## Quantifying the health benefits of face masks and respirators to mitigate exposure to severe air pollution

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#### Abstract

Familiarity with the use of face coverings to reduce the risk of respiratory disease has increased during the coronavirus pandemic; however, recommendations for their use outside of the pandemic remains limited. Here, we develop a modeling framework to quantify the potential health benefits of wearing a face covering or respirator to mitigate exposure to severe air pollution. This framework accounts for the wide range of available face coverings and respirators, fit factors and efficacy, air pollution characteristics, and exposure-response data. Our modeling shows that N95 respirators offer robust protection against different sources of air pollution, reducing exposure by more than a factor of 14 when worn with a leak rate of 5%. Synthetic-fiber masks offer less protection with a strong dependence on aerosol size distribution (protection factors ranging from 4.4 to 2.2.), while natural-fiber and surgical masks offer reductions in exposure of 1.9 and 1.7, respectively. To assess the ability of face coverings to provide population-level health benefits to wildfire smoke, we perform a case study for the 2012 Washington state fire season. Our models suggest that although natural-fiber masks offer minor reductions in respiratory hospitalizations attributable to smoke (2-11%) due to limited filtration efficiency, N95 respirators and to a lesser extent surgical and synthetic-fiber masks may lead to notable reductions in smoke-attributable hospitalizations (22-39%, 9-24%, and 7-18%, respectively). The filtration efficiency, bypass rate, compliance rate (fraction of time and population wearing the device) are the key factors governing exposure reduction potential and health benefits during severe air pollution events.

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## **Key Points:**

- We developed a framework to quantify potential health benefits of wearing a face mask or respirator during episodes of severe air pollution.
- N95 respirators offer protection against wildfire PM<sub>2.5</sub>, reducing exposure by more than a factor of 14 and hospitalizations by 22-39%.
- Natural-fiber (e.g., cotton) masks offer only minor protection against wildfire PM<sub>2.5</sub>, reducing hospitalizations by only 2-11%.

## Abstract

Familiarity with the use of face coverings to reduce the risk of respiratory disease has increased during the coronavirus pandemic; however, recommendations for their use outside of the pandemic remains limited. Here, we develop a modeling framework to quantify the potential health benefits of wearing a face covering or respirator to mitigate exposure to severe air pollution. This framework accounts for the wide range of available face coverings and respirators, fit factors and efficacy, air pollution characteristics, and exposure-response data. Our modeling shows that N95 respirators offer robust protection against different sources of air pollution, reducing exposure by more than a factor of 14 when worn with a leak rate of 5%. Synthetic-fiber masks offer less protection with a strong dependence on aerosol size distribution (protection factors ranging from 4.4 to 2.2.), while natural-fiber and surgical masks offer reductions in exposure of 1.9 and 1.7, respectively. To assess the ability of face coverings to provide population-level health benefits to wildfire smoke, we perform a case study for the 2012 Washington state fire season. Our models suggest that although natural-fiber masks offer minor reductions in respiratory hospitalizations attributable to smoke (2-11%) due to limited filtration efficiency, N95 respirators and to a lesser extent surgical and synthetic-fiber masks may lead to notable reductions in smoke-attributable hospitalizations (22-39%, 9-24%, and 7-18%, respectively). The filtration efficiency, bypass rate, compliance rate (fraction of time and population wearing the device) are the key factors governing exposure reduction potential and health benefits during severe air pollution events.

#### **Plain Language Summary**

The use of face coverings (e.g., cloth masks, surgical masks, N95 respirators) has increased dramatically during the coronavirus pandemic; however, recommendations for their use outside of the pandemic as a means to reduce exposure to other health risks, such as severe air pollution, remains limited. In this study, we develop a modeling framework to quantify the potential health benefits of wearing a face covering as a means to reduce exposure to severe air pollution. This framework accounts for the wide availability of masks and respirators, how well they fit, the characteristics of air pollution, and the relationship between exposure and adverse health outcomes. We find that N95 respirators offer a promising means to reduce air pollution exposure and the associated health risk; however, the public health benefits are strongly dependent on how often and by how many people the respirator is worn. Using realistic estimates of mask wearing compliance to protect against wildfire smoke in a case study in Washington state in 2012, we estimate that the use of N95 respirators could reduce respiratory hospitalizations attributable to wildfire smoke by 22-39%. Conversely, natural-fiber masks offer only limited protection against air pollution due to poor filtration efficiency and poor fit.

## **1** Introduction

The use of face coverings (i.e., natural- and synthetic-fiber face masks and respirators) by the general population has increased substantially during the coronavirus pandemic as a means to reduce the risk of airborne infectious disease transmission (Cheng et al., 2020; Lyu et al., 2020). Outside of the coronavirus pandemic, face masks and respirators have been used previously in

Asia to limit exposure to infectious droplets and air pollutants (Lay et al., 2004; Langrish et al., 2009; Cherrie et al., 2018). However, in many western countries (including the United States) their use in non-occupational settings has historically been limited (e.g., Sugerman et al., 2012). Moreover, specific recommendations on the effectiveness of face coverings for mitigating risk factors contributing to respiratory disease among the public are limited (e.g., Laumbach et al., 2019; Rajagopalan et al., 2020). While studies of mask efficacy in the laboratory have become increasingly common during the coronavirus pandemic (e.g., Leith et al., 2021; Rothamer et al., 2021), we lack a rigorous framework to estimate potential health benefits of widespread mask use as means of mitigating exposure risk from aerosol and air pollution hazards.

