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The Impact of Wildfire Smoke on Asthma Control in California: A Microsimulation Approach

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Key Points:

- Exposure to wildfire smoke worsens asthma outcomes, but microsimulation methods have rarely been applied to describe this association
- Our novel microsimulation model accurately reflects altered distribution of asthma control and healthcare use after a wildfire
- Such a model can be valuable for informing and evaluating preventive measures to reduce to burden of wildfire smoke on asthma

Supporting Information:

Supporting Information may be found in the online version of this article.

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The Impact of Wildfire Smoke on Asthma Control in California: A Microsimulation Approach

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Abstract Wildfire smoke exposure leads to poorer health among those with pre-existing conditions such as asthma. Particulate matter in wildfire smoke can worsen asthma control, cause acute exacerbations, and increase health resource utilization (HRU) and costs. Research to date has been retrospective with few opportunities to project changes in underlying asthma control and HRU given exposure to wildfire smoke. Using a microsimulation of 5,000 Californians with asthma, we calculated changes in asthma control distribution, risk of exacerbation, and HRU and cost outcomes in the 16 weeks during and after a wildfire. The model was calibrated against empirical values on asthma control distribution and increased HRU after exposure to wildfire smoke. Without smoke exposure, 48% of the cohort exhibited complete or well control of asthma, and 8% required acute healthcare per cycle. Following two consecutive weeks of wildfire smoke, complete or well control of asthma fell to 27%, with an additional 4% HRU. This corresponds to total additional $601,250 in all-cause medical costs and eight fewer quality-adjusted life years over 16 weeks of model time. Our model found increased asthma health and cost burden due to wildfire smoke that were aligned with empirical evidence from a historic wildfire event. This study establishes a framework for a more nuanced understanding of asthma impacts from wildfire smoke that can help inform the development of public health policies to mitigate harm and promote resilience among asthma patients in the face of climate change.

Plain Language Summary This study looks at how wildfire smoke affects people with asthma in California. It is known that wildfire smoke exposure can make asthma worse, but we wanted to understand exactly how it impacts asthma control, the risk of asthma attacks, and the need for asthma-related healthcare. We created a computer simulation with 5,000 virtual Californians who have asthma and looked at what happened to them during and after a wildfire, compared to if there was no wildfire. Without wildfire smoke, about half of the virtual group had good control over their asthma, and only a small percentage needed to go to the hospital for asthma-related reasons. During and after the wildfire, the number of people with good asthma control dropped as people were exposed to smoke, and more people needed to use healthcare services. This increase in asthma problems led to higher medical costs and reduced quality of life for the group exposed to wildfire smoke. Our findings were in line with observations made after a well-documented past wildfire in California. This and similar computer models can help policymakers make better decisions to protect people with asthma from the effects of wildfire smoke.

1. Introduction

In the state of California, the annual occurrence of devastating wildfires has become an alarming and recurring concern (Goss et al., 2020). The health consequences of smoke from these wildfires of increasing magnitude and intensity are many, ranging from impacts on mental health to poor pregnancy and birth outcomes and worse cardiovascular health (DeFlorio-Barker et al., 2019; Gould et al., 2023; Liu et al., 2015; Reid & Maestas, 2019; Silveira et al., 2021; Stowell et al., 2021; Zhao et al., 2022). The impacts of wildfire smoke can reach far beyond the immediate area where it occurs as smoke plumes can travel long distances and cause health problems across whole regions (Fischels, 2021; Wang et al., 2021). Wildfire smoke consists of harmful chemicals and pollutants, with the predominant component being fine particulate matter ($PM_{2.5}$) (Urbanski et al., 2009). Wildfire $PM_{2.5}$ is composed of a greater concentration of smaller particles and oxidative compounds compared to $PM_{2.5}$ from other sources, making it more deleterious to health than air pollution from other sources (Aguilera et al., 2021; Verma et al., 2009). In the short-term, exposure to wildfire smoke can lead to greater risk for respiratory health, including asthma-related events (Casey et al., 2021; Cisneros et al., 2018; DeFlorio-Barker et al., 2019; Gould et al., 2023; Reid & Maestas, 2019; Stowell et al., 2021; Xu et al., 2020).

