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Air Cleaning Systems for Reducing Exposures Indoors to Pollutant Emissions from Wildfires

Wanyu Rengie Chan, William J. Fisk

wrchan@lbl.gov **https://iaqscience.lbl.gov/**

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Health benefits and costs of filtration interventions that reduce indoor exposure to PM2.5 during wildfires

Abstract Increases in hospital admissions and deaths are associated with increases in outdoor air particles during wildfires. This analysis estimates the health benefits expected if interventions had improved particle filtration in homes in Southern California during a 10-day period of wildfire smoke exposure. Economic benefits and intervention costs are also estimated. The six interventions implemented in all affected houses are projected to prevent 11% to 63% of the hospital admissions and 7% to 39% of the deaths attributable to wildfire particles. The fraction of the population with an admission attributable to wildfire smoke is small, thus, the costs of interventions in all homes far exceeds the economic benefits of reduced hospital admissions. However, the estimated economic value of the prevented deaths exceed or far exceed intervention costs for interventions that do not use portable air cleaners. For the interventions with portable air cleaner use, mortality-related economic benefits exceed intervention costs as long as the cost of the air cleaners, which have a multi-year life, are not attributed to the short wildfire period. Cost effectiveness is improved by intervening only in the homes of the elderly who experience most of the health effects of particles from wildfires.

W. J. Fisk, W. R. Chan

Indoor Environment Group, Lawrence Berkeley National Laboratory, Berkeley, CA, USA

Key words: Benefits; Costs; Health; Filtration; Wildfires; Homes.

W. J. Fisk
Indoor Environment Group
Lawrence Berkeley National Laboratory
1 Cyclotron Road
Berkeley
CA 94720
USA
Tel.: + 510 486 5910
e-mail: wjfisk@lbl.gov

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ORIGINAL ARTICLE

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Effectiveness and cost of reducing particle-related mortality with particle filtration

W. J. Fisk | **W. R. Chan**

Indoor Environment Group, Lawrence Berkeley National Laboratory, Berkeley, CA, USA

Correspondence
William J. Fisk, Indoor Environment Group, Lawrence Berkeley National Laboratory, Berkeley, CA, USA.
Email: wjfisk@lbl.gov

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Abstract

This study evaluates the mortality-related benefits and costs of improvements in particle filtration in U.S. homes and commercial buildings based on models with empirical inputs. The models account for time spent in various environments as well as activity levels and associated breathing rates. The scenarios evaluated include improvements in filter efficiencies in both forced-air heating and cooling systems of homes and heating, ventilating, and air conditioning systems of workplaces as well as use of portable air cleaners in homes. The predicted reductions in mortality range from approximately 0.25 to 2.4 per 10 000 population. The largest reductions in mortality were from interventions with continuously operating portable air cleaners in homes because, given our scenarios, these portable air cleaners with HEPA filters most reduced particle exposures. For some interventions, predicted annual mortality-related economic benefits exceed $1000 per person. Economic benefits always exceed costs with benefit-to-cost ratios ranging from approximately 3.9 to 133. Restricting interventions to homes of the elderly further increases the mortality reductions per unit population and the benefit-to-cost ratios.

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2003 Southern California Wildfires

Six counties for 10-day period

- PM levels (Wu 2006)
- Hospital admission rates (Delfino 2009)
- Effects on mortality (Kochi 2012)

Can filtration substantially reduce wildfire-related hospitalizations and deaths?

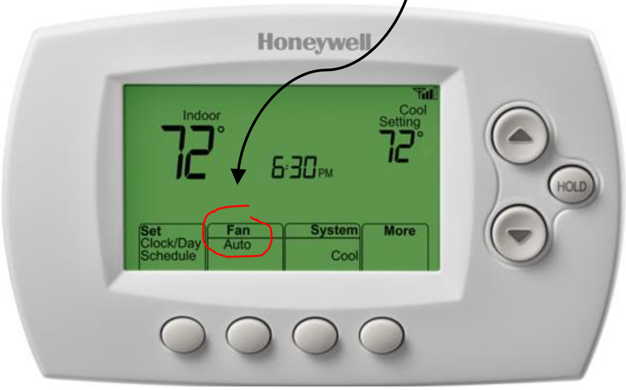
Would interventions be cost-effective?