One such risk factor contributing to increased risk of respiratory disease is acute exposure to airborne particulate matter during episodes of severe air pollution (Fan et al., 2016; Lim et al., 2016). Short-term exposure to fine particulate matter ( $PM_{2.5}$ ; particles with aerodynamic diameters smaller than 2.5 µm) is associated with increased risk of asthma, chronic obstructive pulmonary disease, and respiratory infection (Bell et al., 2013; DeVries et al., 2017; Horne et al., 2018; Zuo et al., 2019). Face masks and respirators, with their ability to filter out a fraction of particulate matter, may offer a means to reduce exposure to  $PM_{2.5}$  and thus reduce the associated risk of acute respiratory outcomes.

Climate change has increased the frequency and severity of wildfires in the Western United States, thereby increasing the number of smoke-impacted days in populated areas (Westerling et al., 2006; O'Dell et al., 2019; Ford et al., 2018). Wildfire smoke events can produce an appreciable public health burden as a result of large population exposure to potentially high concentrations of PM<sub>2.5</sub> (Val Martin et al., 2015; Brey et al., 2017; Sorensen et al., 2021). Of the constituents in smoke, PM<sub>2.5</sub> is thought to be the primary contaminant leading to increased risk factors of ill health, though gas-phase components may also contribute to negative health outcomes (e.g., O'Dell et al., 2020). Emerging research has further suggested that PM<sub>2.5</sub> from wildfire smoke may be more toxic and thus pose an even larger increased risk of respiratory disease than other air pollutant emission sources (Gan et al., 2017; Alman et al., 2016; Borchers Borchers Arriagada et al., 2019; Aguilera et al., 2021).

Face coverings (e.g., cloth masks, synthetic masks, and respirators) may reduce the risk of adverse respiratory outcomes by limiting the intake of PM<sub>2.5</sub>. The degree to which a mask or respirator reduces the intake of PM<sub>2.5</sub> is commonly quantified by the protection factor (PF), which describes the ratio of particles upstream and downstream of the device. The PF is a function of the filtration efficiency of the mask and how well it fits over the face (influencing the amount of air that bypasses the mask itself) (Leith et al., 2020). Mask filtration efficiency varies greatly between different face coverings and is dependent on the material (type of fabric, fiber diameter, fabric structure), number of layers, and velocity of air flow through the mask (Chua et al., 2020; Leith et al., 2021). Mask filtration efficiency can exhibit a strong size dependence, where particles with relatively small diameters (~0.01 to ~0.1  $\mu$ m) are collected by the mask primarily by diffusive mechanisms and particles with relatively larger diameters (~0.7 to ~10  $\mu$ m) are collected primarily by inertial mechanisms (Hinds, 1999). For some face coverings, such as most N95 respirators, particle collection across all sizes may be enhanced by the presence of electrostatic charge imbued on the fibers themselves (Hossain et al., 2020; Kerner et al., 2020).

Due to the strong particle size dependence of face masks and respirators, the PF is also dependent on the particle size distribution to which an individual is exposed. Thus, a face mask may be more or less effective against certain types of aerosol hazards (depending on the underlying size distribution).

The large variability in the type, fit, filtration ability, and wearability of face coverings has led to conflicting results regarding the effectiveness of face masks and respirators at reducing exposure (and associated health risks) to ambient PM<sub>2.5</sub> air pollution (Rajagopalan et al., 2020). Langrish et al. (2009) tested a variety of commercially available face coverings and found penetrance of diesel exhaust particles through the mask ranged from 0.3% for highly efficient respirators, 20% for surgical masks, and up to 72% for a cotton handkerchief. Similarly, Cherrie et al. (2018) tested commercially available face masks with diesel exhaust and found penetrance ranging from 0.3-29%; however, the leakage rate of air around the masks (3-68% for sedentary tasks and 7-66% for active tasks) severely limited their overall effectiveness. A randomized crossover trial showed that wearing a dust respirator when walking around Beijing, China, appeared to improve a range of cardiovascular health measures (Langrish et al., 2012). Specifically for protection against wildfires, Kunzli et al. (2006) found that children who wore face masks reported lower rates of symptoms (sneezing and wheezing) than those that did not; however, Mott et al. (2002) described no self-reported protective effects associated with mask use and speculated this may be due to inconsistent use, bad fit, or variable filtration efficiency. The importance of the fit of a face covering or respirator is further demonstrated in Kelley (2020), where training on achieving a proper fit from an N95 respirator increased the expected reduction in exposure to a test aerosol from 50% to 90%. Given these results, a need exists to develop a framework that can quantify population health benefits of face masks and respirators, while accounting for factors such as aerosol size distribution, mask wearability and effectiveness, and known exposure-response relationships for a given aerosol hazard. The framework should also account for uncertainty surrounding each of these factors.

In this study, we describe a framework to quantify the potential health benefits from wearing a face covering as a means to mitigate air pollution exposure at the population level. To demonstrate this framework, we perform a health impact assessment (HIA) over the fire season (July to October) in Washington state in 2012 to estimate population-level health benefits from mask wearing during acute wildfire smoke events. While this framework is applied here to examine possible reductions in health risk due to severe air pollution from wildfires, it can be applied to other types of aerosol hazards (e.g., urban air pollution, dust storms, and airborne infectious pathogens). In Section 2.1, we discuss the method of measuring filtration efficiency across a range of particle diameters relevant for aerosol hazards. In Sections 2.2-2.4, we present our methodology for calculating protection factors, health risk, and uncertain input parameters. In Sections 3.1 and 3.2, we present measurements of mask filtration efficiency and protection factors relevant for different types of air pollution. In Sections 3.3 and 3.4, we apply the HIA to a case study in Washington state. In Section 3.5, we perform a sensitivity analysis on the HIA to determine the influence of uncertain input model parameters. Finally, in Section 4, we discuss study limitations and conclusions.