Asthma affects nearly 9% of the California population (California Department of Public Health, 2022), costing over $3 billion annually in healthcare expenditures in the state (Nurmagambetov et al., 2017). Those living with asthma experience 3% more healthcare encounters overall, and 34% more respiratory health encounters, compared to those without asthma. As a result, those with asthma incur excess all-cause medical costs over $900 per person per year (Wenjia et al., 2016). Exposure to wildfire smoke is associated with acute exacerbations of asthma symptoms which may result in costly emergency room visits or hospitalizations, worsen control of asthma symptoms, and decrease quality of life in asthma patients (Casey et al., 2021; Hutchinson et al., 2018; Malig et al., 2021; Rossiello & Szema, 2019; Wu et al., 2019). Between 2008 and 2012, premature deaths and respiratory hospitalizations related to wildfire $PM_{2.5}$ cost an estimated $63 billion across the US (Fann et al., 2018). More frequent wildfires are likely to further increase the need for respiratory healthcare for asthma along with associated costs to patients and the healthcare system (Limaye et al., 2020; Smith & Katz, 2013).

While there is some research describing associations between wildfire smoke and asthma outcomes, the focus to date has been on acute exacerbations and on cohort-level studies. Few studies have extensively investigated chronic outcomes such as asthma control, which relate not only to symptoms and quality of life but also to sub-symptomatic outcomes that may be overlooked but impact asthma experience nonetheless. Additionally, no studies to our knowledge have used microsimulation techniques to estimate individual-level outcomes for asthma, other than investigating effects of pharmaceutical interventions. Yet, microsimulation methods provide several advantages for examining the impacts of wildfires on asthma and informing preventive strategies. First, microsimulations accommodate highly heterogenous populations as they are able to incorporate greater numbers of parameters compared to traditional Markov models (Spielauer, 2011), making this approach uniquely suited to investigate climate-health associations, which manifest differently even across small geographic regions (e.g., the intensity and impact of wildfire smoke can greatly vary between counties). Second, microsimulations model individuals rather than cohorts, with interacting individual attributes and characteristics, therefore they assess the distribution of health impacts across heterogenous populations (Lay-Yee & Cotterell, 2015). Such nuanced assessments can inform very specific and targeted public health messaging and interventions to protect the well-being of those most at risk for poor outcomes. Third, microsimulations make use of "memory," wherein a simulated individual's past experiences may impact their future outcomes (Spielauer, 2011). This is useful when estimating the effects of recurring and historical exposures, such as those occurring with wildfires of increasing frequency (Agyapong et al., 2022). Finally, microsimulations can portray any number of health conditions and interventions without the "state explosions" constraining Markov cohort models (Roberts et al., 2012). This permits the addition of new substance whenever suggested by empirical data.

This study aimed to develop a microsimulation approach that provides a nuanced understanding of the relationship between wildfire exposure and asthma health and cost outcomes by building and validating a model that accurately reflects a well-documented large wildfire event (the 2018 Camp Fire). Our model is intended as a framework through which the impacts of future potential wildfires on asthma can be investigated, and targeted interventions and resilience strategies could be evaluated. Such research helps inform evidence-based policy decisions and the development of adequate prevention measures, as well as promote resilience and adaptation efforts.

2. Materials and Methods

2.1. Simulated Cohort Characteristics

The virtual cohort was defined using 2021 American Community Survey data obtained through IPUMS USA (Ruggles et al., 2023). We extracted select variables of interest that are driving asthma risk as described in literature, including age, geographic location, and socioeconomic level for the full data set, then created a subset comprised only of those residing in California (Busby et al., 2021; Nardone et al., 2020; Newcomb & Li, 2019; Talreja & Baptist, 2011).

Next, we utilized age- and county-specific asthma prevalence data based on the 2019–2020 California Health Interview Survey (California Department of Public Health, 2022). Prevalence data was partially missing for younger age groups (0–17 years) and were imputed using population-weighted averages (see Supporting

Information S1). Asthma prevalence was adjusted for household income using published risk ratios for asthma (American Lung Association, 2020). Using these adjusted prevalence values as probabilities, we randomly assigned each individual in the full sample a binary asthma status. Individuals who had the asthma flag were randomly assigned into one of five asthma control categories (i.e., disease states, described below) based on the distribution of asthma control in the population (Schatz et al., 2006; Soler et al., 2018).

The initial cohort consisted of a random sample of 5,000 individuals with asthma who resided in counties affected from wildfire smoke (i.e., any presence of wildfire smoke as described below). This value was chosen to allow sufficient stochastic variability to ensure precision in results while limiting computing requirements, and it is equivalent to roughly 0.2% of the California population with asthma. Further details of the generation of microdata as well as all data sources are available in Supporting Information S1.

