Preventive Medicine Reports 53 (2025) 103033

Contents lists available at ScienceDirect

Preventive Medicine Reports

journal homepage: www.elsevier.com/locate/pmedr

Short communication

Racial-ethnic composition of U.S. school districts, wildfire smoke $PM_{2.5}$ levels, and reduced in-person learning among schoolchildren and adolescents during the COVID-19 pandemic

Daniel Kim

Department of Public Health and Health Sciences, School of Community Health and Behavioral Sciences & School of Public Policy and Urban Affairs, Northeastern University, Boston, MA 02115, USA

A B S T R A C T

Background: In 2023, the U.S. Biden administration called for an "all-hands-on-deck" response to address chronic absenteeism and disrupted learning among primary and secondary school students due to school closures and remote learning during the pandemic. To identify student populations that might benefit from interventions, this study examined the racial-ethnic composition of school districts as a predictor of wildfire smoke $PM_{2.5}$ levels and in-person student visits to schools.
Methods: In a lagged cross-sectional study, multivariable logistic regression was employed to investigate school district quartiles of mean percentages of non-White students as predictors of: 1) mean levels of wildfire smoke $PM_{2.5} > 35$ μg/m^3 during school days for grade 3–8 students; and 2) being above the median for the mean decline in in-person K-12 student attendance (vs. pre-pandemic) during the 2020–2021 and 2021–2022 school years.
Results: The highest (vs. lowest) quartile for the district-level percentage of non-White students predicted a nearly 3-fold higher odds (adjusted odds ratio, AOR = 2.78; 95 % CI = 2.07–3.74; $P < .001$) of high wildfire smoke exposure and 5-fold higher odds (AOR = 4.95; 95 % CI = 3.84–6.38; $P < .001$) of substantially reduced in-person learning levels. Successively higher odds for both outcomes were observed in higher quartiles (P for trend $< .001$). Similar patterns were seen when percentages of Asian-, Black-, and Hispanic-American students were modeled simultaneously.
Conclusions: Districts with higher percentages of non-White students showed elevated odds of high wildfire smoke $PM_{2.5}$ levels and distance learning. Distributing portable air filtration devices in these districts could be a cost-effective intervention to address these concomitant risks and mitigate learning loss among children and adolescents in the USA.

1. Introduction

In September 2023, the Biden administration in the United States called for an "all-hands-on-deck" response to address chronic absenteeism and disrupted learning among K-12 students that spiked during the COVID-19 pandemic due to school closures and shifts to remote learning (The White House, 2023). Such learning disruptions are linked to test score declines with lifelong implications for earnings and well-being (Goldhaber and Ozek, 2019). Learning losses have been demonstrated to be larger in lower-income and minority school districts and in school districts that maintained distance learning for longer periods during the pandemic, and have only partially been reversed (Fahle et al., 2023; Goldhaber et al., 2022; Fahle et al., 2024). Average daily cumulative wildfire smoke levels during the school year on school days of 35 μg/m^3 have been linked to significantly lower test scores (~0.15% of a standard deviation) among schoolchildren (Wen and Burke, 2022), and elevated wildfire smoke levels can exacerbate medical conditions in children such as asthma that can contribute to absenteeism (Reid et al., 2016).

Average wildfire smoke $PM_{2.5}$ levels will likely increase over time nationwide due to global warming, and while the coronavirus pandemic has been declared over, COVID-19 school outbreaks which have disproportionately affected communities of color are ongoing (Jones, 2021).

There is evidence of variations in wildfire smoke exposure by racial/ethnic group such as in the state of California (Velásquez et al., 2023). Given evidence linking wildfire smoke exposure to lower test scores (Wen and Burke, 2022) and evidence of higher learning losses in racial-ethnic minority school districts including during the pandemic (Fahle et al., 2023), we hypothesized that school districts with higher concentrations of racial-ethnic minorities might experience higher levels of wildfire smoke as one potential mechanism for higher learning losses.