Wu, et al. (2006) Exposure assessment of PM air pollution before, during, and after the 2003 southern CA wildfires, Atmos. Environ.
Delfino, et al. (2009) Relationship of respiratory & cardiovascular hospital admissions to southern CA wildfires 2003, Occup. Environ. Med.
Kochi, et al. (2012) Valuing mortality impacts of smoke exposure from major southern California wildfires, J. Forest Econ.

Current Housing Stock

- Some homes have no forced air system
- Homes with forced air system typically have low-efficiency furnace air filters; system only runs for short period of time (varies by season)

Fan AUTO



Why typical filtration in residential forced air systems are not effective for PM2.5

PM2.5 Removal Rate = Filter Efficiency x Flowrate x Duty Cycle

	Parameters
Air filter PM2.5 removal efficiency	0.12
Typical forced air system flowrate	4.3 per hour
Typical duty cycle (CA, summer)	0.2
PM2.5 removal rate =	0.1 per hour (not effective)

For comparison, typical PM2.5 indoor deposition rate = 0.4 per hour.

Filtration Interventions

1. Upgrade to high efficiency air filters (MERV 12*)
2. Change to Fan ON mode to run system continuously
3. 1 + 2
4. Buy an air cleaner (HEPA filter, 1 AER)
5. Buy an air cleaner + 1 + 2

* Reduced to MERV 9 because of air leakage bypass.

Modeling Approach

- Assumes that adverse health effects are largely a consequence of increased PM2.5 exposures
- Mass balance model to predict PM2.5 reduction if filtration interventions had been implemented
  - Accounts for time spent in non-home environments (work/school, vehicle, outdoor)
  - 22% of homes in study areas with residents age 65+
- Calculate an effective change in outdoor PM2.5 concentration (C_{oe}) from filtration interventions
- Relate the change in C_{oe} to expected reduction in hospital admission rates and premature deaths