## 2 Materials and Methods

## 2.1 Measurements of mask filtration efficiency

Measurements of mask filtration took place within a 0.7 m<sup>3</sup> aerosol chamber at the Center for Energy Development and Health at Colorado State University. Face masks and respirators were attached to an 89 mm (inner) diameter cylinder, meant to be roughly representative of the area air flows through a mask when worn. The cylinder was attached to a vertical sampling column within the chamber. Total flow rate through the sampling column was kept constant at 15 L min<sup>-1</sup>, meant to approximate the flow rate during inhalation at rest and not speaking (Bailey & Hoit, 2002). This laboratory setup and procedure is discussed in further detail in Leith et al. (2021).

To measure filtration across a wide range of particle diameters relevant to ambient PM air pollution (~0.01 to 10 µm), we combined separate measurements from a Scanning Mobility Particle Sizer (Classifier Model 3802, CPC Model 3787, TSI Inch Shoreview, MN), measuring particles with electrical mobility diameters ranging from 0.015 µm to 0.7 µm, and an Aerodynamic Particle Sizer (APS Model 3321, TSI Inch Shoreview, MN), measuring aerodynamic particle sizes between 0.5 to 10 µm. To generate particles with diameters in the smaller size range, a 2-Jet Collison Nebulizer (Mesa Labs; https://bgi.mesalabs.com) generated ammonium sulfate aerosol from 2% w/w aqueous ammonium sulfate, resulting in polydisperse aerosol with a geometric count median diameter of 68 nm and geometric standard deviation of 2.1. For the larger size range (greater than 0.5 µm), nonvolatile compressor oil droplets (Ace Hardware Corp., Oak Brook, IL) were generated with a second nebulizer (Micro Mist 1880, Hudson Respiratory Care Inc., Temecula, CA) as described in Leith et al. (2021). Mask filtration efficiency was measured separately for each aerosol type (i.e. the ammonium sulfate and the compressor oil droplets were not emitted simultaneously). Two or three minute samples were taken either by the APS or SMPS, respectively, with and without the mask attached to the sampling column. Mask filtration efficiency was then calculated from the measured particle counts when the mask is attached to the column divided by measured particle counts without the mask (following Equation 4 in Leith et al., 2021).

The SMPS measures particle electrical mobility diameters while the APS measures aerodynamic diameters. To combine the separate measurements from each instrument, we convert both diameters to volume equivalent diameters following the discussion in Tryner et al. (2020) and DeCarlo et al. (2004). We assume the ammonium sulfate aerosol has a shape factor of 1 and density of 1.77 g cm<sup>-3</sup> while the compressed oil has a density of 0.867 cm<sup>-3</sup>.

We characterize filtration efficiency for four mask types: re-usable natural-fiber (cotton) face masks ("Natural"), a disposable synthetic-fiber mask ("Synthetic"), a medical procedure mask ("Surgical"), and KN95/N95 ("N95") respirator. To reflect the many different available options, the natural-fiber mask type is the average of three different natural-fiber masks, composed of either two or three layers of fabric. The disposable synthetic-fiber mask is composed of only one layer of material. The KN95 respirator meets the requirements for breathability and filtration efficiency for an N95, and so we assume this filtration efficiency as a typical N95 efficiency for

our modeling purposes. These face masks and respirators are the same as reported in Leith et al. (2021). In response to the coronavirus pandemic, ASTM International created standard specifications for face masks that were neither medical nor respirators (ASTM F3502-21). We use these standards to contextualize the masks investigated here. The Level 1 standard is defined as a filtration efficiency greater than or equal to 20% for sub-micron aerosol (against a challenge aerosol distribution with count median diameter of 75 nm and geometric standard deviation of 1.9), while the Level 2 standard is greater than or equal to 50% filtration efficiency for a similar aerosol.

2.2 Calculation of protection factors

To calculate the protection factor (PF) of each face mask and respirator, we use a simplified form of the equation discussed in Leith et al. (2021) that only includes inhalation while not speaking:

$$PF = \frac{1}{P(1-B) + B}$$
(1)

where PF is the protection factor, P is the integrated filter penetration over the size range weighted by the aerosol mass distribution of exposure, and B is the bypass (or leakage) rate. As P is integrated over the entire size range, the resulting protection factor is thus a function of the particle size distribution of exposure. In this study, we do not measure the bypass rate for each mask, and instead use a range of reasonable values from published literature (discussed in Section 2.4).

## 2.3 Health impact assessment (HIA) including face coverings

To quantify the health benefits of face masks and respirators in a population, we expand upon HIAs developed to quantify the increased risk and associated health outcomes due to acute exposure to  $PM_{2.5}$ . These HIAs are based on epidemiologic studies that link the increased risk of a health outcome to a standard increase in  $PM_{2.5}$  concentration (usually 10 µg m<sup>-3</sup>). The increased risk due to a given ambient  $PM_{2.5}$  concentration ( $PM_{amb}$ ) can be calculated from:

$$RR = exp\left(\beta \frac{PM_{amb}}{PM_0}\right) \tag{2}$$

where *RR* is the relative risk,  $\beta$  is the natural log of the odds ratio describing the increased risk from an incremental increase PM<sub>2.5</sub> concentration termed *PM*<sub>0</sub>.