This study aimed to identify higher-risk student populations that might benefit from interventions to reduce learning disruptions by estimating the linkages between the racial and ethnic composition of school districts, average wildfire smoke $PM_{2.5}$ levels, and year-over-year declines in in-person student visits to schools during the pandemic.

E-mail address: d.kim@northeastern.edu.

https://doi.org/10.1016/j.pmedr.2025.103033
Received 15 July 2024; Received in revised form 20 February 2025; Accepted 9 March 2025
Available online 13 March 2025

2. Methods

2.1. Study population

The study population consisted of all school districts across the United States. Wen & Burke previously gathered data on cumulative smoke exposure during the school year across nearly ~11,700 school districts between 2009 and 2016 (Wen and Burke, 2022). Of these districts, data were available on in-person student visits to schools, as described in the Outcomes subsection below (Parolin and Lee, 2021), across 11,190 school districts.

2.2. Exposures

The percentage of non-White students in each U.S. school district was calculated by subtracting the percentage of White students from 1, with the percentage of White students being estimated through the Common Core of Data and aggregated by the Stanford Education Data Archive to the district level (Wen and Burke, 2022). 5-year (2012–2016) district-level mean percentages of non-White students were calculated and grouped into quartiles. Likewise, to take into account possible heterogeneity in relationships across non-White racial-ethnic subgroups, district-level mean percentages of Black-, Hispanic-, and Asian-American students were estimated and used to derive high (vs. low) dichotomous variables according to median values (Wen and Burke, 2022).

2.3. Outcomes

5-year (2012–2016) student population-weighted mean levels of wildfire-smoke-attributable particulate matter <2.5 μm in diameter ($PM_{2.5}$) across districts were based on satellite-derived smoke plume data from the NESDIS Hazard Mapping System (HMS) merged with gridded estimates of daily $PM_{2.5}$ concentrations (Wen and Burke, 2022). A weighted average of school-level exposure based on the size of the student population for each school was employed to estimate aggregate exposure at the district level on school days for grade 3–8 students from August 15 to June 15 of the following year and categorized as high based on wildfire smoke $PM_{2.5}$ levels >35 $\mu g/m^3$, according to the EPA health standard (Wen and Burke, 2022). Smoke-attributable $PM_{2.5}$ was calculated as the deviation from location-specific median $PM_{2.5}$ on non-smoke days in the same month. Hence, the resulting measure of smoke $PM_{2.5}$ isolated the smoke component from overall $PM_{2.5}$ (Wen and Burke, 2022).

In-person student attendance was estimated from the US School Closure and Distance Learning Database, a public database that tracked month-to-month distance learning for K-12 public schools based on aggregated, anonymized mobile phone data from SafeGraph (Parolin and Lee, 2021). SafeGraph captures GPS data from approximately 10% of US mobile devices to monitor mobility patterns and foot traffic including to schools (Parolin and Lee, 2021). SafeGraph data had been used to measure in-person visits to 80,785 public schools spanning 12,727 school districts (94% of all US districts) to evaluate how the mean number of school visits in a given month from September 2020 to May 2021 and September 2021 to May 2022 compared with the same calendar month in 2019 (Parolin and Lee, 2021). A large year-over-year decline in in-person visits signified that a school had shifted primarily to distance learning (Parolin and Lee, 2021).

2.4. Covariates

All models controlled for the district-level mean percentage of students eligible for free/reduced-price school lunches provided (Wen and Burke, 2022) (as a proxy for socioeconomic disadvantage), student enrolment, number of schools, area type (i.e., city/town/suburb/rural, using data drawn from the Common Core of Data (Wen and Burke, 2022)), and state fixed effects.

2.5. Statistical analysis

Using a lagged cross-sectional study design, multivariable logistic regression models were fit to investigate quartiles of mean percentages of non-White students and high (vs. low) percentages of Black-, Hispanic-, and Asian-American students as predictors of: 1) high mean levels of wildfire smoke $PM_{2.5}$; and 2) being above the median in the mean year-over-year decline in in-person student attendance. Standard errors were adjusted for clustering of school districts within states. All analyses were conducted using SAS Version 9.4.