Mass Balance Model

$C_{indoor} = K \times C_{outdoor}$

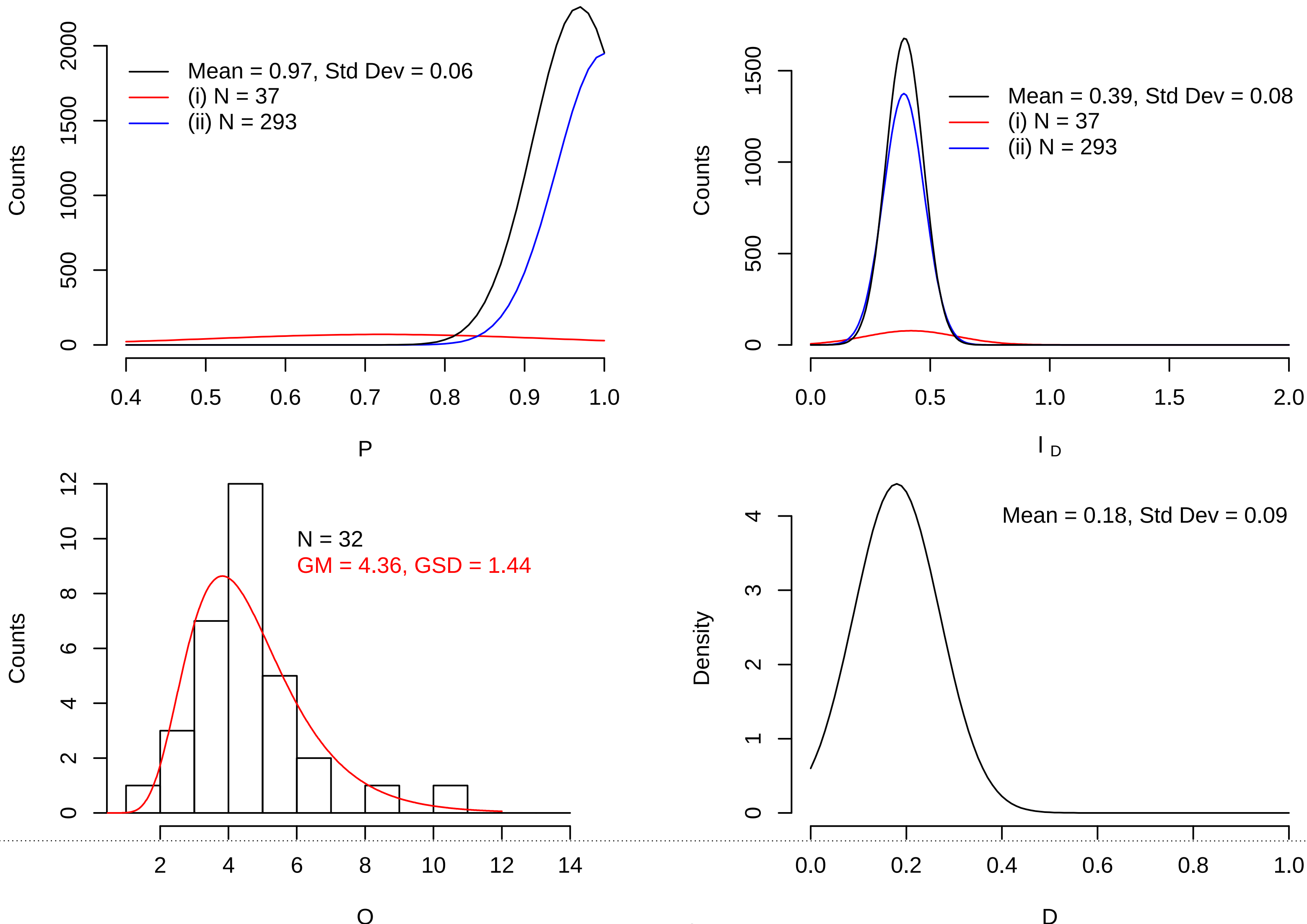
P = Particle penetration factor
λ_V = Ventilation rate
λ_D = Particle removal by deposition
λ_F = Particle removal by filtration

Q_ε = Forced air system airflow rate
D = Fractional system runtime
ε_L = Air filter particle removal efficiency

Q_P = Air cleaner airflow rate
ε_P = Air filter particle removal efficiency

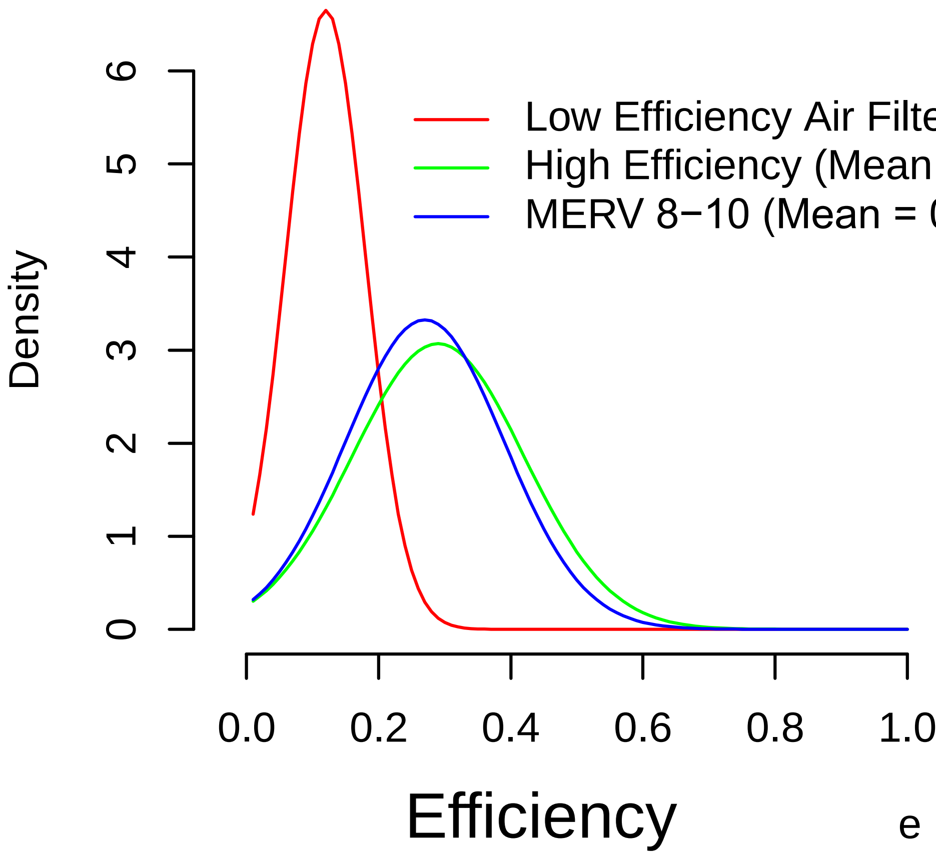
- Sampled from distributions of model input parameter values
- Assumes windows kept closed
- Air filter efficiency based on typical size distributions of outdoor PM (not specific to wildfire)
- Other indoor environments assumed mechanically ventilated, modeled using a simplified mass balance similar to home