If a face mask or respirator is worn, we assume that the ambient  $PM_{2.5}$  concentration used to estimate health risk can be scaled based on the protection factor of the mask and the fraction of the day the mask is worn, producing a mean exposure concentration resulting from use of a mask ( $PM_{mask}$ ). Thus,  $PM_{mask}$  can be calculated using  $PM_{amb}$ , the PF of the mask in question, and the fraction of the day spent wearing a mask ( $f_{day}$ ):

$$PM_{mask} = \left(\frac{PM_{amb}}{PF}f_{day}\right) + \left(PM_{amb}\left(1 - f_{day}\right)\right)$$
(3)

Finally, the health outcome (i.e., number of hospital admissions) across the entire population can be calculated from:

$$Outcome = \left[\frac{RR_{amb} - 1}{RR_{amb}} * BR * N * (1 - f_{mask})\right] + \left[\frac{RR_{mask} - 1}{RR_{mask}} * BR * N * f_{mask}\right]$$
(4)

where  $RR_{amb}$  is the relative risk if no mask is worn (based on  $PM_{amb}$ ), BR is the baseline incidence rate of the health outcome, N is the exposed population,  $f_{mask}$  is the fraction of the population wearing a mask, and  $RR_{mask}$  is the relative risk if a mask is worn (based around  $PM_{mask}$ ). In the absence of any mask use (i.e., when  $f_{mask}$  or  $f_{day}$  is set to 0), this expanded HIA will simplify to a standard HIA model for acute exposure to PM<sub>2.5</sub>.

We apply this HIA in a case study to estimate the number of respiratory hospital admissions (ICD-9-CM: 460-519) as well as the number of hospital admissions for asthma (ICD-9-CM: 493; this number is included in the all-respiratory outcome) due to acute exposure to wildfire smoke PM2.5 in Washington state between July and October 2012. Smoke PM2.5 concentrations were estimated in a previous study (Lassman et al., 2017) using surface monitors and a chemical-transport model. Corresponding odds ratios for the health outcomes considered here, respiratory and asthma hospital admissions, were calculated in Gan et al. (2017) using the smoke PM<sub>2.5</sub> concentrations from Lassman et al. (2017) and a dataset of zip-code level hospital admissions. The odds ratios calculated in Gan et al. (2017) are specific to a 10  $\mu$ g m<sup>-3</sup> increase (PM<sub>0</sub> in Equation 2) in wildfire smoke PM<sub>2.5</sub>, and thus the PM<sub>amb</sub> in Equations 2 and 3 refer to the ambient wildfire smoke PM2.5 concentration (i.e., the proportion of ambient PM2.5 that is attributable to a wildfire source). There is no threshold wildfire smoke PM2.5 concentration below which there are no associated health effects in Gan et al. (2017). The previous studies by Gan et al. (2017) and Lassman et al. (2017) allow for a convenient case study on the potential of mask use to reduce the number of hospitalizations due to acute exposure to wildfire smoke PM2.5. For simplicity, we use the lag-0 exposures and odds ratio, referring to the increased risk of hospital admission due to smoke exposure that took place that same day. We do not include age or genderspecific risk modifiers. To calculate distributions of estimates of wildfire smoke attributable hospital admissions, we randomly sample across an assumed range of input parameters (described in the following section).

## 2.4 Model sensitivity analysis

This HIA is based on uncertain model input parameters related to mask use, mask wearability and filtration efficiency, characteristics of the PM<sub>2.5</sub> exposure, and health statistics. The uncertain input parameters to the model framework as well as their default values and uncertainty ranges are described in Table 1. To quantify the sensitivity of estimated wildfire smoke attributable hospital admissions to the uncertainty in model input parameters, we perform two types of sensitivity studies. The first is a one-at-a-time sensitivity study to explore the dependence on the number of respiratory hospital admissions in the case study to the fraction of the population wearing a mask and the mask filtration efficiency. To accomplish this, we vary  $f_{mask}$ from 0 to 1 and calculate the number of hospital admissions with the average and +/- 1 standard deviation in measured mask filtration efficiency.

The second sensitivity study is a global variance-based sensitivity analysis (Saltelli et al., 2007). Here, we sample ~10,000 sets of input parameters (sampling from the input parameter ranges described in Table 1) and calculate the total number of respiratory and asthma hospital admissions as well as the relative decrease in admissions attributable to wildfire smoke with a mask relative to without a mask. This approach allows for the quantification of the contribution of each uncertain input parameter to the total variance in the model output (respiratory or asthma hospital admissions). We use the Fourier Amplitude Sensitivity Test (FAST; Saltelli et al., 1999) implemented in Python (Herman and Usher, 2017) to sample the input parameter space and apportion the variance in the output distribution to the contribution by each input parameter. In this study, we report only the main effect index (or the first-order or additive effect), which describes the expected reduction in uncertainty if each parameter was held fixed (Saltelli et al., 2010). We assume the odds ratio follows a normal distribution, following the reporting in Gan et al. (2017), while all other input parameters are sampled from uniform distributions.

## **3** Results

3.1 Measurements of mask filtration efficiency

The minimum filtration efficiency for each device has a clear dependence on the method of filtration (Figure 1 and Table 2). The face masks which rely on mechanical filtration (the natural- and synthetic-fiber masks) exhibit minima in filtration efficiency for particle diameters of 0.5-0.6  $\mu$ m. The N95 respirator and surgical mask, which use a combination of mechanical and electrostatic filtration, exhibit minima in filtration efficiency for particle diameters of 0.04-0.05  $\mu$ m, in good agreement with previous studies (Rengasamy et al., 2014; Kerner et al., 2020).

The average filtration efficiency of natural-fiber masks reaches a minimum of 20% for particle volume-equivalent diameters of 0.5-0.6  $\mu$ m compared to a minimum of roughly 50% for the synthetic-fiber mask. The natural- and synthetic-fiber masks thus roughly adhere to the ASTM International barrier standards for Level 1 (at least 20% efficiency for sub-micron particles) and Level 2 (at least 50% efficiency for sub-micron particles), respectively (ASTM F3052-

21). The filtration efficiency for natural-fiber masks increases rapidly for particle sizes larger than 2  $\mu$ m (due to collection via impaction) and gradually for particle diameters smaller than 0.2  $\mu$ m (due to collection via diffusion). The synthetic-fiber mask achieves filtration efficiencies roughly equal to the N95 respirator for particle diameters larger than 3  $\mu$ m.