3. Results

Across 11,190 (82.4% of all) US school districts, the highest (vs. lowest) quartile for the percentage of non-White students predicted a nearly 3-fold higher odds (adjusted odds ratio, AOR = 2.78; 95% CI = 2.07–3.74; $P < .001$) for high wildfire smoke $PM_{2.5}$ levels (Fig. 1A) and 5-fold higher odds (AOR = 4.95; 95% CI = 3.84–6.38; $P < .001$) for substantially reduced in-person learning levels (Fig. 1B). Successively higher odds for both outcomes were observed in higher quartiles (P for trend < .001). In supplementary analyses with the exposure modeled as continuous, a 5-percentage point increase in the percentage of non-White students predicted a 1.3 times higher odds (AOR = 1.30; 95% CI = 1.17–1.43; $P < .001$) for high wildfire smoke $PM_{2.5}$ levels and a nearly 2-fold higher odds (AOR = 1.93; 95% CI = 1.77–2.11; $P < .001$) for substantially reduced in-person learning levels. When the outcomes were also modeled as continuous variables, the association with high wildfire smoke levels became non-significant ($\beta = -0.36$, $P = 0.44$) while a significant relationship with reduced in-person learning levels remained present ($\beta = -0.055$, $P < .001$).

Similar patterns were seen when high (vs. low) percentages of Asian-, Black-, and Hispanic-American students were modeled simultaneously (Fig. 2A and Fig. 2B). In additional analyses with the outcomes modeled as continuous, high (vs. low) percentages of Asian- and Hispanic-American students but not of Black-American students were associated with high wildfire smoke $PM_{2.5}$ levels ($\beta = 2.38$, $P = 0.003$ for Asian-American students; $\beta = 2.33$, $P = 0.01$ for Hispanic-American students; and $\beta = -0.66$, $P = 0.39$ for Black-American students). High (vs. low) percentages of each category of students were associated with high declines in in-person learning levels (all $\beta < 0$, $P < .001$).

4. Discussion

U.S. school districts with higher percentages of non-White students exhibited a convergence of elevated odds of high wildfire smoke $PM_{2.5}$ levels and distance learning, with evidence of dose-response relationships.

In subgroup comparisons, Wen & Burke (Wen and Burke, 2022) reported that U.S. school district levels of ambient wildfire smoke $PM_{2.5}$ were comparable across racial-ethnic subgroups and levels of socioeconomic disadvantage. The mean percentages of U.S. public school closures have been found to be inversely associated with the school percentages of White students (Parolin and Lee, 2021).

In the present study, racial-ethnic composition was determined to be a key predictor of exposure to both high wildfire smoke levels and distance learning. Possible reasons for higher wildfire smoke levels among racial-ethnic minorities might include lower home prices in fire-prone areas and historical patterns of settlement and migration that have shaped the geographic distribution of racial and ethnic groups in the country (Davies et al., 2018; Loomis, 2004; Downey and Hawkins, 2008). For example, American Indians are concentrated on federal reservations in regions that are more vulnerable to wildfires (Davies et al., 2018).