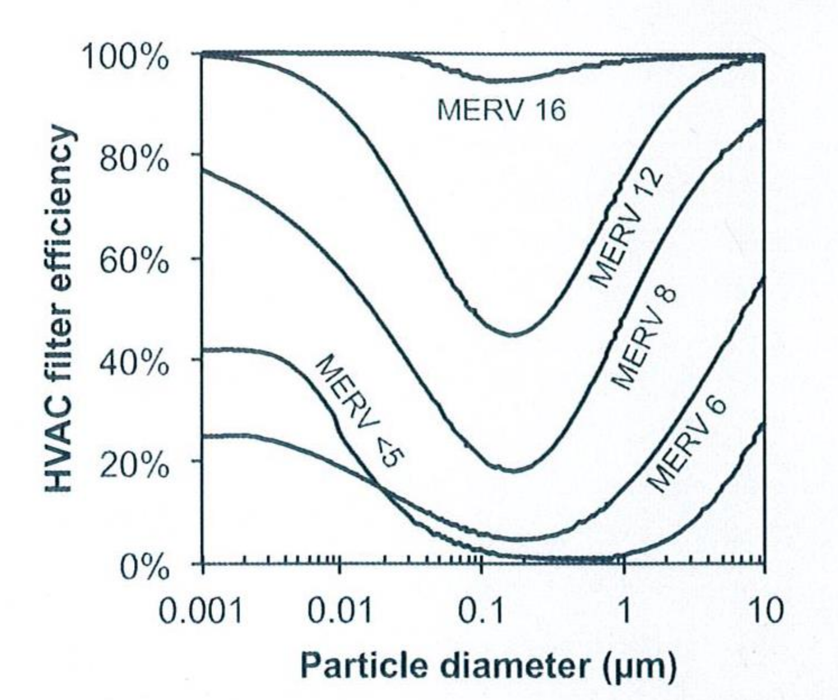
PM2.5 Model Input Parameters



DOI: 10.1111/ina.12285 Supporting Information

PM2.5 Removal Efficiency by Filtration





Source: El Orch et al. (2014)
Building and Environment 74: 106 - 118

Predicted PM2.5 Concentrations (μg/m³)

