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Research article

Self-reported health impacts of do-it-yourself air cleaner use in a smoke-impacted community

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ABSTRACT

Background: Smoke exposure from wildfires or residential wood burning for heat is a public health problem for many communities. Do-It-Yourself (DIY) portable air cleaners (PACs) are promoted as affordable alternatives to commercial PACs, but evidence of their effect on health outcomes is limited.
Objective: Pilot test an evaluation of the effect of DIY PAC usage on self-reported symptoms, and investigate barriers and facilitators of PAC use, among members of a tribal community that routinely experiences elevated concentrations of fine particulate matter ($PM_{2.5}$) from smoke.
Methods: We conducted studies in Fall 2021 ("wildfire study"; N = 10) and Winter 2022 ("wood stove study"; N = 17). Each study included four sequential one-to-two-week phases: 1) initial, 2) DIY PAC usage ≥8 h/day, 3) commercial PAC usage ≥8 h/day, and 4) air sensor with visual display and optional PAC use. We continuously monitored PAC usage and indoor/outdoor $PM_{2.5}$ concentrations in homes. Concluding each phase, we conducted phone surveys about participants' symptoms, perceptions, and behaviors. We analyzed symptoms associated with PAC usage and conducted an analysis of indoor $PM_{2.5}$ concentrations as a mediating pathway using mixed effects multivariate linear regression. We categorized perceptions related to PACs into barriers and facilitators of use.
Results: No association was observed between PAC usage and symptoms, and the mediation analysis did not indicate that small observed trends were attributable to changes in indoor $PM_{2.5}$ concentrations. Small sample sizes hindered the ability to draw conclusions regarding the presence or absence of causal associations. DIY PAC usage was low; loud operating noise was a barrier to use.
Discussion: This research is novel in studying health effects of DIY PACs during wildfire and wood smoke exposures. Such research is needed to inform public health guidance. Recommendations for future studies on PAC use during smoke exposure include building flexibility of intervention timing into the study design.

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1. Introduction

Wildfires are a significant and growing source of particulate and gaseous ambient air pollutants linked to adverse health outcomes [1]. To reduce exposure during smoke events, the U.S. EPA and other public health agencies recommend reducing time spent outdoors, restricting outdoor physical activity, creating cleaner indoor air spaces, avoiding activities that generate indoor air pollution (e.g., cooking, sweeping) and using portable air cleaners (PACs) with a high-efficiency filter (MERV13 or higher) [2]. The use of PACs as an intervention to reduce adverse health effects of air pollution is a growing body of research. Evidence of the effectiveness of PACs is still limited, particularly for the more accessible and affordable do-it-yourself (DIY) PACs, made from a readily-available box fan and furnace filter(s) [3]. The *ASPIRE-Health* pilot studies presented in this manuscript aimed to test the feasibility of evaluating the effect of DIY PAC usage on indoor fine particulate matter ($PM_{2.5}$) concentrations and consequently on health outcomes in a residential setting during periods of wildfire smoke and residential wood stove use.

An early study on the efficacy of various public health efforts to reduce the negative health effects of wildfire smoke took place on the Hoopa Valley Indian Reservation in northern California after a large fire in 1999 [4]. The study found that a longer duration of self-reported commercial PAC use was significantly associated with decreased respiratory symptoms. Since that study, researchers have continued to examine the link between commercial PAC usage and health and found inconsistent evidence of an association. However, as noted by Cheek et al. many studies have not provided quantitative evidence of PAC usage by study subjects [3]. Participant adherence to PAC usage [5] and opening/closing windows and doors in a home [6] can significantly affect both the reduction in $PM_{2.5}$ concentrations indoors and health outcomes. Neither factor is commonly measured or reported in PAC efficacy studies; both are challenging to measure and control in real-world settings.

Commercial PACs and/or replacement filters are not always readily available or affordable, especially in times of high need. Therefore, public health agencies and tribal air quality programs often encourage the use of DIY PACs [7,8]. DIY PACs are made from components available at most hardware stores—a box fan and a furnace filter. A filter rated Minimum Efficiency Reporting Value (MERV)-13 or higher is recommended [2]. Configurations vary, depending on the design, with variations of filter thickness and number of filters used.