The surgical mask exhibits moderate size dependence on filtration efficiency in the submicron diameter range, reaching a minimum in filtration efficiency of 90% at 0.04  $\mu$ m. Conversely, the N95 respirators exhibit only minor size dependence, with a minimum in efficiency of 97% at 0.05  $\mu$ m.

## 3.2 Protection factors for typical air pollution size distributions

To assess the degree of protection offered by each mask to air pollution exposure, we assume 3 lognormal size distributions characteristic of different sources of PM<sub>2.5</sub>: urban (i.e. fossilfuel combustion) aerosol with a number median diameter (NMD) of 0.03  $\mu$ m and a geometric standard deviation ( $\sigma_g$ ) of 2, wildfire smoke (with an NMD of 0.1  $\mu$ m and  $\sigma_g$  of 2), and dust (trimodal distribution with NMDs of 0.16, 1.4, and 10  $\mu$ m and  $\sigma_g$  values of 2.1, 1.9, and 1.6, respectively; d'Almeida et al., 1987; Karydis et al., 2011). In this calculation, we assume default values for the bypass rate of air around the filtering piece of the face mask or respirator (Table 1): 5% for the natural-fiber mask, 5% for the synthetic-fiber mask, 50% for the surgical mask, and 5% for the N95. This assumption is intended to provide optimistic (and realistic) protection factors for each face covering.

As expected, the N95 respirator offers the highest degree of protection against all three hypothetical exposure size distributions with PFs exceeding 14 for smaller urban aerosol size distributions and 18 for larger dust aerosol size distributions (Figure 2 and Table 2) when worn with a 5% bypass rate. Conversely, the surgical mask, which has filtration efficiencies exceeding 90% throughout the size distribution, has PFs of only 1.9. This is due to the poor fit typically reported for surgical masks (e.g., Brooks et al., 2021), allowing a relatively high percentage (in this case 50%) of the air flow to bypass the filtering piece.

The non-electrostatic filtering masks (the natural- and synthetic-fiber masks), worn with a bypass rate of 5%, have the lowest PFs for the aerosol size distribution corresponding to wildfire PM (1.4 and 2.2, respectively). The filtration efficiency for the mechanical-filtering masks reaches a minima around 0.5-0.6  $\mu$ m, which is near the peak size in the assumed aerosol mass distribution for wildfire smoke. The effectiveness of the synthetic-fiber mask has a strong particle size dependence. The PFs vary by ~2x (4.4 to 2.2) across the size distributions tested here. While the PF for the synthetic-fiber mask is notably lower than for the N95 respirator, it still provides a fair amount of protection against PM<sub>2.5</sub> exposure. Exposure to wildfire PM<sub>2.5</sub> may be reduced by more than a factor of 2 over not wearing a mask. Interestingly, the synthetic-fiber mask provides a relatively large degree of protection (PF of 3.9) to the size distribution representing fossil-fuel combustion emissions. This may be of interest to cyclists commuting in traffic (to limit exposure to car exhaust) or workers in toll booths or tunnels. Finally, the natural-fiber masks offer only limited protection at all three size ranges, ranging from 1.4-2.0. A well-fitting

natural-fiber mask (with low filtration efficiency) is able to achieve nearly to the same PF (1.4) for wildfire smoke as the poor fitting (with high filtration efficiency) surgical mask (PF of 1.9).

3.3 Relative health risk

To relate this reduction in exposure to a reduction in health risk, we calculate the increased risk of respiratory hospitalization due to acute exposure to a range of wildfire smoke  $PM_{2.5}$  concentrations. For this calculation, we use the default values specified in Table 1. The relatively low bypass rate and relatively large fraction of the day the mask is worn represent realistic "best case" scenarios for mask use.

Acute exposure to 100  $\mu$ g m<sup>-3</sup> of wildfire smoke PM<sub>2.5</sub> is associated with an increased population-mean relative risk (RR<sub>100</sub>) of 66% for respiratory hospitalization (Figure 3 and Table 2) when no mask is worn. The curves for asthma hospitalizations are similar to that of respiratory hospitalizations and included in the Supplemental Material (Figure S1). The natural-fiber masks reduce the increased risk of respiratory hospitalization at this exposure from 66% in the no-mask case to 50% when worn with the default parameter assumptions (5% bypass rate for 2/3<sup>rds</sup> of the day). The poorly fitting surgical mask (bypass rate of 50%) further reduces the increased risk down to 41%. The synthetic-fiber mask reduces this increased risk down to 38%, while the N95 respirators reduce the risk down to 21%. Note that while the N95 respirator removes at least 97% of the particles, the increased risk is only reduced by about 2/3<sup>rds</sup> due to the limiting assumptions of (1) a 5% bypass rate and (2) the respirator being worn 66% of the day.

These curves are highly dependent on the input parameters (particularly the fraction of the day the mask is worn,  $f_{day}$ ). An individual at a higher risk of respiratory disease can take care to wear a mask for longer periods of time and with a tight fit to achieve notable reduction in risk. We note that the assumption of wearing a mask  $2/3^{rds}$  of the day (and with minimal bypass) may not be reasonable assumptions for all members of the population. In the following sections, we relax these assumptions to show reasonable population-level health benefits for mask use.

## 3.4 Case Study: Health Impact Assessment in Washington 2012

Between July 1st and October 1st 2012, there were a number of large wildfires impacting air quality in Washington state (Lassman et al., 2017). Daily population-weighted  $PM_{2.5}$  from wildfire smoke exceeded 120 µg m<sup>-3</sup> in several zip codes on the heaviest smoke-impacted days (Figure 4). Over this period there was a total of 1,456 hospital admissions for asthma and 9,657 respiratory hospital admissions (including asthma).