	Mean (5th–95th)	% ↓
Outdoor	56.9	
Home Base Case (w/ Forced Air System)	29.2 (12.1–45.2)	
Filter Upgrade	26.1 (9.5–43.2)	11%
Fan ON	22.1 (6.8–40.2)	24%
Fan ON + Filter Upgrade	15.5 (3.7–33.0)	47%
Fan ON + Air Cleaner	14.2 (3.7–30.0)	51%
Fan ON + Filter Upgrade + Air Cleaner	11.2 (2.6–25.5)	62%
Home Base Case (w/o Forced Air System)	31.9 (14.6–46.8)	
Air Cleaner	17.4 (5.2–33.9)	45%
Vehicle	34.1 (28.5–39.8)	
Other Indoor Environments (e.g. Work)	21.5 (5.8–39.6)	

Economic Benefits and Costs of Filtration Interventions

- Benefits
  - Delfino (2009): Fractional change in hospital admissions per 10 $\mu g/m^3$ change in outdoor PM2.5
  - Kochi (2012): 25% increase in cardio-respiratory deaths during the study period
  - Economic values of avoided hospital admissions and premature deaths
- Costs
  - Electricity
  - Purchase price of air filters and air cleaners

Number of Prevented Hospital Admissions

- Fractional reductions in hospital admission rates R_j for health outcome j

$R_j = X_j (C_o – C_{oe})/(10 \text{ ug/m}^3)$ ← Delfino (2009)

$Rj = \exp(\beta \, \Delta PM) – 1$ ← Supplemental analysis

Type of Admission	X_j (95% CI)	Total Admissions*
All respiratory	0.028 (0.014–0.041)	21,019
Asthma	0.048 (0.021–0.076)	3,022
Acute bronchitis / bronchiolitis	0.096 (0.018–0.179)	618
COPD	0.038 (0.004–0.075)	2,860
Pneumonia	0.028 (0.007–0.050)	6,440

* Included 20 days before the wildfire, 10 days during the wildfire, and 16 days after the wildfire. For six Southern CA counties affected by wildfire smoke.

Number of Prevented Premature Deaths

- Kochi (2012) estimated that wildfires during the 10-day period resulted in 133 (95% CI: 26–262) excess cardio-respiratory deaths
- About 25% increase relative to the number of cardio-respiratory deaths (N=536) for the reference period
- Assuming excess deaths vary in proportional to total PM2.5 intake (I):

$M = 133 \times \Delta I / I_{\text{base case}}$ ← Kochi (2012)

$M = M_{ref} \times [\exp(\alpha\ \Delta PM) - 1]$ ← Sup. Analysis

Prevented

	Number Increased During Wildfire	Filter Upgrade	Fan ON	Fan ON + Filter Upgrade	Fan ON + Filter Upgrade + Air Cleaner
All respiratory	417 (265–655)	47 (30–74)	106 (67–167)	201 (128–317)	261 (166–411)
Asthma	109 (62–192)	12 (7–22)	28 (16–49)	53 (30–93)	68 (39–120)
Acute bronchitis	43 (19–99)	4.9 (2–11)	11 (5–25)	21 (9–48)	27 (12–62)
COPD	81 (32–207)	9 (4–23)	21 (8–52)	39 (15–100)	51 (20–129)
Pneumonia	120 (56–257)	13 (6–29)	30 (14–65)	58 (27–124)	75 (35–161)
Premature death	133 (26–262)	9 (2–18)	21 (4–41)	40 (8–79)	52 (10–102)

Filtration interventions in all homes in the six-county region would have prevented 47 to 261 respiratory hospital admissions, and 9 to 52 premature deaths, related to PM2.5 exposures during the 10-day study period.

Costs of Filtration Interventions

	Model Input Parameters	Typical 2000-sqft home
Forced air system power consumption	1,090 $W/m^3/s$	$18
Residential electricity retail price CA 2003	$0.132/kWh	
MERV 11–13 (1 inch) air filters	$9–11	$3.3 incremental cost
MERV 6–8 (1 inch) air filters	$6–8	
Cost of buying 1 air cleaner	$296 (Brand X*) $460 (Brand Y**)	$239 $607
Air cleaner power consumption	602 $W/m^3/s$ (X) 495 $W/m^3/s$ (Y)	$2.3 $1.9

* Less expensive Brand X has a CADR for smoke 24% above 1 AER for typical 2000-sqft home. ** More expensive Brand Y has a CADR 76% for the same home.