The increased use and affordability of DIY PACs and the pandemic caused by SARS-CoV-2 virus (2019–present), have prompted evaluations of efficacy in laboratory, residential [6], and commercial and public building settings [9]. DIY PAC usage during periods of elevated outdoor $PM_{2.5}$ concentrations caused by wildfire smoke has been associated with a 56–90 % average reduction of indoor $PM_{2.5}$ concentrations [6,10]. Additionally, a study of multiple DIY PAC configurations found that the estimated clean air delivery rate (CADR) of DIY PACs run on the lowest fan speed, using 2–5-inch-thick MERV-13 to −16 filters, exceeded a "best-in-class" commercial PAC with HEPA filter [11]. Although DIY PACs have proven to be highly effective in reducing indoor $PM_{2.5}$ associated with wildfire smoke, no studies to our knowledge have examined the relationship between DIY PACs and health outcomes in laboratory or real-world settings.

The Hoopa Valley Indian Reservation in California is often subjected to periods of elevated ambient $PM_{2.5}$ concentrations, causing poor air quality. During the summer months, wildfire smoke episodes routinely impact the valley. In recent years, Hoopa has experienced 20 days of unhealthy or worse air quality. During these wildfire events, the daily average $PM_{2.5}$ concentration reached as high as 754 $\mu g/m^3$, greatly exceeding the level of the primary (health-based) 24-h average National Ambient Air Quality Standard of 35 $\mu g/m^3$. Residents also experience wintertime pollution episodes because of the common use of wood stoves for residential heating, open burning of trash or debris, and frequent thermal inversions in the valley. The air quality in the wintertime is comparatively much better than during the wildfire season, nonetheless the community experienced moderate air quality conditions for 5, 10, and 37 days, respectively, in the past three winters (2019–2021), with the daily maximum $PM_{2.5}$ concentrations around 25 $\mu g/m^3$ [12].

This manuscript presents the results of two pilot studies designed to test feasibility of evaluating the effect of DIY PAC use on health. We report both the results of our analysis as well as a discussion on lessons learned, to inform design, implementation, and analysis of future related studies. The results of our analysis include an assessment of the effect of DIY PAC use on self-reported symptoms associated with exposure to $PM_{2.5}$ from wildfire smoke and residential wood stove use. We then present a brief description of barriers and facilitators to PAC usage. The air quality effects of the studies' PAC interventions are reported by Prathibha et al. [13]; both sets of evaluations are part of the broader Wildfire Advancing Science Partnerships for Indoor Reductions of Smoke Exposures (ASPIRE) Study investigating the impact of wildfire smoke on indoor air quality (https://www.epa.gov/air-research/wf-aspire).

2. Methods

2.1. Setting

We conducted two studies in Hoopa, CA: the "wildfire study" (September–October 2021) and the "wood stove study" (January–March 2022). We selected the wildfire study period because the community had historically experienced exposure to wildfire smoke during these months. The wood stove study was designed to capture elevated $PM_{2.5}$ concentrations due to prevalent wood burning for residential heating and thermal inversions that trap smoke in the valley. This study period also coincided with frequent open burning of trees and brush downed by a recent large snowstorm, resulting in degraded air quality during much of the wood stove study.

Hoopa, CA is comprised of about 3000 residents, about 84 % of whom are American Indian/Alaska Native (AI/AN) [14]. The 2021 median household income was $17,966 [15]. Approximately 94 % of the Hoopa population has health care coverage, with 58 % insured by public insurance [16]. Hoopa is located in Humboldt County, where primary health issues of concern are the effects of long-term alcohol, tobacco, and drug use and a shortage of primary care and behavioral health providers [17]. In Humboldt County, the AI/AN population's lifespan is about 12 years shorter than their white counterparts [18]. The economic, social, and health disparities of the AI/AN population in Hoopa and Humboldt County reflect those of other AI/AN groups and are rooted in historical practices and policies aimed at assimilating the AI/AN population [19,20]. The resulting economic, social, and health vulnerabilities make identifying economically feasible interventions that protect health during smoke exposures critical for these communities.

2.2. Recruitment

The study was advertised on the tribal radio station, in a local newspaper, through flyers, a website (https://www.epa.gov/epastudies), and by the local partner, the Hoopa Valley Land Management Department/Tribal EPA. Interested individuals were instructed to call a federal recruitment contractor for eligibility screening. Participants were required to be age 18 or older, live on the Hoopa Valley Indian Reservation, speak English, have access to a telephone and/or the internet, live in a home where no one smoked indoors (self-report), and (for wood stove study only) use an indoor woodburning appliance for home heating. Informed consent was obtained from individuals who were eligible for and interested in participating in the study. Prospective participants could elect to participate in one or both studies.

