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Research

Evaluating portable air cleaner effectiveness in residential settings to reduce exposure to biomass smoke resulting from prescribed burns

Amanda J Wheeler[a,b,c,h], Fabienne Reisen[a], Christopher T Roulston[a], Martine Dennekamp[d,e], Nigel Goodman[f,g] and Fay H Johnston[b]

[a] CSIRO, Environment, Melbourne, Victoria, Australia
[b] Menzies Institute for Medical Research, University of Tasmania, Hobart, Australia
[c] Mary MacKillop Institute for Health Research, Australian Catholic University, Melbourne, Victoria, Australia
[d] Environment Protection Authority Victoria, Melbourne, Australia
[e] School of Population Health and Preventive Medicine, Monash University, Melbourne, Victoria, Australia
[f] School of Property Construction and Project Management, RMIT University, Melbourne, Victoria, Australia
[g] National Centre for Epidemiology and Population Health, Australian National University, Canberra, ACT, Australia
[h] Corresponding author: Amanda.Wheeler@csiro.au

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Key points

- During extreme air pollution events, such as landscape fires, public health agencies often recommend that vulnerable individuals use portable high-efficiency particulate air (HEPA) cleaners to reduce their exposure to smoke
- We quantified the impact of HEPA cleaners in residential settings during smoke events due to prescribed burns
- HEPA cleaners substantially improved indoor air quality when used in appropriately sized rooms

Abstract

Aim: Prescribed burning is the most common method employed to reduce fuel loads in flammable landscapes. This practice is designed to reduce the hazard associated with uncontrolled bushfires. Prescribed burns are frequently conducted close to residential areas, and the associated smoke impacts can adversely affect community health. Particulate matter is the predominant pollutant within the smoke and is strongly and consistently linked with adverse health effects. Outdoor smoke readily infiltrates buildings and reduces the quality of indoor air. Portable air cleaners containing high-efficiency particulate air (HEPA) filters are a promising indoor air quality intervention for reducing outdoor smoke exposure.

Methods: We provided 10 homes from semirural regions of Victoria, Australia, with HEPA cleaners and conducted continuous monitoring of indoor and outdoor fine particulate matter ($PM_{2.5}$) for 2–4 weeks during prescribed burning periods. We calculated the potential improvements to indoor air quality when operating a HEPA cleaner during a smoke episode. Ventilation measures were conducted to identify points of smoke ingress and housing characteristics that could lead to higher infiltration rates.

Results: Depending on the house, the use of HEPA cleaners resulted in a reduction in indoor $PM_{2.5}$ concentrations of 30–74%.

Conclusions: HEPA cleaners have the potential to substantially improve indoor air quality during episodic smoke episodes.

Introduction

The evidence for health impacts associated with exposures to smoke generated by landscape fires and domestic wood heaters is increasing.[1-5] In Australia, landscape fires typically refer to bushfires or prescribed burns (planned and controlled use of fire in an area to reduce fuel loads). One-third of Australians are at high risk of experiencing negative health impacts due to smoke from landscape fires.[2] A study of the Australian Black Summer bushfires that occurred between October 2019 and February 2020 estimated that bushfire smoke was responsible for 417 (95% CI [Confidence Interval], 153, 680) excess deaths, 1124 (95% CI, 211, 2047) hospitalisations for cardiovascular problems and 2027 (95% CI, 0, 4252) for respiratory problems, and 1305 (95% CI, 705,1908) presentations to emergency departments with asthma.[1]

Future Australian fire seasons are likely to increase in frequency and severity due to a changing climate[6], increasing the burden of disease in the community and demands on the health system. Prescribed burns to reduce fuels are the most common method employed to mitigate the hazard of uncontrolled bushfires.[7] As with all landscape fires, prescribed burns generate smoke containing a range of pollutants. Particulate matter is the predominant pollutant within the smoke that is most strongly and consistently linked with adverse health effects.[8,9]

Current health protection advice regarding managing exposures to outdoor smoke recommends that members of the public should avoid strenuous exercise, stay indoors, and use an air conditioner to recirculate indoor air.[10] This advice has a limited evidence base for reducing exposure and virtually no evidence base for health protection.[11] There is evidence that outdoor air pollutants generated from smoke emissions infiltrate indoors, resulting in poor indoor air quality.[12-15] Portable air cleaners are a promising intervention for reducing exposure to all outdoor smoke.[8] Air cleaners with high-efficiency particulate air (HEPA) filters can remove particulate matter and are commonly used in response to smoke pollution incidents in North America.[8,16] The effectiveness of HEPA cleaners depends on several factors, including outdoor smoke concentrations, room size, housing characteristics and building ventilation.[8,12,16-18]

We designed this study to evaluate the efficacy of HEPA cleaners in improving residential indoor air quality during prescribed burns.