Consistent with this study's main findings, a previous study (Davies

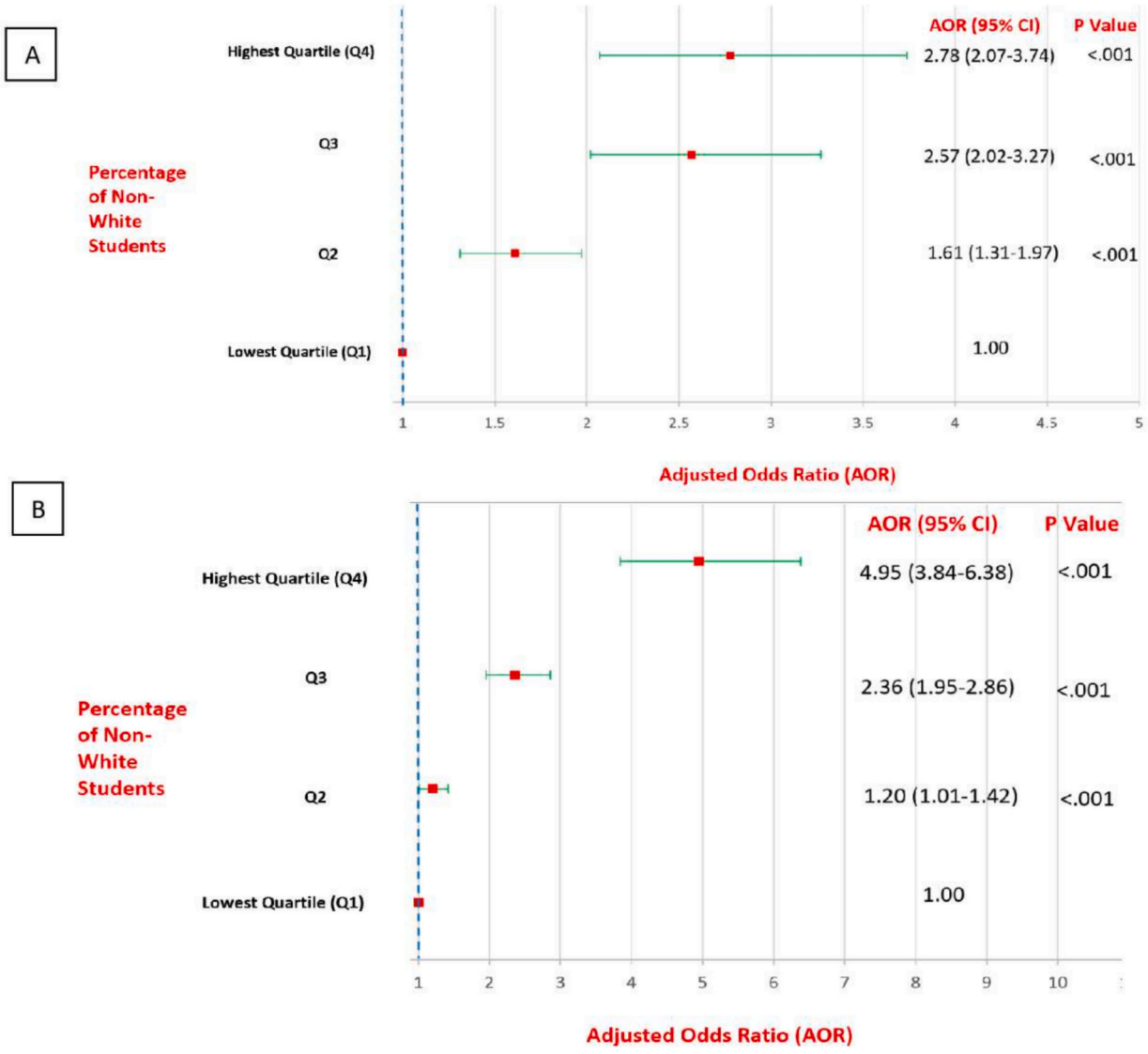

Fig. 1. Multivariable-adjusted odds ratios of A) mean levels of wildfire smoke PM2.5 above 35 μg/m3 during school days for grade 3–8 students and of B) high mean decline in in-person student attendance from September 2020 to May 2021 and September 2021 to May 2022 (vs. same month in 2019) for K-12 students, according to quartile of percentage of non-White students across 11,190 school districts in the United States, 2012–2016. All models are adjusted for the school district-level mean percentage of students eligible for free/reduced-price school lunches, total student enrolment, number of schools, area type (city/town/suburb/rural), and state fixed effects.