2.2. Model Structure

We simulated a closed cohort of 5,000 individuals with asthma who resided in counties exposed to wildfire smoke during the selected wildfire event (see below) based on monitoring data. In keeping with prior asthma models, we used discrete time steps of 1 week to ensure only a single event occurs within each cycle (FitzGerald et al., 2020; Gerzeli et al., 2012). Projections were made out to 16 weeks, which exceeded the number of cycles required for disease states to re-equilibrate after the disruption.

Two scenarios were modeled, one with no wildfire occurrence (thus no smoke exposure) and one reflecting smoke pollution from a wildfire event. In order to reduce noise due to stochastic variability and ensure that differences between scenarios were only due to changes in wildfire exposure, we used a fixed random seed for both scenarios. The model was developed in R version 4.1.3 and the code is available on GitHub (Maya, 2024).

During each cycle, we calculate a set of transition probabilities for each individual based on disease state (i.e., asthma control state) in which they enter the cycle, their age, their exposure to wildfire smoke in the previous cycle, and their exposure to wildfire smoke in the active cycle. These transition probabilities are then used for a random draw to determine that individual's next disease state. A second random draw is done to determine whether and which type of acute healthcare will be required for the individual during that cycle based on the new disease state they enter. Lastly, we deterministically calculate the health state utility and costs incurred in the cycle based on the new disease state (Oh et al., 2022; P. W. Sullivan et al., 2017).

Our model structure is not susceptible to threshold effects akin to those that might occur in models of communicable diseases (e.g., where a new sub-population may be seeded) (Ji & Jiang, 2014). We also modeled a relatively large sample size which helped limit sampling variability and led to stable estimates. We ensured the impact of the random seed on results was minimal by running the simulation 10 times with different random seeds, which did not generate any meaningful difference in results. Thus, we report findings from a single run.

2.3. Asthma Control and Transition Probabilities

Disease states were defined by the level of asthma control. This led to challenges in terms of populating model parameters as most asthma models in literature used acute exacerbations or health resource utilization (HRU) as their Markov states (Bateman et al., 2008, 2010; FitzGerald et al., 2020; Gerzeli et al., 2012). Nevertheless, we preferred to model asthma control to be able to distinguish small changes in asthma burden in response to wildfire smoke exposure, allowing a more nuanced depiction of the impact on quality of life and financial burden.

We included five asthma control states based on the GINA classification which relies on both asthma symptom control (e.g., frequency of daytime symptoms or reliever medication need) and risk factors for poor asthma outcomes (e.g., lung function, exposures, medications): completely controlled, well controlled, somewhat controlled, poorly controlled, and not controlled at all (Global Initiative for Asthma, 2019; Schatz et al., 2006). Two additional absorbing health states were defined for those who die of asthma and those who die of other causes. A "no asthma" state was also defined but was not used as the sample only consisted of those with asthma.

We were unable to readily identify transition probabilities for this 5-state asthma control framework in literature, as prior models had different definitions of asthma disease states. We resolved this by generating a transition probability matrix calibrated to produce predictions consistent with published empirical data on prevalence of asthma and the distribution of asthma control across the five GINA categories. The proportion of those with each level of asthma control in the calibrated model had a small cumulative difference of 4% × 4% from published proportions (see Supporting Information S1). The asthma risk factors included in the final model were age (categorical) and 2-week smoke exposure (continuous, see details below).

2.4. Wildfire Smoke Exposure

The 2018 California Camp Fire (8–25 November 2018) was selected as the fire event to model given wide availability of evidence on both the smoke pollution it caused and health outcomes it led to (Krystal & Angela, 2022; MacPherson, 2021; Naughten et al., 2022). Exposure was defined at the county level as the number of days with wildfire-specific smoke pollution in the past 2 weeks. Counties were exposed to median 8.0 $\mu g/m^3$ (interquartile range [IQR]: 5.3–11.4) of daily $PM_{2.5}$ in the 2 months leading to the wildfire. During the 2 weeks of wildfire activity, median daily $PM_{2.5}$ pollution (across all counties) rose to 36.1 $\mu g/m^3$ (IQR: 15.1–67.6), with a maximum of 342 $\mu g/m^3$ in Butte County on 16 November 2018 (US Environmental Protection Agency, 2018). As done previously, we calculated the specific impact of the Camp Fire on $PM_{2.5}$ pollution by first calculating the background pollution as the median daily $PM_{2.5}$ concentration in each county in the 2 months leading up to the wildfire, then subtracting this background pollution value from the daily average $PM_{2.5}$ concentration on each day the wildfire was active (Gan et al., 2020). Wildfire-specific pollution exposure was then defined as the number of days on which excess daily average $PM_{2.5}$ concentrations were greater than 35 $\mu g/m^3$ (Wu et al., 2019). Dates outside of the wildfire period were assigned zero for wildfire-specific $PM_{2.5}$ exposure. Each day of exposure to wildfire-specific $PM_{2.5}$ over the past 14 days was associated with a 1.049 odds ratio per day for worse asthma control (Wu et al., 2019).