Materials and methods

Study design and data collection

We used convenience sampling in semirural regions of Victoria to recruit 10 homes based on their proximity to prescribed burns that were scheduled to take place within approximately 5 km from the residence. We selected sites based on several factors, including: a) the size of the prescribed burn, b) likelihood of a populated area being impacted; and c) proximity to Melbourne to ensure ease of travel for the team. We prioritised larger burns likely to last more than 1 day, as identified in discussion with the Department of Environment, Land, Water and Planning (DELWP) and tracked via the Forest Fire Management Victoria (FFMV) site.[19]

Exposure assessment

We administered a baseline survey about the residence to understand potential sources of particulate matter and reasons for potential building leakiness.

We continuously monitored indoor and outdoor fine particulate matter ($PM_{2.5}$) data averaged to provide 5-minute intervals. CSIRO-developed Smoke Observation Gadgets V2 (SMOG)[20], which included Plantower 3003 sensors to measure $PM_{2.5}$ (using CF1 data series). We connected the units to a server via the household wi-fi to remotely track smoke levels indoors and outdoors.

At the end of the study, we tested all working units side by side in a smoke chamber at CSIRO to evaluate their accuracy and to determine a correction factor per sensor. This removed biases between sensors and put all units on the same measurement scale.

We installed HEPA cleaners (Winix, model AUS-1250AZPU) in the residences. Where possible, we placed them in a bedroom with a closed internal door, as the manufacturer states that these specific air cleaners operate best in a room with a floor area of approximately 49 m^2. When no spare bedrooms were available, we placed the HEPA cleaner in the main living area (most were open plan). No participants were willing to have the HEPA cleaner installed in the main bedroom due to concerns about noise. During smoke episodes, all participants closed their doors and windows. If participants were unlikely to be home for extended periods (e.g., working away from home), we provided a smart plug that allowed them to switch on the HEPA cleaner using their smartphone.

Houses 2, 3, and 9 had an additional room where we installed a second indoor SMOG unit. These were deployed to assess smoke conditions inside the home in locations where the HEPA cleaner was not operating. Due to the limited availability of functioning units, we could not install them in all homes.

We conducted ventilation testing in each home using blower door tests per ASTM Standard Test Method for Determining Air Leakage Rate by Fan Pressurization[21] and ISO 9972:2006. We calculated the number of air changes per hour at 50 Pa of pressure (ACH50) and the permeability of the building envelope using proprietary software (Retrotec FanTestic) and Microsoft Excel. We calculated building floor area, volume, and surface area from floor plans (e.g. architectural drawings) and onsite measurements. We measured precipitation, relative humidity and temperature using a rain gauge and electronic weather station (Nylex Model: 719035). We noted significant points of air leakage on the floor plan of each building and took thermal images to provide a graphical summary of temperature gradients around areas of potential air leakage.

Statistical analysis

We cleaned raw instrument data using a protocol developed by CSIRO.[22] This process managed outliers and instrumental noise (artefacts in the data where measurements artificially spike high and then immediately return to the previous measurement range); removed values where relative humidity and temperature were outside regular measurement ranges for the Plantower sensors; removed any values when $PM_{2.5} > PM_{10}$; and applied a third-order polynomial fit to the SMOG data against a 1405-DF TEOM (ThermoFisher Scientific, Australia), which is a standard particulate matter air quality monitor used by regulatory agencies. The limit of detection for the SMOG units was 5.5 μg/m^3.

Due to missing data, we calculated average exposures rather than cumulative exposures during smoke periods by selecting only time periods when outdoor $PM_{2.5}$ concentrations exceeded 20 μg/m^3. We calculated differences in average exposures for periods when the HEPA cleaner was on and off to determine the potential improvements to indoor air quality when operating a HEPA cleaner during a smoke episode. We used the difference between Outdoor and HEPA ON measurements to estimate reductions of $PM_{2.5}$ due to the HEPA filter. We used the difference between Outdoor and HEPA OFF measurements to estimate the reduction of $PM_{2.5}$ due to the protection provided by the house envelope.