As a baseline case, we calculate the number of asthma and respiratory hospital admissions in Washington between July-October 2012 assuming no mask use. We calculate that of the 1,456 asthma hospital admissions, 83 (with standard deviation [SD] ranging from 54-111) are attributable to acute exposure to wildfire smoke PM<sub>2.5</sub>. Of the 9,657 respiratory admissions, we estimate 385 (SD: 293-478) are attributable to acute exposure to wildfire smoke PM<sub>2.5</sub>. (Figure 4 and Table 2). The one standard deviation uncertainty range is due to the uncertainty in the odds ratio that determines the shape of the exposure-response curve (see following Section for further

discussion of uncertainties). The geographic regions with the highest number of admissions are roughly the confluence of the population and smoke concentration.

To quantify the expected health benefit for each type of filtering device, we calculate the percent difference in hospital admissions from acute wildfire smoke PM<sub>2.5</sub> exposure with each face covering relative to the case of no mask or respirator use. In this calculation, we randomly sample from the assumed input parameter ranges for the fraction of the population and fraction of the day the mask or respirator is worn, the bypass rate, filtration efficiency, exposure size distribution, and odds ratio (bounds shown in Table 1). The relative decrease in admissions is similar for both asthma and respiratory outcomes and thus only the respiratory outcome is shown here. Across the input parameter space for the use of N95 respirators, the number of respiratory hospitalizations attributable to wildfire smoke PM<sub>2.5</sub> is reduced on average by 30% (SD: 22-39%) over a population not wearing a face covering during the wildfire smoke season (Figure 5 and Table 2). Despite high filtration efficiencies and high protection factors when assuming only a 5% bypass rate, realistic parameter ranges across the population for wearing compliance and bypass rate limit the predicted range in public health benefits of the N95 respirator at the population level. The surgical and synthetic-fiber masks offer a moderate amount of reduction in hospitalizations, reducing hospitalizations by 17% (SD: 9-24%) and 13% (SD: 7-18%), respectively. Similar to the N95 respirator, the public health benefit of wearing surgical and syntheticfiber masks is reduced when considering the assumed input parameter space across the population compared to optimistic assumptions for bypass rate and fraction of day the mask is worn. Finally, we estimate use of natural-fiber masks leads to an average of only 6% (SD: 2-11%) reduction in respiratory hospitalizations when considering the assumed range of input parameters across the population.

### 3.5 Sensitivity of hospital admissions to uncertain input parameters

The fraction of the population wearing a face mask or respirator is one of the key uncertainties in this modeling framework. To explore this sensitivity, we perform a one-at-a-time sensitivity analysis by calculating the number of respiratory hospital admissions as a function of the fraction of population wearing a mask or respirator and filtration efficiency. The remaining input parameters are held constant at their default values (Table 1). Mask wearing compliance among the population has a strong influence on potential health benefits for this case study (Figure 6). If the entire population wore an N95 respirator for  $2/3^{rds}$  of the day with a minimal (5%) bypass rate (an admittedly unrealistic scenario), respiratory hospital admissions attributable to acute wildfire PM<sub>2.5</sub> exposure in Washington would be reduced to 148 admissions as opposed to 380 in the no mask scenario (a 61% decrease). Even with 50% mask-wearing compliance, N95 respirators could reduce hospital admissions by greater than 30% if worn with a 5% bypass rate and for 2/3<sup>rds</sup> of the day. The maximum health benefit for the synthetic-fiber mask with 100% compliance (and worn with 5% bypass rate for 2/3<sup>rds</sup> of the day) would be a greater than 38% reduction in hospital admissions. These optimistic assumptions for mask-wearing compliance and bypass rate result in a larger predicted public health benefit for the synthetic-fiber mask than the average predicted benefit when sampling over a realistic input parameter space. Conversely, the surgical and natural-fiber masks show only a limited reduction in hospital admissions (30% and 14% decreases, respectively) even with 100% mask-wearing compliance. This suggests that N95 respirators and to a lesser degree synthetic-fiber masks have the potential to offer a larger reduction in health risk from wildfire smoke exposure than what is initially suggested in Figure 5 due to the sensitivity of the population mask-wearing compliance.

To test the sensitivity of HIA calculations to the full list of uncertain model inputs, we perform a global variance-based sensitivity analysis. The benefit of this approach is that the variance in the model output (i.e., the predicted number of respiratory hospital admissions) can be apportioned into the contribution from each uncertain model input parameter (see Table 1). When calculating the total number of respiratory hospital admissions under each mask or respirator scenario, the odds ratio contributes the majority of the variance in the number of respiratory hospital admissions (91%, 92%, 81%, and 75% for the natural-fiber, synthetic-fiber, surgical, and N95, respectively; Supplemental Figure S2). Only in the case of the N95 respirator and the surgical mask do other uncertain model inputs contribute more than 10% to the uncertainty in the number of hospital admissions. Thus, for the absolute number of hospital admissions, HIA models are still most sensitive to uncertainties in exposure-response associations as opposed to assumptions regarding mask use.