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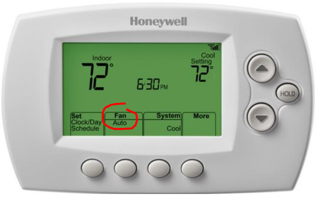
Total Intervention Costs



- Operating forced air system continuously for 6.92 million homes is expected to cost $110 million in electricity.
- The incremental cost of purchasing higher efficiency filters plus electricity cost is $133 million.
- Energy costs of operating air cleaners is $13–16 million.
- Estimated cost of buying portable air cleaners range from $1.8 to $4.4 trillion, though it is unlikely that anyone would make the purchase just for the 10-day period.

Economic Benefits ($m) from Prevented Hospital Admissions & Premature Deaths

Intervention	Hospital Admissions*	Premature Deaths**	Total Benefits
Filter Upgrade	1.0 (0.7–1.6)	75 (15–147)	76 (15–147)
Fan ON	2.4 (1.5–3.7)	169 (33–332)	171 (34–334)
Fan ON + Filter Upgrade	4.5 (2.9–7.1)	321 (63–632)	325 (65–634)
Fan ON + Air Cleaner	4.9 (3.1–7.7)	349 (68–688)	354 (71–691)
Fan ON + Filter Upgrade + Air Cleaner	5.8 (3.7–9.2)	416 (81–820)	422 (84–823)

From BenMAP Environmental Benefits Mapping and Analysis Program (2015):

* Each prevented all respiratory admission = $22,300

** Each premature death = $8.04 million

Economic Benefits and Costs ($m) of Filtration Interventions

Intervention	Total Benefits	Total Costs	If Excluded Cost of Buying Air Cleaners
Filter Upgrade	76 (15–147)	23	--
Fan ON	171 (34–334)	110	--
Fan ON + Filter Upgrade	325 (65–634)	133	--
Fan ON + Air Cleaner	354 (71–691)	1,790–4,350	123–126
Fan ON + Filter Upgrade + Air Cleaner	422 (84–823)	1,810–4,370	146–149

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Summary

- Economic benefits from reduced premature deaths exceed intervention costs, w/o cost of air cleaners.
- Economic benefits from reduced premature deaths are not sufficient to pay for portable air cleaners, but greatly exceed the cost of running air air cleaners.
- In 22% of homes with age 65+ residents*
  - Benefit-to-cost ratio increased from about 2:1 to about 16:1 for interventions w/o air cleaners
  - Benefits from reduced hospitalization and premature deaths are sufficient to pay for purchase of the less expensive (Brand X) air cleaners.

* Assumes elderly reminded indoors at home through the study period.

Discussion

- Two studies that evaluated the use of air cleaners in homes during wildfires:
  - Barn (2008) found 65% (+/-35%) reduction in PM2.5 in 17 homes during summer wildfire periods
  - Henderson (2005) estimated 63–88% reduction in PM2.5 in 5-paired of homes, w and w/o air cleaners
- Similar results, compared to 51% reduction in PM2.5 using Fan ON + Air Cleaner intervention

Barn, et al. (2008) Infiltration of forest fire and residential wood smoke: an evaluation of air cleaner effectiveness, J. Eposure. Sci. Environ. Epidemiol.

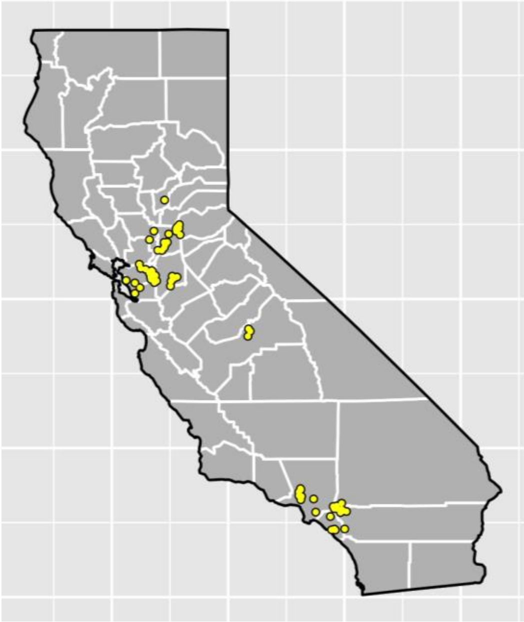
Henderson, et al. (2005) Prescribed burns and wildfires in Colorado: impacts of mitigation measures on indoor air particulate matter, J. Air Waste Manag. Assoc.