Ethics and funding

The Environment Protection Authority Victoria funded this study under Contract No. PRN 2018-051.

The Australian Catholic University's Human Research Ethics Committee provided ethics approval (2019-32H). All study participants provided signed informed consent.

Results and discussion

We recruited a total of 10 residences, but one residence was not included in the study because the prescribed burn was cancelled. We completed a baseline survey to understand potential sources of indoor $PM_{2.5}$ (see results in supplemental information (SI) table SI1, available from: doi.org/10.6084/m9.figshare.23706759). Apart from one, all homes were single-storey and none had attached garages. Five residences included pets that lived inside, such as a dog or a cat.

Results of the side-by-side comparison of the SMOG units demonstrated that they tracked well, as only two units underestimated $PM_{2.5}$ concentrations. Once the individual sensor correction factors were applied from the smoke chamber co-location, all units showed similar decay curves and correlated well. We retained all data, including those below the instrument detection limits. Where air quality instrumentation failure occurred in outdoor settings, we substituted the data with outdoor data from close neighbours. In most situations, participants were all located on adjacent properties, so outdoor data substitution was applied as needed.

Figure 1 shows plots of all 5-minute averaged data by house number from the indoor and outdoor monitors. Only house 3 had two operational indoor SMOG units to compare indoor $PM_{2.5}$ concentrations in rooms with and without a HEPA cleaner present. Figure 1 demonstrates the range in concentrations experienced over the course of the study, including during smoke episodes resulting from the prescribed burns. Outdoor concentrations from the smoke events were similar to other studies conducted in Australia investigating the role of landscape fire emissions on air quality.[15,22,23] Some smoke events in our study peaked at approximately 250 μg/m^3 (e.g. house 7). This suggests that local smoke plumes heavily impacted the location, whereas other homes had limited exposures, potentially because of their locations relative to the burn event.