2.3. Study design

The pilot studies included four consecutive phases. Phase duration was 5–10 days during the wildfire study and approximately 14 days during the wood stove study (Fig. 1).

1) Initial Phase: There was no intervention. We assessed baseline health for each participant and initiated indoor and outdoor $PM_{2.5}$ measurements for each home.
2) DIY PAC Phase: We asked participants to run a DIY PAC (20" × 20″ MERV 13 electrostatic filter taped to a box fan) ≥8 h a day, on highest fan speed, while home and awake.
3) Commercial PAC Phase: We asked participants to run a small commercial PAC with HEPA filtration ≥8 h a day, on highest fan speed, while home and awake.
4) Sensor Display Phase: We installed a lower-cost indoor air quality sensor (Laser Egg; Kaiterra, Inc.) with a visual display showing $PM_{2.5}$ concentrations and the US Air Quality Index (AQI) value. We also provided information on air quality and health [21,22]. Participants could run either or both PACs at their discretion.

The DIY and the commercial PAC used were previously evaluated with simulated wildfire smoke in a controlled laboratory environment and found to have similar CADR. The CADR of the DIY PAC on high speed was 111.2 ± 1.3 ft^3/min, compared to 118.9 ± 0.7 ft^3/min for the commercial PAC on Turbo speed [23]. The DIY PAC also underwent a safety evaluation by the Chemical Insights

Fig. 1. Graphical representation of study design.
DIY: Do-It-Yourself; PAC: Portable air cleaner; $PM_{2.5}$: Fine particulate matter.

Institute of Underwriters Laboratories (UL) [24]. Out of an abundance of caution, we advised study participants to use the PACs only when home and awake. We installed PACs in the room where participants reported spending most of their waking time. The commercial PAC phase was intended to provide a reference point against which to compare the efficacy of the DIY PAC. See Supplemental Materials, Phase Instructions, for handouts provided to participants at the onset of each phase.

For the entire study, we measured 2-min indoor $PM_{2.5}$ concentrations at participants' homes using optical PM sensors (PA–II–SD, PurpleAir, Inc.). We placed sensors about 1.5 m from the ground and about 1–3 m away from the PAC, often on the opposite side of the room from the PAC. We also measured outdoor $PM_{2.5}$ with PurpleAir sensors that were part of the Hoopa Tribal EPA network. We used plug load data loggers (HOBO UX120-018) to measure the PAC usage at 1-min resolution, and we used state data loggers (HOBO UX90-001) to track the number of seconds main doors were open. During the wood stove study, we co-located carbon dioxide (CO_2) monitors (HOBO MX1102) with $PM_{2.5}$ sensors to collect 1-min indoor CO_2.

At the end of each phase, study personnel conducted 20–60-min telephone surveys with participants. The initial survey focused on participants' health, built environments, behaviors that may impact air quality (e.g., burning candles), and access to resources related to air quality. The subsequent surveys focused on changes in participants' health symptoms (upper and lower respiratory, cardiovascular, neurological, and depression/anxiety—see Data), behaviors related to use of each intervention, and perceptions of each intervention during each phase (Supplemental Materials, Surveys). Questions were a mix of multiple choice and open-ended.

This work was approved by the Hoopa Valley Tribal Council, the Human Subjects Research Protocol Office of the U.S. EPA, and the University of North Carolina at Chapel Hill Institutional Review Board.

2.4. Measures

The primary outcomes evaluated were three health symptom scores ("all-cause," "physical," and "mental/neurological"). The all-cause score is a composite score consisting of all upper and lower respiratory, cardiovascular, neurological, and mental health self-reported symptoms (see Supplemental Materials, Surveys; and Supplemental Materials, Pre-Existing Condition Score and Symptom Score Calculation). Symptoms included, but were not limited to, shortness of breath, fast or irregular heartrate, headache, red or irritated eyes, and trouble sleeping. We also asked questions from a validated depression screening questionnaire [25] and a validated anxiety screening questionnaire [26]. Each question corresponded to answer choices on either a four- or five-point scale, with the highest frequency scored as one (indicating poorest health) and the lowest frequency scored as four or five (indicating optimal health). The physical health symptom score consisted of all symptoms except depression and anxiety. The neurological and mental health symptom score consisted of trouble with concentration/memory and sleeping, and the depression and anxiety questions. To create each composite score, for each phase, we summed the values of each response and divided by the total number of relevant questions.