2.5. Health Resource Utilization

Once an individual's next asthma control state was assigned, we used fixed probabilities to determine whether they would require acute HRU, which included oral corticosteroid bursts, urgent care visits, emergency department (ED) visits, and hospitalizations (S. D. Sullivan et al., 2007). Having both poorer asthma control and wildfire smoke exposure (as described above) increased the probability for HRU. That is, wildfire smoke exposure could lead to acute health care needs even without impacting underlying asthma control. A second set of HRU probabilities were calculated to reflect this increase in acute care risk given smoke presence, calibrated to empirical HRU data from prior California wildfires. These adjusted values were applied for individuals who have had at least one day of smoke exposure in that week, whereas the unadjusted HRU probabilities were used for those without exposure.

2.6. Quality-Adjusted Life Years and All-Cause Medical Costs

Asthma health burden was calculated in quality-adjusted life years (QALYs) using published health state utilities. Poorer asthma control was associated with lower health state utility and ranged from 0.95 for completely controlled asthma to 0.71 for not controlled (Oh et al., 2022). Following a severe exacerbation, defined as a decrease in asthma control to the "poorly controlled" or "not controlled at all" states, recovery of health state utility was spread out over 6 weeks, even if asthma control improved (Briggs et al., 2021).

Lastly, we calculated costs per person and total costs, which included all-cause medical costs (inpatient, outpatient, emergency room, and pharmacy expenditures) based on claims data and inflated to 2023 USD. As with health state utilities, poorer control of symptoms also led to greater medical costs, ranging from $5,214 on average for completely controlled asthma to $22,810 on average for not controlled asthma annually (P. W. Sullivan et al., 2017).

3. Results

3.1. Validation of Health Resource Utilization Predictions

The model was validated by comparing HRU outputs with empirical data on changes in asthma-related HRU after a wildfire (Hutchinson et al., 2018; Malig et al., 2021). After running both the "no wildfire smoke" and "wildfire smoke" scenarios, we found an average 31% increase in oral corticosteroid bursts and urgent care visits, 115% increase in ED visits, and 63% increase in hospitalizations. These results were corroborated by at least two empirical studies which looked at the same outcomes for two separate wildfire events in California and found

Table 1
Simulated Health Resource Utilization With and Without Exposure to Wildfire Smoke

	Simulated proportion, no wildfire	Simulated proportion, following 2 weeks of smoke days (peak poor health)	Simulated % change with 2 weeks of smoke exposure versus no smoke
No encounter	0.922	0.886	−4%
Oral corticosteroid burst	0.038	0.052	+35%
Urgent or outpatient care	0.034	0.043	+26%
Emergency department visit	0.005	0.011	+115%
Hospitalization	0.003	0.005	+63%

results in line with estimations made by the model (Table 1 and Supporting Information S1) (Hutchinson et al., 2018; Malig et al., 2021).

3.2. Calculated Health and Cost Burden

In the no wildfire smoke scenario (Figure 1), the model equilibrated with the majority the 5,000-person cohort in the well-controlled disease state (40%), followed by those with somewhat controlled asthma (27%) and poorly controlled asthma (19%). Throughout the modeled 16 weeks, approximately 0.2% of the cohort died of non-asthma causes. No asthma-related deaths occurred. Overall, in the absence of wildfire smoke, a total of 1,214 QALYs were generated over 16 weeks, with 0.24 QALYs per person on average. For context, 16 weeks in perfect health would equate to 1,538 QALYs for a cohort of the same size, equating to 324 QALYs lost due to wildfire smoke.