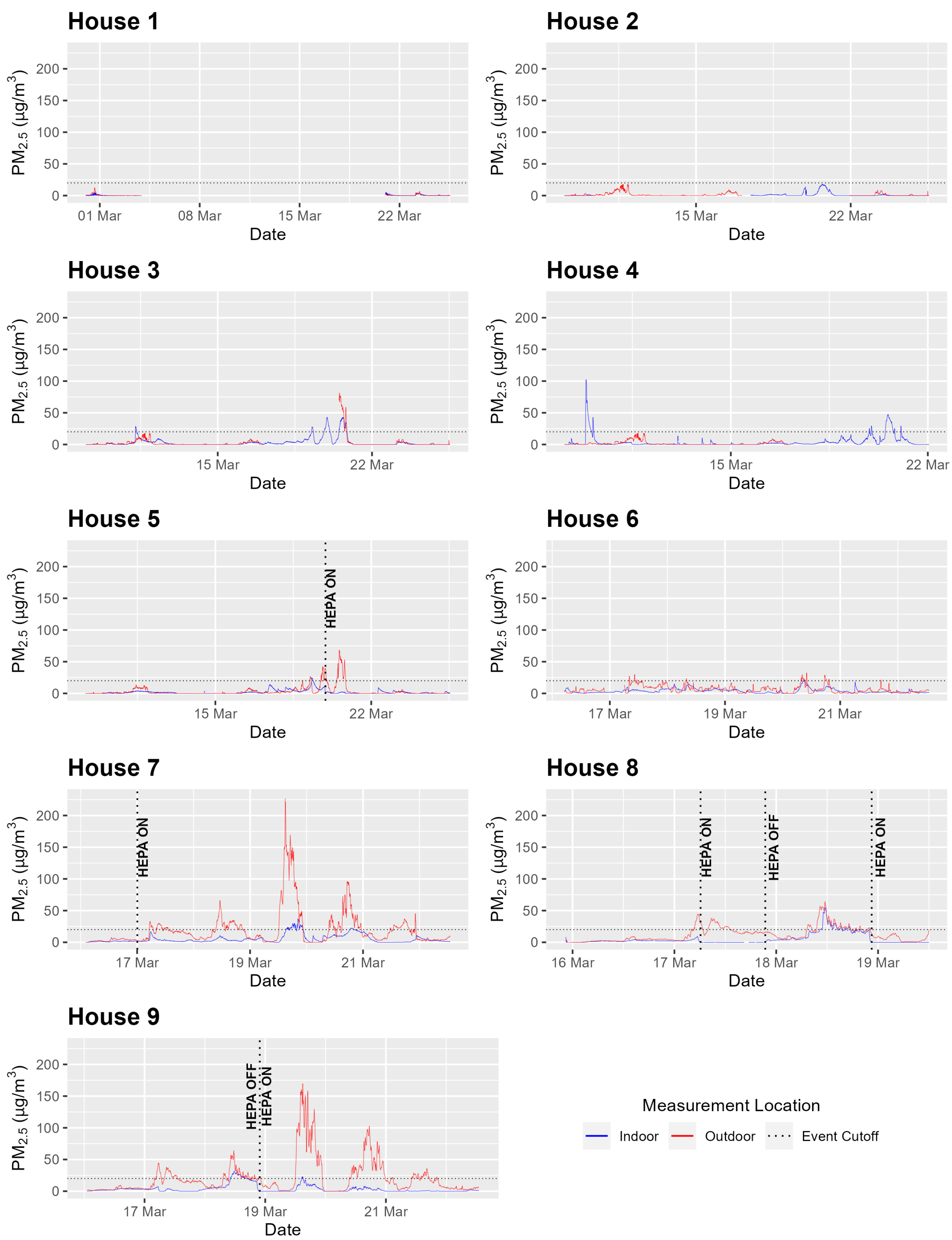
To ensure that we appropriately evaluated the HEPA cleaners' efficacy during a smoke event where outdoor $PM_{2.5}$ concentrations were elevated, we have selected only those homes with outdoor $PM_{2.5}$ concentrations greater than 20 μg/m^3. These were houses 5, 7, 8, and 9 (Figure 2). The other homes either did not have elevated outdoor $PM_{2.5}$ concentrations, had missing data on the use of the HEPA cleaner, or were missing corresponding indoor data making them ineligible for inclusion. Due to the extended monitoring period, we considered daily activity diaries too much of a burden for participants. As a result, it is unclear why some indoor peaks were not associated with outdoor levels.

Based on the time series plots, we can estimate the time it can take for polluted outdoor air to penetrate the buildings' envelope, resulting in poorer indoor air quality. Depending on the leakiness of the building envelope, this infiltration can occur within 60–120 minutes after the outdoor $PM_{2.5}$ concentrations start increasing, which is similar to findings by Reisen et al.[15] Figure 2 provides examples for houses 5, 8 and 9 when the HEPA cleaners were off. Ventilation data from the blower door testing also supports the general findings for these homes (See SI Figure 1 for details, available from: doi.org/10.6084/m9.figshare.23708079). House 5 had the lowest average air change rate of 10.31 m^3/hr/m^2 and provided the highest percentage of building envelope passive protection of 67.5% during a smoke event.

The data can also be used to evaluate how quickly the indoor $PM_{2.5}$ levels can return to background concentrations once outdoor levels have diminished. These data can be important in providing guidance for when homes should be ventilated after an outdoor smoke event has cleared. There were several periods when outdoor $PM_{2.5}$ at house 6 dropped below corresponding indoor $PM_{2.5}$ concentrations for periods of up to 5 hours (See Figure SI2 available from: doi.org/10.6084/m9.figshare.23706735).

All the study houses' average air change rate was between 9.08 and 33.71 h^{1} (ACH50). This is a similar range to previous Australian research on air change rates in new homes (7.9–28.5 h^{-1} ACH50).[24] The Building Code of Australia recommends that the building envelope have