PAC use frequency was the primary exposure metric evaluated, defined by the percent of the days in the phase that participants ran the PAC for at least 8 h per day (33 %). PAC use frequency was a binary variable describing low frequency (PAC used $\geq$8 h per day for $<$33 % of days in the phase) and high frequency (PAC used $\geq$8 h per day for $\geq$33 % of days in the phase) of usage. We employed usage rather than intervention status or study phase as the exposure variable because participants did not always use the PACs for at least 8 h per day, as instructed, so each household experienced a different dosage of the intervention. Furthermore, participants received each intervention in the same order, at the same time, so intervention status/study phase could have been confounded with time-varying variables such as meteorological conditions and related changes in behaviors. Because there was no convention to define usage, we conducted sensitivity analyses in which we also defined usage 1) as a continuous measure of the percent of the total phase that PACs were running; 2) as a categorical measure of the percent of the total phase that PACs were running, with cutoffs at time-tertiles of use, and 3) as a binary measure of whether the PAC was run for at least 33 % of the total phase compared to under 33 % of the phase.

Indoor $PM_{2.5}$ concentrations were regarded as a mediating variable between PAC usage and health symptoms. Indoor and outdoor $PM_{2.5}$ concentrations were measured continuously over the study period and averaged for each phase. We excluded $PM_{2.5}$ data if agreement between the 2 p.m. sensors within each PurpleAir failed quality control criteria, defined as an hourly median absolute difference greater than 5 μg/m^3 and relative difference greater than 70 % between the two sensors. We defined two forms of indoor $PM_{2.5}$: infiltrated indoor $PM_{2.5}$ and total indoor $PM_{2.5}$. Infiltrated indoor $PM_{2.5}$ was used to decipher whether outdoor pollution sources (e.g., wildfire, wood stoves, or open burning) and/or indoor pollution sources (e.g., cooking, wood stove smoke backing into the room) of $PM_{2.5}$ were associated with health effects. The infiltrated indoor $PM_{2.5}$ was the phase averaged indoor $PM_{2.5}$, with spikes from suspected indoor sources of $PM_{2.5}$ removed [13]. These spikes were identified by comparing indoor $PM_{2.5}$ to outdoor $PM_{2.5}$ and durations when the door was open. We excluded indoor-outdoor $PM_{2.5}$ pairs if more than 15 % of data were missing. All $PM_{2.5}$ sensors were collocated in a laboratory chamber to adjust for precision relative to each other using a linear correction factor. We used the log base 10 of the phase averaged infiltrated and total indoor $PM_{2.5}$ in linear modeling analyses.

We identified factors that could confound the relationships of interest. First, we controlled for pre-existing conditions based on responses from the initial survey. We created two pre-existing health scores: physical health (including respiratory, vascular, smoking history, and allergy conditions) and depression/anxiety. Each score was constructed by summing the relevant questions (binary, 1 = has condition, 0 = does not have condition) and dividing by the total number of relevant questions in that category (see Supplemental Materials, Pre-Existing Condition Score and Symptom Score Calculation). In addition to pre-existing conditions, other control variables included log base 10 phase averaged outdoor $PM_{2.5}$ concentrations (measured continuously over the study), the percent of the phase that the door was open (measured continuously over the study), whether respondents reported using a personally-owned PAC during the study phase (asked each phase), and the average percent of time respondents reported spending at home in a typical week (asked at the initial interview). In the wood stove study, we also measured CO_2 in participants' homes. We substituted log base 10 phase averaged CO_2 for the percent of phase the door was open and the amount of time spent at home. We made that substitution because

CO_2 was highly correlated with the door being open (and outside temperature), and CO_2 was likely a better measure of amount of time spent at home than participants' rough estimate of their average time at home.

2.5. Analysis

The primary relationship of interest was the total effect of PAC use frequency on health symptoms reported during interviews (Supplemental Materials, Conceptual Models, Relationship 1). We examined DIY and commercial PAC usage both as pooled data (either PAC) and separately. We ran multivariate linear regression models with a random effect for participant to account for repeated measures. Sensitivity analyses defined PAC usage as the percent of the total phase, tertiles of total phase, and at least 33 % of the total phase. We did not perform the tertile sensitivity analysis in the model with DIY and commercial PACs included individually due to lacking sufficient variation for tertiles to be meaningful. We also conducted a sensitivity analysis on the wood stove study data in which we used the same covariates as the wildfire study models (i.e., percent door open and time spent at home instead of CO_2).