However, when calculating the relative change in the number of respiratory hospital admissions the odds ratio does not contribute to overall model uncertainty. This occurs because the number of hospital admissions calculated in a pair of model simulations (with a face covering and without a face covering) assume the same odds ratio. The natural-fiber masks exhibit a wide variability in the magnitude of filtration efficiency along with a strong dependence of filtration efficiency on particle diameter (Figure 1). As a result, 32% and 17% of the variance in the relative decrease in smoke-attributable hospitalizations are due to the uncertainty in the filtration efficiency and aerosol size distribution, respectively (Figure 7 and Table 2). Additionally, the bypass rate of air around the mask (i.e., mask leakage), which also has a wide range of values (Table 1), contributes 24% of the model variance. The large variability in filtration efficiency and bypass rate outweighs the uncertainty in the fraction of the population wearing a mask (14%) and the fraction of day the mask is worn (11%). Conversely, the variance in the relative reduction of respiratory hospitalizations for the surgical mask is dominated by the uncertainty in the bypass rate (57%), underscoring the impact of mask fit to predicted health benefits. The relative contribution to model variance for the synthetic-fiber mask is split between the bypass rate (48%) and the parameters describing mask use: the fraction of the population wearing a mask (20%) and the fraction of the day spent wearing the mask (20%). The uncertainty for the N95 respirator is almost entirely contributed by the fraction of the population wearing a mask (44%), the time spent wearing the mask (44%), and the bypass rate (8%). Only for the N95 respirator do the input parameters corresponding to the use of the respirator (fraction of the population wearing the mask and fraction of the day the respirator is worn) contribute more to model variance than the parameters corresponding to respirator efficacy (filtration efficiency and bypass rate). For all face coverings the bypass rate of air around the mask is a key uncertain input parameter limiting the ability to predict health benefits.

## **4** Conclusions and Limitations

In this study, we developed a framework to quantify the potential health benefits following the use of face coverings by the general population as a means to reduce health risks from acute exposure to PM<sub>2.5</sub> air pollution. This framework can be used to support recommendations and guidelines on the effectiveness of wearing face masks and respirators as a personal intervention during periods of severe air pollution, such as during wildfire smoke events.

We find that natural-fiber face masks are generally ineffective at providing populationlevel health benefits (such as reductions in respiratory or asthma hospital admissions) during wildfire events. Our case study during the Washington state fire season in 2012 predicts that the use of natural-fiber face masks could reduce wildfire smoke attributable respiratory hospitalizations by only 7% (SD: 2-11%), when sampling across a range of estimates for wearing compliance, mask efficacy, aerosol size distributions, and health-response associations. The effectiveness of natural-fiber face masks at providing population-level health benefits is limited by poor filtration efficiency across particle sizes relevant for wildfire smoke. Laboratory measurements of natural-fiber mask filtration efficiency show a minimum in efficiency around 0.5-0.6 µm, roughly coinciding with the mass median diameter of wildfire smoke aerosol size distributions. As a result, even assuming an optimistic bypass rate for natural-fiber masks of 5%, the protection factor for natural-fiber masks against wildfire smoke PM<sub>2.5</sub> is only approximately 1.2 (with some uncertainty due to the size distribution in wildfire smoke aerosol). The average of the three natural-fiber face masks roughly meet the ASTM International barrier face covering standard Level 1, developed to address the COVID-19 pandemic. Thus, standards for face masks developed to reduce the risk of respiratory viral infection may not be useful for determining adequate protection from other forms of air pollution.

Face masks made from synthetic fibers may offer moderate protection against a range of air pollution sources; however, the degree of protection exhibits a strong dependence on particle size. Assuming an optimistic bypass rate of 5%, synthetic-fiber masks may reduce exposure to fossil-fuel-combustion sized particles by a factor of 4 and wildfire-combustion sized particles by over a factor of 2. If the mask is worn for two-thirds of the day with a 5% bypass rate, the increased risk of respiratory hospitalization due to 100 µg m<sup>-3</sup> of ambient wildfire PM<sub>2.5</sub> would decrease from 66% assuming no face mask to 38%. While this level of health benefit might be achieved by a motivated individual, such benefits are less likely achieved at the population level. Relaxing these assumptions by sampling across a realistic input parameter space for a large population in the case study in Washington state predicts reductions in respiratory and asthma hospitalizations of 7-18% over the assumption of no face mask. The main driver of uncertainty in this estimate of health benefits is the bypass rate (i.e., mask fit), accounting for nearly 50% of the variance in estimated reductions in hospitalizations. The bypass rate is assumed to range from 5% (a nearly-sealed mask) to 70% (where most of the air bypassed the filtering device). Thus, while the protect factor may reduce wildfire smoke exposure by over a factor of 2 when worn with a bypass rate of 5%, the predicted public health benefit when considering the full range of possible bypass rates is greatly reduced.

Despite relatively high filtration efficiency (greater than 90%) across the full range of particle diameters measured, the protection offered by the surgical mask is strongly limited by poor fit leading to large bypass rates of air around the mask. Assuming an estimated bypass rate of 50%, the protection factor against wildfire smoke PM<sub>2.5</sub> of the surgical mask is only slightly higher (1.9) than for the natural-fiber masks (1.4) and is lower than the synthetic-fiber mask (2.2). Sampling across the full input parameter space, our HIA suggests that the surgical mask may offer moderate public health benefits during a wildfire event (9-24% reductions in respiratory hospital admissions). The uncertainty in the bypass rate largely drives the uncertainty in this estimate.

N95 respirators offer robust protection against  $PM_{2.5}$  air pollution, with protection factors exceeding 14 and reducing the increased risk of respiratory hospitalization from 100 µg m<sup>-3</sup> of wildfire  $PM_{2.5}$  from 66% assuming no mask use to 21% when the N95 is worn with only a 5% bypass rate and for 2/3<sup>rds</sup> of the day. In our case study, we predict that the use of N95 respirators could reduce respiratory hospital admissions by 22-39% when sampling across the full input parameter space. The main drivers of uncertainty in this estimate are what fraction of the day the respirator is worn and by how many people. These assumptions of wearing compliance limit the predicted public health benefit of the N95 respirator across a large population as compared to predicted health benefits assuming optimistic estimates of wearing compliance. For instance, with 100% of the at-risk population wearing a mask for 2/3<sup>rds</sup> of the day with 5% bypass, the use of N95 respirators could reduce respiratory hospital admissions by as much as 60%.