et al., 2018) identified residents (not limited to schoolchildren) of racial/ethnic minority Census tracts as experiencing larger increases in the number of days of heavy smoke between 2011 and 2021. In a study of wildfire smoke $PM_{2.5}$ levels among schoolchildren in California (Velásquez et al., 2023), only American Indian and Alaskan Native students showed consistently elevated mean number of days with elevated wildfire smoke levels from 2008 to 2016 coincident with the timeframe for wildfire smoke measurements in the current study, while Hispanic American students had a lower mean number of days with elevated wildfire smoke levels from 2016 to 2021 than non-Hispanic White American students. However, in contrast to these prior studies as well as the Wen & Burke study (Wen and Burke, 2022) which all reported on bivariate relationships, the current study fit multivariable regression models with racial-ethnic composition co-adjusted for socioeconomic disadvantage, thereby reducing residual confounding and allowing for examination of independent relationships.

4.1. Study limitations

Study limitations include measurement of racial-ethnic composition and wildfire smoke $PM_{2.5}$ levels during pre-pandemic time periods and prior to the measurement of in-person student learning (Wen and Burke, 2022), and its reliance on GPS data as a proxy for location of schoolchildren (Parolin and Lee, 2021). The study's findings should be generalizable to all U.S. school districts included.

4.2. Public health implications

Under the conditional assumption of an independent causal relationship between higher wildfire smoke $PM_{2.5}$ levels at school and lower test scores (e.g., despite the Wen & Burke study's lack of control for $PM_{2.5}$ levels at home or for school closures due to wildfire smoke (Wen and Burke, 2022)), reducing exposure to high wildfire smoke levels could be beneficial to student learning. With higher percentages of non-White students being at greater risk of both higher wildfire smoke levels and distance learning, these elevated risks could be jointly mitigated