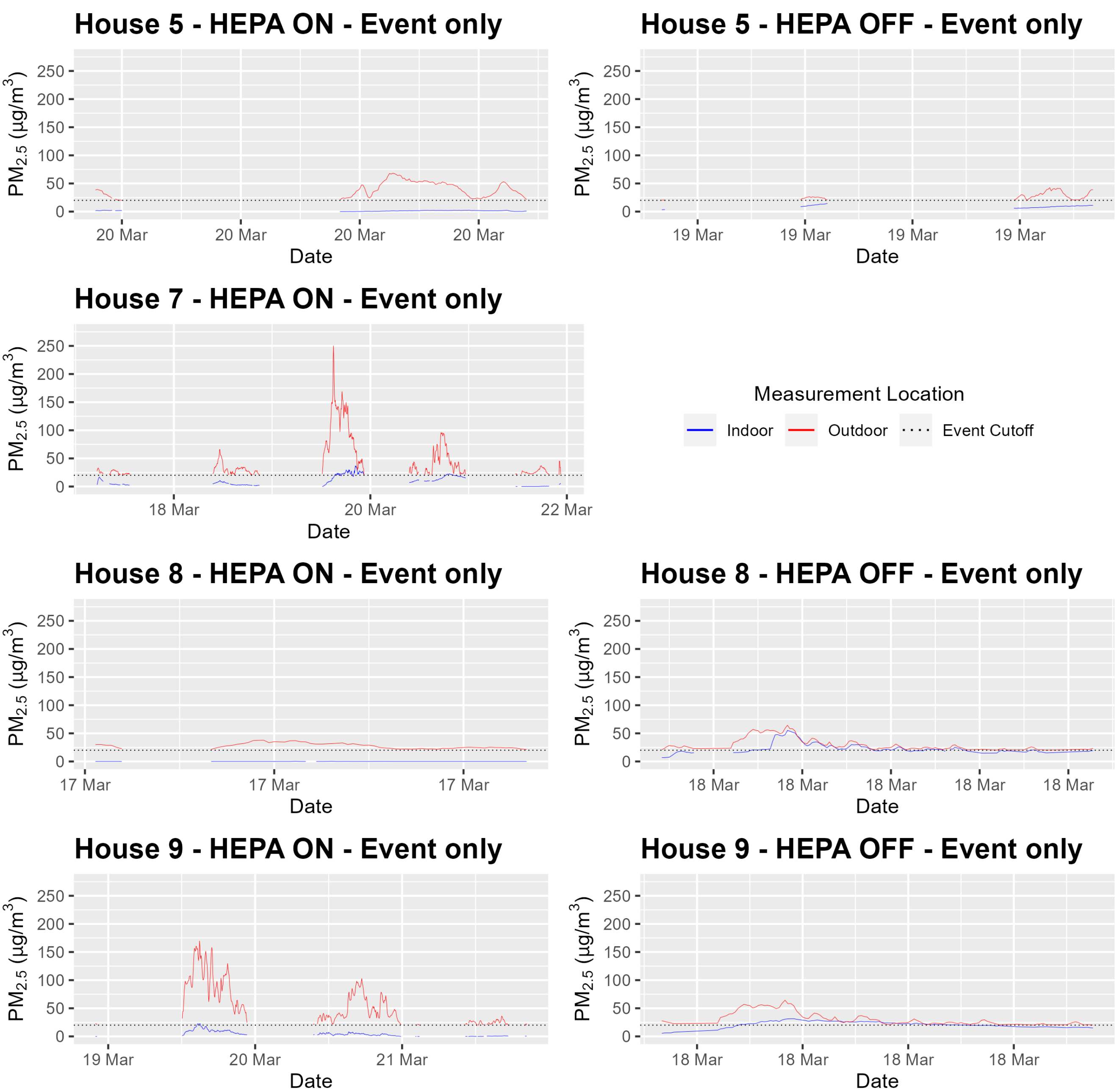
Figure 1. Time series of indoor and outdoor $PM_{2.5}$ 5-minute averaged concentrations by house number



Note: We have noted when participants switched HEPA cleaners on or off where these data were available. All data is from 2021.

a permeability of not more than 10 m³/hr.m² at 50 Pa.[25] These results suggest that only three of the study houses would comply with the national construction code. We identified many air leakage points during ventilation testing (e.g. bathroom fans, external doors, and wall vents (See Figure SI1, available from: doi.org/10.6084/m9.figshare.23708079). Although it is difficult to attribute specific locations of air leakage to the infiltration of smoke, studies have shown that more airtight buildings (e.g. those with fewer gaps and openings) can substantially delay smoke infiltration.[26] Figure 2 shows findings on HEPA cleaner effectiveness.