There are several important limitations in this study. The first is the uncertainty in our assumptions regarding the fraction of the population wearing a mask or the fraction of day spent wearing a mask, both of which have not been quantified in previous studies (as use of face coverings during severe air pollution episodes has previously been uncommon in the US). We accounted for this uncertainty by sampling from an assumed range of input values, as well as providing optimistic scenarios to predict realistic maximum benefits of wearing each face covering. While these optimistic assumptions are unlikely to be achieved by the general population, these results provide information relevant for high-risk individuals who are potentially vulnerable to severe air pollution exposure. However, we also note that individuals at high risk for respiratory disease from exposure to air pollution (such as people with asthma or chronic obstructive pulmonary disease) may be less apt to wear a face mask or respirator for long periods of time. While previous research has suggested that face masks and respirators do not pose a substantial risk for people with asthma or other respiratory issues, this is still uncertain (Hopkins et al., 2021). Despite these assumptions, the framework developed here can provide quantifiable metrics for guidelines of the use of face coverings by the general population as a means of limiting health risk from exposure to air pollution.

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Parameter	Description	Default value	Uncertainty Range	References
$f_{\text{mask}}$	The fraction of the population wearing a mask	N/A	0.4-0.8	Cheng et al. (2020)
$\mathbf{f}_{day}$	The fraction of the day the mask is worn	0.66	0.4-0.8	
Bypass	The bypass (or leakage) rate of air around the mask [fraction]	N95: 0.05 Surgical: 0.50 Natural/synthetic: 0.05	N95: 0.01-0.25 Surgical: 0.2-0.9 Natural/synthetic: 0.05-0.7	Han et al. (2010); Cherrie et al. (2018); Vuma et al. (2019); Pan et al. (2021); Brooks et al. (2021); Rothamer et al. (2021)
Efficien- cy	The measured filtration effi- ciency of the mask	The average of the measurements	95% confidence interval (+/- 1.96 * standard deviation about the mean)	
NMD	The number median diameter of the aerosol size distribution	0.1 μm	0.05-0.3 μm	Sakamoto et al. (2015)
$\sigma_{g}$	The geometric standard devia- tion of the aerosol size distribu- tion	2.0	1.7-2.2	Sakamoto et al. (2015)
Odds Ratio	The calculated odds ratio repre- senting the increased risk of hospitalization from a $10 \ \mu g \ m$ - 3 increase in wildfire smoke	Asthma: 1.076 Respiratory: 1.052	Asthma: 1.019-1.136 Respiratory: 1.025-1.080	Gan et al. (2017)

## Table 1. Input parameters for the health impact assessment

Table 2. Summary of face mask and respirator metrics for the particle diameter of minimum filtration efficiency, minimum filtration efficiency, protection factor (PF) for three typical size distributions, the respiratory hospitalization relative risk at 100  $\mu$ g m<sup>-3</sup> of wildfire PM<sub>2.5</sub> (RR<sub>100</sub>), and simulated number of smoke-attributable respiratory hospital admissions. The PF and RR<sub>100</sub> are calculated assuming default values, while the respiratory hospitalizations are calculated through a random sampling of the full parameter ranges (Table 1).

Mask/ respira- tor	Minimum filtration efficiency diameter [µm]	Minimum fil- tration efficien- cy	PF: urban, wildfire, dust	Respiratory RR <sub>100</sub>	Smoke-at- tributable res- piratory hospi- tal admissions
None	N/A	N/A	N/A	1.66	385 (SD: 93)
Natural	0.6	0.21	1.7, 1.4, 2.0	1.50	361 (SD: 90)
Synthet- ic	0.6	0.45	3.9, 2.2, 4.4	1.38	337 (SD: 84)
Surgical	0.04	0.91	1.9, 1.9, 2.0	1.45	320 (83)
N95	0.05	0.97	14.6, 16.2, 18.6	1.21	267 (73)



**Figure 1**. Measurements of mask filtration efficiency as a function of volume equivalent diameter. The shaded regions represent one standard deviation in the measurements.



**Figure 2**. Calculated protection factors for each mask type exposed to aerosol size distributions representative of urban (or fossil-fuel combustion), biomass burning, and dust when assuming default bypass rates (Table 1).



**Figure 3**. Population-mean relative risk of respiratory hospital admission as a function of ambient wildfire smoke  $PM_{2.5}$  concentration with and without the use of a face mask or respirator when assuming default values for bypass rate, filtration efficiency (solid line), and fraction of the day the mask or respirator is worn. The shaded regions correspond to a one standard deviation uncertainty range in filtration efficiency.

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**Figure 4**. Washington state (**a**) population, (**b**) daily averaged population-weighted wildfire smoke PM<sub>2.5</sub> on a heavily smoke impacted day, and (**c**) the number of wildfire smoke-at-tributable respiratory hospital admissions across the study period (July-October).

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**Figure 5**. The percent decrease in the number of respiratory hospital admissions due to acute exposure to wildfire smoke  $PM_{2.5}$  for the different mask groups relative to the case of no use of face masks or respirators by the population. The distribution in estimates is created through a random sampling across the full range of the input parameter space (described in Table 1).

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**Figure 6**. The number of respiratory hospital admissions as a function of the fraction of population wearing each face mask or respirator. The shaded region represents one standard deviation on the measurements of mask filtration efficiency. All other parameters are set to default values (Table 1).



**Figure 7**. The fractional contribution to variance in the relative decrease of respiratory hospital admissions contributed by each uncertain input parameter for the **a**) natural-fiber masks, **b**) synthetic-fiber mask, **c**) surgical mask, **d**) N95 respirator.