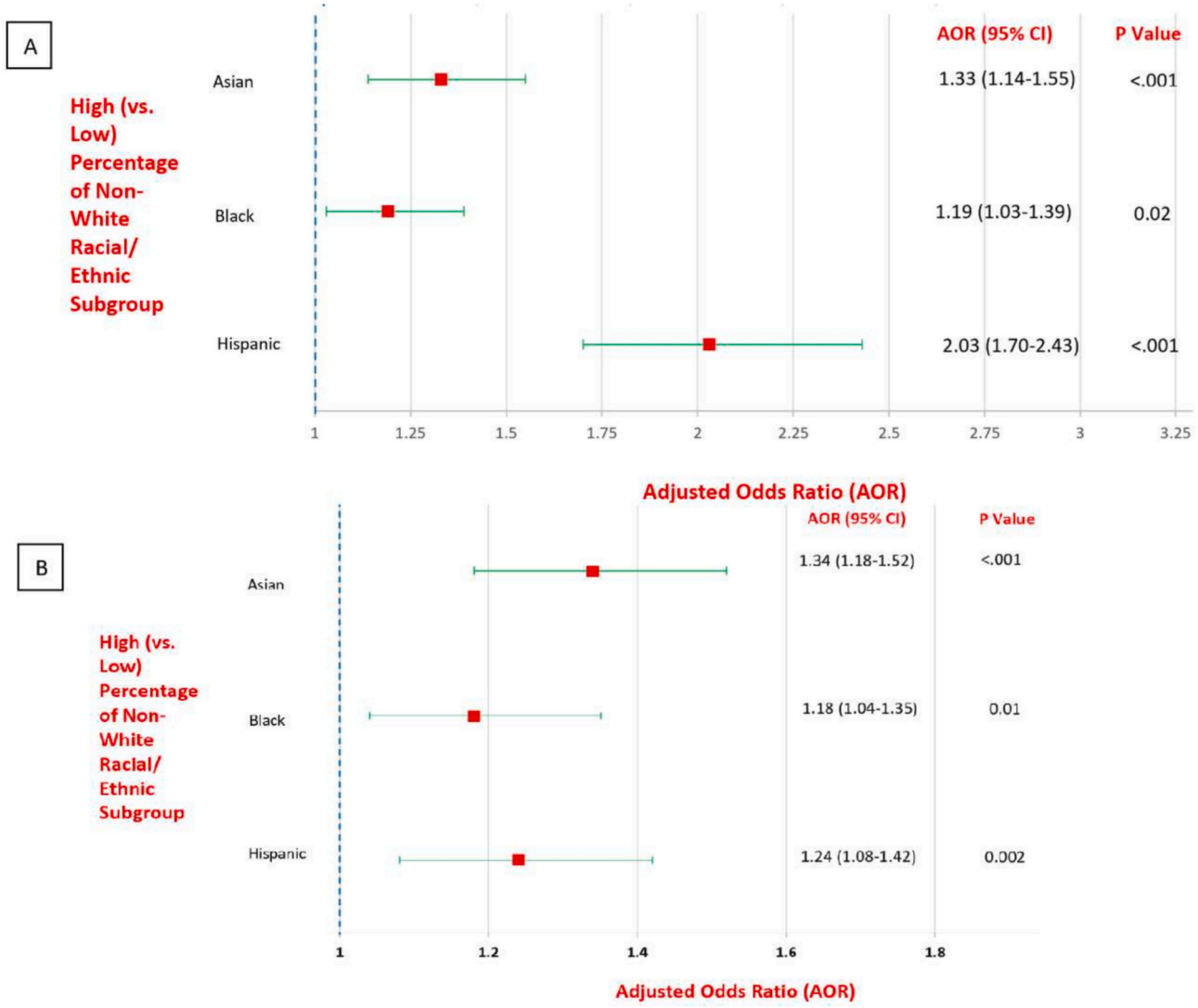

Fig. 2. Multivariable-adjusted odds ratios of A) mean levels of wildfire smoke PM2.5 above 35 μg/m3 during school days for grade 3–8 students and of B) high mean decline in in-person student attendance from September 2020 to May 2021 and September 2021 to May 2022 (vs. same month in 2019) for K-12 students, according to high (vs. low) percentage of Asian-, Black-, and Hispanic-American students across 11,190 school districts in the United States, 2012–2016. All models are adjusted for the school district-level mean percentage of students eligible for free/reduced-price school lunches, total student enrolment, number of schools, area type (city/town/suburb/rural), and state fixed effects.

through DIY inexpensive portable devices such as Corsi-Rosenthal (C-R) boxes. Evidence has shown the effectiveness of these boxes in reducing $PM_{2.5}$ concentrations and the transmission of airborne particulates carrying the coronavirus in classrooms (Gasparrini et al., 2022).

Supplying C-R boxes to districts in the highest three quartiles of percentages of non-White students nationally could markedly reduce learning disruptions and wildfire smoke and COVID-19 health impacts (Wilson, 2023) and related inequities at less than $1 billion annually—on the basis of three-quarters of the 129,069 K-12 schools in the USA (National Center for Education Statistics, 2025) employing C-R boxes in up to 50 spaces per school, and each C-R box assumed to have a maximum cost of $100 and an operational duration of half the school year. This total cost represents less than 2% of the $51 billion (out of an original $191 billion) in federal relief that were available to school districts until September 2024 to address pandemic-related needs including learning loss (Dellinger, 2023). Without such an intervention to address learning disruptions, even at current levels of recovery, widened student achievement gaps will persist and are more likely to become permanent (Fahle et al., 2024).

Ethics statements

All data were publicly available and anonymized and deemed exempt by the author's institution from ethical compliance.

Funding

No grant was received for this research from any funding agency in the public, commercial or not-for-profit sectors.

CRediT authorship contribution statement

Daniel Kim: Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

The author declares that there are no known competing financial

interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data used in this study are available upon request to the author.

References

Davies, I.P., Haugo, R.D., Robertson, J.C., Levin, P.S., 2018 Nov 2. The unequal vulnerability of communities of color to wildfire. PLoS One 13 (11), e0205825.