In the wildfire smoke scenario (Figure 1), one or more days of exposure to excess $PM_{2.5}$ concentrations above 35 μg/m^3 during a wildfire event led to worse asthma control. The cohort of 5,000 had a total of 49,650 person-days of exposure to excess $PM_{2.5}$ concentration, approximately 10 days of exposure per person. After the 2-week

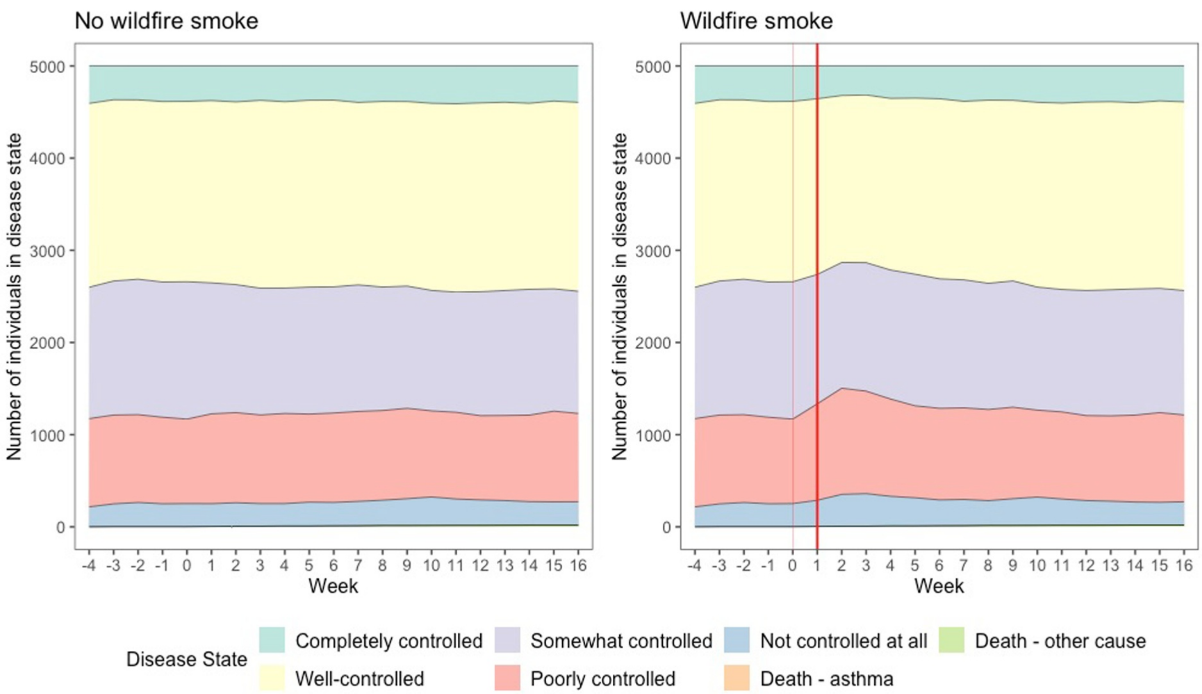

Figure 1. Simulation trace without and with wildfire smoke in the first 2 weeks. Vertical lines indicate smoke exposure throughout the following cycle, with thicker lines representing greater exposure intensity.

fire duration, when the exposure to wildfire smoke subsided, 351 additional individuals out of 5,000 had worsened asthma control, representing a 1.34 relative risk of worsening compared to the scenario without wildfire smoke exposure. Consequently, compared to the same timepoint in the no wildfire smoke cohort, the proportion of individuals with completely or well controlled asthma was 17% and 10% lower, respectively, in the wildfire smoke cohort. Poorly controlled and not controlled asthma symptoms increased by 21% and 33%, respectively. The proportion with somewhat controlled asthma remained stable across the two scenarios. While the average per person reduction in QALYs was small (0.7% decrease), the wildfire cohort experienced eight fewer QALYs over 16 weeks.

Worsening asthma control and increased health resource utilization in turn increased medical costs. Over 16 weeks, mean all-cause medical costs per person in the no-wildfire scenario were $2,533. In the wildfire scenario, this increased by 4.7%, to $2,653. Overall, the wildfire cohort incurred an additional $601,250 compared to the no-wildfire cohort, for a total cost of $13.2 million in 16 weeks for 5,000 individuals.

4. Discussion

We modeled the impact of wildfire smoke exposure on asthma outcomes in California using microsimulation methods, calibrated to empirical estimates of the distribution of asthma control and wildfire smoke-related HRU increase. Our findings indicate 34% greater risk of worsening asthma control among those exposed to PM2.5 pollution from a wildfire, with 17%–10% lower prevalence of complete and well-controlled asthma, and up to one-third greater prevalence of poorly and not controlled asthma during and immediately after exposure to wildfire smoke. The rate of return to baseline symptoms post-wildfire were aligned with observational studies. Similarly, projected increases in acute HRU, including a doubling of ED visits for asthma during the wildfire, was in line with previous observations from California wildfires.