Limitations

- Uncertainties on the effects of wildfires on mortality.
- Focused on the period of wildfire smoke exposure, did not consider post-wildfire hospital admissions.
- Model did not consider wildfire-generated gaseous air pollutants (e.g., nitrogen oxides, aldehydes).
- Model may have overestimated PM reductions, if PM size distribution from wildfires tends to be smaller than typical PM.
- Some of the interventions may have already been implemented in a subset of homes.

California Homes are Changing

- A recent study (2016–2018) of 70 new homes (all mechanically ventilated, most using exhaust ventilation), found medium to high efficiency air filters
- Title 24 (2019) updated air filter requirement to MERV 13, 2-inch minimum depth



MERV Rating	Number of Air Filters (N=112)
6 - 7	4
8	57
10	18
11	22
12	1
13	9
14	1

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Related Research by LBNL Indoor Environment Group

- Benefits-costs of reducing premature mortality with improved PM filtration in homes & commercial bldgs*
  - Largest estimated mortality reductions from interventions in homes (e.g., >1,000 prevented premature deaths per year in LA County)
  - Estimated benefit-cost ratios always exceeded unity
    - 6–13:1 for interventions using portable air cleaners in homes
    - 74–133:1 for improvements in efficiency of filters in commercial buildings
- Ongoing sampling** at two California schools with paired classrooms that have MERV 8 vs 13 air filters, for different mechanical ventilation equipment

* Fisk and Chan (2017). Indoor Air.
** CEC sponsored project, in collaboration with UC Davis.

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Indoor Environment Group, Lawrence Berkeley National Laboratory, Berkeley, CA, USA

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Extra Slides

High-Efficiency Standalone Air Cleaners Total Cost Lower or Comparable to HVAC Filtration

- Air cleaners cost vary (basic models vs. quiet/low-power)
- Assumed air cleaners have 5-year service life

	HVAC MERV 8	Standalone HEPA
Purchase Cost	--	\$1,000–\$2,000 (over 5 years)
Filter replacement	\$30	\$100–\$300
Annual electricity cost (\$)	\$680	\$90
Annual total cost (\$)	\$710	\$390–\$790

Air-Sealing Reduces PM2.5 Infiltration

LBNL study evaluated nine ventilation and filtration systems in an unoccupied 2006 house located 250-m downwind of freeway (Sacramento CA)

Building leakage = 5.0 ACH50, with exhaust ventilation:

- Black carbon reduced by 40%
- **Outdoor PM2.5 reduced by 70%**
- Outdoor UFP reduced 80%

Singer et al. (2016) Measured performance of filtration and ventilation systems for fine and ultrafine particles and ozone in an unoccupied modern California house. Indoor Air.

Potential Risks and Concerns

California new home field study (2016–2018)

PM filtration

- Low performance – airflow, runtime, removal efficiency as a function of particle size
- Costs – device, filter replacement, energy
- Air cleaners that generate pollutants

Reduced infiltration

- Inadequate ventilation
- Buildup of indoor-generated pollutants

California Regulates Ozone Generating Air Cleaners

California Air Resources Board (ARB) developed and adopted a regulation in September 2007 to limit the ozone emitted from indoor air cleaning devices in order to protect public health. **All air cleaning devices sold in California must meet the regulation** requirements as of **October 18, 2010**, the full compliance date.

<u>California new home field study (2016–2018)</u>