Dellinger, H., 2023. Federal COVID relief for schools dwindles, as learning loss persists. September 6. Accessed at: https://www.msn.com/en-us/news/us/federal-covid-relief-for-schools-dwindles-as-learning-loss-persists/ar-AA1gj2am.

Downey, L., Hawkins, B., 2008. Race, income, and environmental inequality in the United States. Sociol. Perspect. 51, 759–781.

Fahle, E.M., Kane, T.J., Patterson, T., Reardon, S.F., Staiger, D.O., Stuart, E.A., 2023. School District and Community Factors Associated with Learning Loss during the COVID-19 Pandemic. Center for Education Policy Research at Harvard University, Cambridge, MA, USA. May. Accessed at. https://cepr.harvard.edu/sites/hwpi.harvard.edu/files/cepr/files/explaining_covid_losses_5.23.pdf.

Fahle, E., Kane, T.J., Reardon, S.F., Staiger, D.O., 2024 January. The First Year of Pandemic Recovery: A District-Level Analysis. Center for Education Policy Research at Harvard University, Cambridge, MA, USA. Accessed at. https://educationrecoveryscorecard.org/wp-content/uploads/2024/01/ERS-Report-Final-1.31.pdf.

Gasparrini, W., Akter, S., Russell, B., Assanah, F., Brugge, D., Cole, M., et al., 2022. Testing the Efficacy of the 'Corsi-Rosenthal' Box fan Filter in an Active Classroom Environment. Cambridge Open Engage, ChemRxiv. Cambridge.

Goldhaber, D., Ozek, U., 2019. Can standardized tests predict adult success? What the Research Says. October 6. Accessed at: https://www.edweek.org/teaching-learning/opinion-can-standardized-tests-predict-adult-success-what-the-research-says/2019/10.

Goldhaber, D., Kane, T.J., McEachin, A., Morton, E., Patterson, T., Staiger, D.O., 2022. *The consequences of remote and hybrid instruction during the pandemic* (working paper no. 30010). National Bureau of Economic Research. Accessed at. https://www.nber.org/system/files/working_papers/w30010/w30010.pdf.

Jones, J.M., 2021 Sep. The dual pandemics of COVID-19 and systemic racism: navigating our path forward. Sch. Psychol. Forum 36 (5), 427.

Loomis, J., 2004. Do nearby forest fires cause a reduction in residential property values? J. For. Econ. 10, 149–157.

National Center for Education Statistics, 2025. Fast Facts: Educational Institutions. Accessed at. https://nces.ed.gov/FastFacts/display.asp?id=84.

Parolin, Z., Lee, E.K., 2021 Apr. Large socio-economic, geographic and demographic disparities exist in exposure to school closures. Nat. Hum. Behav. 5 (4), 522–528.

Reid, C.E., Brauer, M., Johnston, F.H., Jerrett, M., Balmes, J.R., Elliott, C.T., 2016 Sep. Critical review of health impacts of wildfire smoke exposure. Environ. Health Perspect. 124 (9), 1334–1343.

The White House, 2023. Chronic Absenteeism and Disrupted Learning Require an All-Hands-on-Deck Approach. September 13. Accessed at. https://www.whitehouse.gov/cea/written-materials/2023/09/13/chronic-absenteeism-and-disrupted-learning-require-an-all-hands-on-deck-approach/.

Velásquez, E.E., Benmarhnia, T., Casey, J.A., Aguilera, R., Kiang, M.V., 2023 Apr 3. Quantifying exposure to wildfire smoke among schoolchildren in California, 2006 to 2021. JAMA Netw. Open 6 (4), e235863.

Wen, J., Burke, M., 2022 Nov. Lower test scores from wildfire smoke exposure. Nature Sustainability. 5 (11), 947–955.

Wilson, C., 2023. HEPA filters cut covid-19 sick days but we've been slow proving this. November 1. Accessed at: https://www.newscientist.com/article/mg26034630-700-hepa-filters-cut-covid-19-sick-days-but-weve-been-slow-proving-this/#Echobox=1699105339.