We performed a mediation analysis of the relationship between PAC usage and health mediated through indoor $PM_{2.5}$, since the primary pathway by which PAC usage would affect health is through decreasing indoor $PM_{2.5}$ concentrations. After assessing the total effect of PAC use on health, we added indoor $PM_{2.5}$ as a control to the total effect model to determine if the effect of PAC usage lost significance or decreased in magnitude (Supplemental Materials, Conceptual Models, Relationship 2). The next step of a mediation analysis is to study the effect of PAC usage on indoor $PM_{2.5}$. For our study sample, as reported in Prathibha et al. [13], PAC usage was found to be associated with reductions in indoor $PM_{2.5}$ (see Box 1). Lastly, we studied the relationship between indoor $PM_{2.5}$ concentrations and health (Supplemental Materials, Conceptual Models, Relationship 3). All analyses were conducted using R software (version 4.1.0). The lme 4 package was used to run the mixed effects models.

Finally, we used Microsoft Excel to tabulate survey responses regarding perceptions of and behaviors related to PACs. We categorized responses into barriers and facilitators.

Table 1
Descriptive statistics of study sample: Wildfire study (n = 10[a]).

	Phase			
	Initial N (%) or Mean ± SD [Range]	**DIY** N (%) or Mean ± SD [Range]	**Commercial** N (%) or Mean ± SD [Range]	**Sensor** N (%) or Mean ± SD [Range]
All-cause health symptom score	4.28 ± 0.35 [3.57–4.64]	4.46 ± 0.25 [3.86–4.64]	4.40 ± 0.20 [4.14–4.64]	4.50 ± 0.16 [4.21–4.64]
Physical health symptom score	4.44 ± 0.46 [3.40–4.90]	4.74 ± 0.18 [4.50–4.90]	4.63 ± 0.30 [4.20–4.90]	4.75 ± 0.18 [4.50–4.90]
Mental/neurological health symptom score	3.92 ± 0.38 [3.00–4.17]	3.97 ± 0.38 [3.00–4.17]	4.00 ± 0.25 [3.50–4.17]	4.02 ± 0.18 [3.67–4.17]
Frequency of pooled PAC use[b]				
Low (<33 % days)	10 (100.0)	8 (80.0)	2 (20.0)	6 (60.0)
High (≥33 % days)	0 (0.0)	2 (20.0)	8 (80.0)	4 (40.0)
Frequency of DIY PAC use[b]				
Low (<33 % days)	10 (100.0)	8 (80.0)	10 (100.0)	9 (90.0)
High (≥33 % days)	0 (0.0)	2 (20.0)	0 (0.0)	1 (10.0)
Frequency of commercial PAC use[b]				
Low (<33 % days)	10 (100.0)	10 (100.0)	2 (20.0)	7 (70.0)
High (≥33 % days)	0 (0.0)	0 (0.0)	8 (80.0)	3 (30.0)
Phase averaged total indoor $PM_{2.5}$	18.98 ± 10.96 [5.11–34.24]	13.73 ± 10.78 [2.21–29.29]	15.29 ± 9.10 [2.44–23.96]	13.98 ± 12.92 [0.62–33.15]
Phase averaged infiltrated indoor $PM_{2.5}$	10.89 ± 3.46 [7.14–15.28]	6.79 ± 3.87 [1.56–12.09]	6.91 ± 3.44 [1.57–10.80]	4.43 ± 3.43 [0.81–9.66]
Phase averaged outdoor $PM_{2.5}$	12.61 ± 1.77 [11.08–17.40]	6.80 ± 1.72 [5.90–10.28]	9.46 ± 1.39 [8.87–13.28]	3.58 ± 0.76 [3.11–5.63]
Pre-existing physical health conditions score[c] (21 questions)	13.81 ± 7.60 [9.52–33.33]			
Depression/anxiety score[c] (2 questions)	20.00 ± 34.96 [0.00–100.00]			
Used personally owned PAC in last 5 days *(ref = no)*	4 (40.0)	3 (30.0)	1 (10.0)	0 (0.0)
Percent of phase door was open	19.09 ± 9.12 [1.72–27.97]	18.48 ± 8.12 [0.42–26.74]	8.86 ± 4.27 [1.56–14.36]	4.94 ± 3.32 [0.75–9.34]
Average time spent at home/week				
<50 %	4 (40.0)			
50–80 %	2 (20.0)			
>80 %	4 (40.0)			

[a] N = 8 participants for phase averaged infiltrated $PM_{2.5}$ and phase averaged outdoor $PM_{2.5}$.
[b] Percent of days participants used PAC ≥8 h.
[c] Score is calculated by summing the number of conditions participants reporting having in each category and dividing by the number possible conditions.