Our simulation showed that wildfire smoke exposure had a modest effect on asthma-associated QALYs. Over 16 weeks during and after a single fire event, mean QALYs per person were only 0.002 fewer than if there was no wildfire. While this seems small, it added up to eight QALYs lost in 4 months for a cohort of 5,000. Scaled up to the full California population, we estimate that 4,320 QALYs would be lost due to asthma-related impacts of smoke from a single wildfire incident.

The financial impacts of wildfire smoke exposure for people with asthma is similarly likely to be substantial. While we could not identify any studies specific to people with asthma, it is estimated that the Camp Fire led to $210 million in medical expenditures in California in the year that followed (Wang et al., 2021). In our model, we estimated that 5,000 Californians with asthma would incur over $600,000 in excess all-cause medical costs within 4 months of being exposed to smoke from a wildfire that burned for 2 weeks. Scaled up, this would suggest $324 million excess costs, even in the absence of additional wildfires.

The use of microsimulation in climate and health research to date has been limited (Marvuglia et al., 2020; Stephen & Barnett, 2017; Symonds et al., 2019). Yet, it is a powerful tool that can estimate changes in population health over time and across heterogeneous populations, and inform intervention design and evaluate benefits before interventions are implemented (Kopasker et al., 2023). Potential uses are numerous, including investigation of a wide array of climate-sensitive health conditions from heat-related illnesses to mental health impacts of extreme weather events, development of preventive strategies and their evaluation and comparison, and identification of most vulnerable populations for targeting interventions.

Results from this microsimulation model should be considered along with several limitations. First, our exposure variable was defined at the county-level as opposed to the individual-level; thus, it is possible that some misclassification of exposure has occurred, especially considering that the residents of most affected counties would have evacuated. We assume the effect of this would be negligible given that smoke carries to nearby counties where people in the immediate area of the fire would have evacuated to, where they would still be exposed to smoke and remain at risk for poor asthma outcomes (Butte County Office of Emergency Management, 2020). Second, we assumed transition probabilities are not time-dependent that is, they do not depend on how long the individual has been in a given disease state. This is likely an over-simplification, and its effect on results is difficult to estimate. On one hand, if individuals who have had consistently controlled asthma symptoms are less likely to transition to poorer control, we may have overestimated the negative impact of wildfire smoke exposure on asthma burden. On the contrary, if those who have had consistently poor asthma control are less likely to improve, we may have underestimated the negative impact of wildfire smoke exposure on asthma burden. It is likely that both these statements are true, which would suggest that these effects could, at least partially, offset one another. However, this might be an important point to consider in future iterations of the model to better represent asthma control dynamics, especially if modeling multiple wildfire exposures over longer time horizons. Lastly, we implicitly capture the impact of asthma medication adherence on control by calibrating the model for distribution of asthma control, thus we are unable to explicitly account for and modify this factor. This limits the use of the current model for testing interventions affecting medication adherence.

5. Conclusions

As the threat of wildfires grows in California and other vulnerable areas of the world, it will become increasingly important to understand their impacts on health and associated costs, and how those impacts can be mitigated. Our model exemplifies one such effort to evaluate the impact of wildfire smoke on asthma-related health and costs, and it is novel in its approach of using nuanced disease states and a highly customizable microsimulation structure. Further applications of this simulation can enhance our understanding of complex relationships between wildfire smoke exposure and asthma in ways that allow highly targeted interventions. For instance, by incorporating projections of future wildfire risk in specific geographies, it will be possible to predict regional and local acute HRU needs, which can drive concrete interventions to proactively increase hospital, clinic and community resilience before the healthcare structure becomes overwhelmed. Mitigation interventions to prevent health harms of wildfire smoke, such as the use of air filters to reduce exposure or mobile warning systems to influence health behavior (Adibi et al., 2023; Barrett et al., 2018), may also be evaluated to inform decision-making. Furthermore, the model can help identify specific sub-populations that may be disproportionately vulnerable for adverse outcomes or financial impacts, and who might benefit most from interventions to alleviate these risks. Such insights are crucial to designing effective and equitable policies and interventions to improve health in the face of climate change.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Data Availability Statement

All data, code, and supporting documents used in this analysis are available in Maya (2024).

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