss due to sickness increased by 2%
Estimated number and cost of work loss		
Average annual incidence rate of work-loss days	2.17 (based on 1996 NHIS)	2.86 (based on CHIS 2015–2018 data)
Medium daily wage ($)	189.6	249.04 from the Bureau of Labor Statistics in 2015–2018
Work-loss days related to 1 $\mu g/m^3$ increase in $PM_{2.5}$ exposure	249 450 days (online supplemental table 3) (using annual incidence rate=2.17)	1 390 808 days (table 1) (using annual incidence rate=2.86)
Related economic loss due to work loss	$47 283 191 (online supplemental table 3) (using medium daily wage=$189.6)	$346 366 706 (table 1) (using updated medium daily wage=$249.04)

*Improvements/updates of methodology in the current study compared with Ostro's study.
AQS, Air Quality System; MODIS, Moderate Resolution Imaging Spectroradiometer; NASA, National Aeronautics and Space Administration; $PM_{2.5}$, particulate matter with an aerodynamic diameter smaller than 2.5 µm; USEPA, US Environmental Protection Agency; β, coefficient.

of fuel burned and the burning conditions. Therefore, together with the uncertainties regarding the extent to which certain species of fire-attributable PM may be more or less toxic than others,[26] using the effect coefficients from the epidemiological studies (eg, Ostro's 1987 study and our study) that examined the impacts of total

$PM_{2.5}$ exposure but did not specifically consider wildfire components may underestimate or overestimate impacts. Also, the daily salaries range widely by regions and occupations in California, using state-wide averages, which may underestimate or overestimate the actual economic cost.

The impacts of air pollution on public health have become great concern worldwide, along with ongoing global climate change, contributing to increased frequency, intensity and spread of wildfires, especially in the US western coast. California's hot, dry summers make the state very vulnerable to seasonal wildfires. About half of the top 20 most destructive California wildfires happened from 2015 to 2018. Our findings imply that the current federal and state $PM_{2.5}$ standards might not be strong enough to protect the health of the population, especially given that the current national ambient air quality standards do not count the high $PM_{2.5}$-exposed days due to the wildfire events, while the wildfire-generated $PM_{2.5}$ might be more toxic due to their different compositions. The findings related to the elevated impacts on work loss due to exposures to wildfire are novel since many wildfire studies found no significant health effects on mortality, cardiopulmonary-related hospitalisation or emergency room visits, though these adverse health impacts were indicated in the conventional PM exposure studies. Thus, our study would be particularly relevant and crucial given the frequency and intensity of wildfire which can elevate total ambient PM that has already been linked with acute/subacute health outcomes.

Our findings of current health and economic burdens related to work loss due to sickness are significant since labour is a vital component in every economy; it could thus have a direct or indirect negative influence on economic growth. More studies are needed to understand the impact of air pollution exposure (both conventional and wildfire related) on adverse health outcomes that do not require doctor or hospital visits but affect a majority of the population. Therefore, updating the BenMAP-CE health benefit calculations for work-loss days will be essential in quantifying the complete health impacts of regulations and policies to help inform the full impact of policy decisions to protect public health, because these results can be translated to inform effective solutions and strategies to reduce climate change and air pollution impacts on health and well-being of Californians, especially in underserved communities, and ultimately to advance health equity in the state and the nation.

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