3. Results

3.1. Characteristics of study sample

A sample of 10 adults from 8 homes were recruited for the wildfire pilot study (Table 1). The indoor $PM_{2.5}$ air sensors malfunctioned in two homes, leaving the $PM_{2.5}$ data available only for 8 participants in 6 homes. Ninety percent of participants were female. Forty percent of participants were between age 30–45, 20 % between age 45–60, and 40 % over 60. Nine of ten participants in the wildfire study elected and were qualified (based on home heating source) to participate in the wood stove study also. In all, the wood stove study sample consisted of 17 individuals in 11 homes (Table 2). In the wood stove study, CO_2 measurements were missing for 1 home (1 participant), and 1 participant was missing data from the fourth survey due to illness (pathogen identified). Fifty-three percent of wood stove study participants were female, 41 % male, and 6 % declined to answer. Approximately 24 % of participants were between age 30–45, 24 % between age 45–60, and 53 % over age 60. No participants were current smokers.

In both studies, average all-cause health, physical, and mental health symptom scores were slightly higher during the intervention phases than initial phase, indicating better health during the intervention phases. One exception was during the wood stove study, when the average mental health symptom score of the sensor display phase was slightly below the initial phase (indicating poorer mental health during sensor display phase relative to the initial phase).

Frequency of PAC use varied by the PAC type; participants used DIY PACs less frequently on average than commercial PACs. During the DIY phase of the wildfire and wood stove studies, 20 % and 53 % of participants respectively ran the DIY PAC with high frequency (≥8 h for ≥33 % of days in the phase). In contrast, during the commercial phase of both studies, about 80 % of individuals ran the commercial PAC with high frequency. Additionally, when given the option to run either PAC during the sensor display phase, only one person in each study chose to use the DIY PAC, with that one individual running the DIY PAC with high frequency. Thirty percent and 75 % of participants chose to run the commercial PAC with high frequency during the sensor display phase of the wildfire and wood stove studies, respectively.

The wildfire study began shortly before rain extinguished a nearby wildfire, resulting in wildfire smoke exposure only during the Initial (pre-intervention) Phase of the wildfire study. Therefore, $PM_{2.5}$ concentrations were relatively low during that study, with phase

Table 2
Descriptive statistics of study sample: Wood stove study (n = 17[a]).

	Phase			
	Initial N (%) or Mean ± SD [Range]	**DIY** N (%) or Mean ± SD [Range]	**Commercial** N (%) or Mean ± SD [Range]	**Sensor** N (%) or Mean ± SD [Range]
All-cause health symptom score	4.09 ± 0.29 [3.53–4.40]	4.16 ± 0.29 [3.33–4.40]	4.16 ± 0.25 [3.80–4.40]	4.16 ± 0.27 [3.67–4.40]
Physical health symptom score	4.18 ± 0.36 [3.45–4.55]	4.26 ± 0.40 [3.09–4.55]	4.26 ± 0.31 [3.82–4.64]	4.27 ± 0.31 [3.73–4.55]
Mental/neurological health symptom score	3.96 ± 0.31 [3.17–4.17]	3.97 ± 0.27 [3.33–4.17]	4.00 ± 0.18 [3.67–4.17]	3.94 ± 0.39 [2.83–4.17]
Frequency of pooled PAC[b] use[c]				
Low (<33 % days)	17 (100.0)	8 (47.1)	3 (17.6)	4 (25.0)
High (≥33 % days)	0 (0.0)	9 (52.9)	14 (82.4)	12 (75.0)
Frequency of DIY PAC use[c]				
Low (<33 % days)	17 (100.0)	8 (47.1)	17 (100.0)	16 (100.0)
High (≥33 % days)	0 (0.0)	9 (52.9)	0 (0.0)	0 (0.0)
Frequency of commercial PAC use[c]				
Low (<33 % days)	17 (100.0)	17 (100.0)	3 (17.6)	4 (25.0)
High (≥33 % days)	0 (0.0)	0 (0.0)	14 (82.4)	12 (75.0)
Phase averaged total indoor $PM_{2.5}$	36.37 ± 15.30 [8.17–57.62]	27.15 ± 11.19 [11.83–45.67]	26.23 ± 16.92 [7.02–55.56]	17.82 ± 12.85 [4.22–39.91]
Phase averaged infiltrated indoor $PM_{2.5}$	22.51 ± 12.95 [8.45–48.74]	20.61 ± 8.78 [9.11–31.29]	19.39 ± 12.23 [4.84–43.79]	12.86 ± 8.35 [2.85–28.91]
Phase averaged outdoor $PM_{2.5}$	47.84 ± 24.02 [10.20–68.87]	72.55 ± 34.63 [19.32–99.01]	73.74 ± 39.41 [13.60–104.01]	45.28 ± 24.99 [9.13–66.00]
Phase averaged CO_2	914.34 ± 198.81 [691.63–1277.30]	898.60 ± 189.96 [664.39–1245.48]	905.11 ± 181.28 [682.22–1253.01]	864.10 ± 180.43 [671.66–1219.41]
Pre-existing physical health conditions score[d] (21 questions)	16.53 ± 11.80 [0.00–47.62]			
Depression/anxiety score[d] (2 questions)	14.71 ± 34.30 [0.00–100.00]			
Used personally owned PAC in last 5 days	7 (41.2)	6 (35.3)	5 (29.4)	5 (31.2)