Figure 2. Time series plots of $PM_{2.5}$ concentrations when the 5-min averaged outdoor concentration was greater than or equal to 20 μg/m³



Note: Left panels show smoke events when the HEPA cleaner was on. Right panels show smoke events when the HEPA cleaner was off.

Table 1. Comparison of potential protective effects of house only and HEPA cleaner use on average indoor exposures to $PM_{2.5}$ from houses experiencing outdoor smoke events ($PM_{2.5}$ concentrations >20 µg/m^3)

House number	Percentage reduction of $PM_{2.5}$ with HEPA operating (%)	Percentage passive reduction provided by house only (%)	Reduction of $PM_{2.5}$ from HEPA only (%)	Ventilation (ACH50) (h^{-1})	Permeability ($m^3/hr/m^2$)
5 – All data	96	26	70	10.31	8.34
5 – Event only	97	67.5	30		
7 – All data	79	NA[a]	NA[a]	17.95	16.96
7 – Event only	79	NA[a]	NA[a]		
8 – All data	99.97	25	75	23.35	28.94
8 – Event only	99.94	26	74		
9 – All data	93	31	62	20.40	20.95
9 – Event only	99.1	31	68		

[a] NA missing data for when the HEPA cleaner was switched on or off.

Table 1 provides the percentage reduction of $PM_{2.5}$ attributable to using the HEPA cleaner, which ranged between 30 and 75%. Other international studies suggest that HEPA cleaners can provide approximately 52–67% reductions in $PM_{2.5}$.[12,13,16,17] This variability can be attributed in part to the amount of protection offered by the building envelope. House 5 had a relatively low air change rate, suggesting a tighter building envelope. Less outdoor smoke infiltrated the house, resulting in a relatively small reduction from the HEPA cleaner. During a smoke event, the percentage of passive smoke reduction provided by house 5 was 67.5% with an ACH50 of 10.31 h^{-1} which was approximately half the ACH50 of other homes (ACH50 > 17 h^{-1}). Other study houses had a leaky building envelope resulting in higher indoor $PM_{2.5}$ concentrations, which were improved significantly by the HEPA cleaner.

Our findings have demonstrated that using HEPA cleaners in residential settings can improve indoor air quality during episodic outdoor smoke events. It can take 28–46 minutes to bring indoor $PM_{2.5}$ concentrations back to background levels in rooms where the HEPA cleaners were switched on. This is one of only a small number of studies where HEPA cleaners have been evaluated during a landscape fire episode, which typically generates higher concentrations of $PM_{2.5}$-associated smoke emissions.[13,22] Some limitations of the study include the small number of homes and the lack of concurrent ventilation data to understand these impacts on smoke infiltration. Due to the time the monitoring was undertaken, tracking when particle-generating activities occurred and whether doors and windows were open or closed was challenging. This limits our ability to evaluate the HEPA cleaner's efficacy fully. There are inherent challenges in designing studies to capture data during episodic smoke events, including the uncertainty of when and where they will occur, the duration of the episode, and the wind direction (which will determine which locations are impacted). By collecting data during prescribed burns, we have evaluated the efficacy of HEPA cleaners under conditions that can occur during landscape fires.

Conclusions

Our results suggest that having access to HEPA cleaners and locating them in an appropriately sized room could be a practical and useful addition to the suite of interventions and advice currently provided in Australia and elsewhere to protect against smoke exposures. Our findings also suggest that only limited protection is afforded by staying indoors during smoke events without additional air filtration.

However, as it can take up to an hour or more to bring indoor $PM_{2.5}$ concentrations back to background levels, it is important to tell people whose homes are affected by smoke to ventilate their homes once the outdoor smoke has dissipated.

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Peer review and provenance

Externally peer reviewed, not commissioned.

Competing interests

None declared.

Author contributions

AW contributed to the conceptualisation, methodology, data processing, data analysis, draft and final manuscript. FR contributed towards the methodology, data analysis, and manuscript review. CR contributed to the data processing and interpretation, plotting, and reviewing. MD contributed to the conceptualisation, methodology, and manuscript review. NG contributed to the ventilation assessment, ACH data processing and interpretation, and reviewing. FJ contributed to the conceptualisation, experimental design, data interpretation, and manuscript review.

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