[a] CO_2 measurements were missing for 1 study participant's home during each phase, and 1 participant was missing survey responses during the sensor display phase due to illness.
[b] PAC: Portable air cleaner.
[c] Percent of days participants used PAC ≥8 h.
[d] Score is calculated by summing the number of conditions participants reporting having in each category and dividing by the number possible conditions.

averaged outdoor $PM_{2.5}$ concentrations ranging 3.58–12.61 μg/m^3. In contrast, phase averaged outdoor $PM_{2.5}$ concentrations ranged 45.28–73.74 μg/m^3 during the wintertime wood stove study. Overall, phase averaged total indoor $PM_{2.5}$ concentrations during the wildfire study ranged from 13.73 to 18.98 μg/m^3 and were lower than concentrations during the wood stove study (17.82–36.37 μg/m^3). The phase averaged infiltrated indoor $PM_{2.5}$ ranged from 4.43 to 10.89 μg/m^3 during the wildfire study and 12.86–22.51 μg/m^3 during the wood stove study. In both studies, the phase averaged total and infiltrated indoor $PM_{2.5}$ decreased from the Initial Phase to the intervention phases.

3.2. Association between PAC usage and health

We present the results of the inferential statistics here but caution that, due to very small sample sizes, we do not draw conclusions about either the absence or the presence of associations. During both the wildfire and wood stove studies, associations between pooled PAC usage and all-cause, physical, and mental health symptom scores were null (Fig. 2, Tables S1 and S2). When we examined DIY and commercial PACs separately, in the wildfire study, we observed a borderline significant decline in mental health in relation to DIY PAC usage ($\beta = -0.26$, 95 % CI: 0.55, 0.02, $p = 0.073$), and physical and all-cause health symptom scores were not significantly associated with usage (Table S3). In contrast, in the wood stove study, we observed borderline significant improved all-cause ($\beta = 0.17$, 95 % CI: 0.01, 0.35, $p = 0.061$) and physical health symptom scores ($\beta = 0.24$, 95 % CI: 0.00, 0.48, $p = 0.050$), and changes in mental health symptom scores were not significant (Table S4). In both wildfire and wood stove studies, health estimates associated with commercial PAC usage were all null.

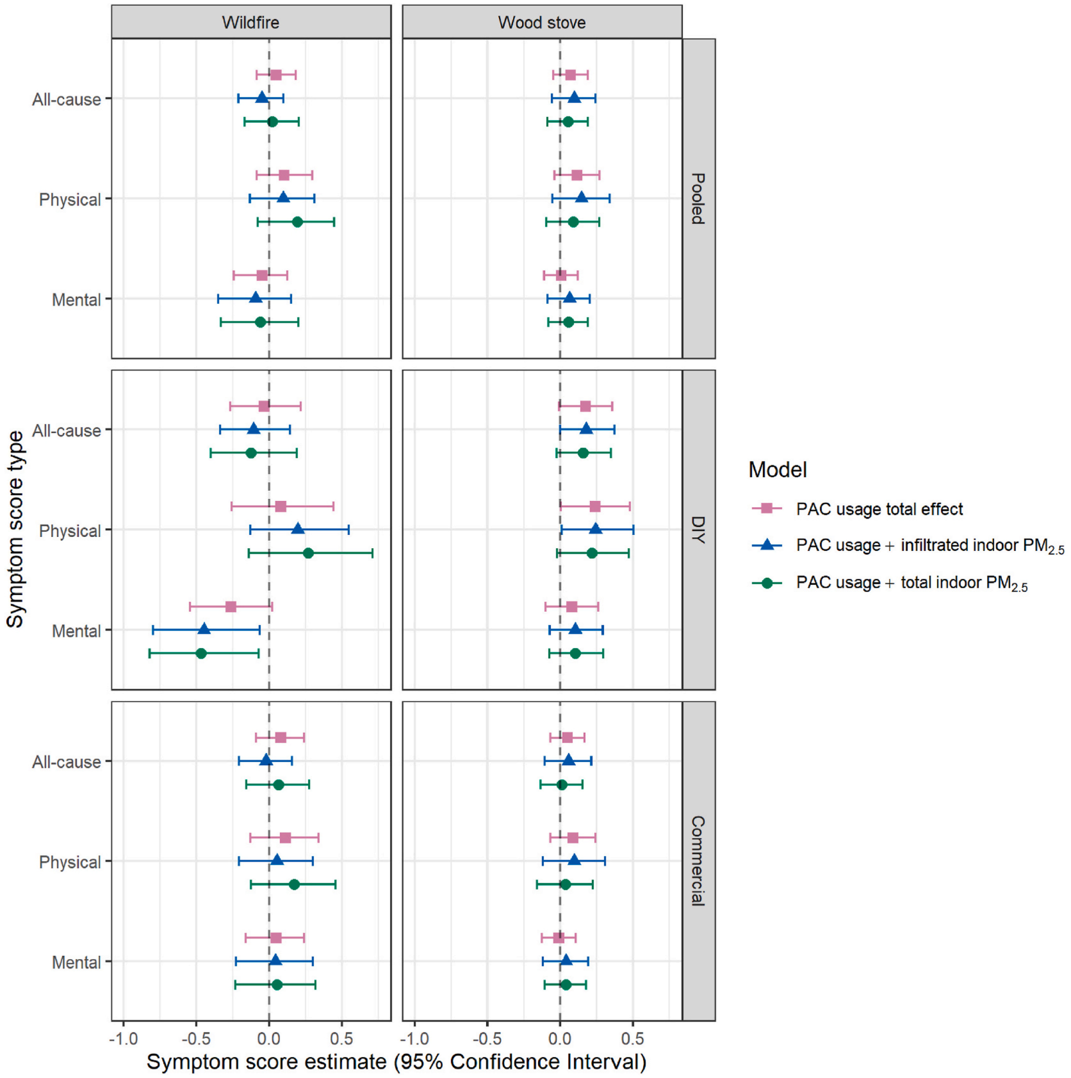


Fig. 2. Forest plot of wildfire and wood stove studies symptom score estimates associated with high frequency of PAC usage relative to low, and mediating effects of adding total and infiltrated indoor $PM_{2.5}$.

The pink lines (total effect models) illustrate the estimated effect of pooled PAC usage on the three types of health symptom scores. The blue and green lines illustrate the effect of adding the hypothesized mediating pathway, indoor $PM_{2.5}$ (infiltrated and total) to the total effects models A symptom score estimate greater than 0 indicates improvement in health (measured by self-reported symptoms), and less than 0 represents a decline in health.

Wildfire study: N = 10 participants and 40 observations in total usage model, N = 8 participants and 32 observations in PAC usage + indoor $PM_{2.5}$ models. Adjusted for log10 phase averaged outdoor $PM_{2.5}$, percent of phase door open, time spent at home, pre-existing conditions, own PAC usage.

Wood stove study: N = 16 participants and 63 observations in all models. Adjusted for log10 phase averaged outdoor $PM_{2.5}$, log10 phase averaged CO_2, pre-existing conditions, own PAC usage.

DIY: Do-It-Yourself.

PAC: Portable air cleaner.

$PM_{2.5}$: Fine particulate matter.

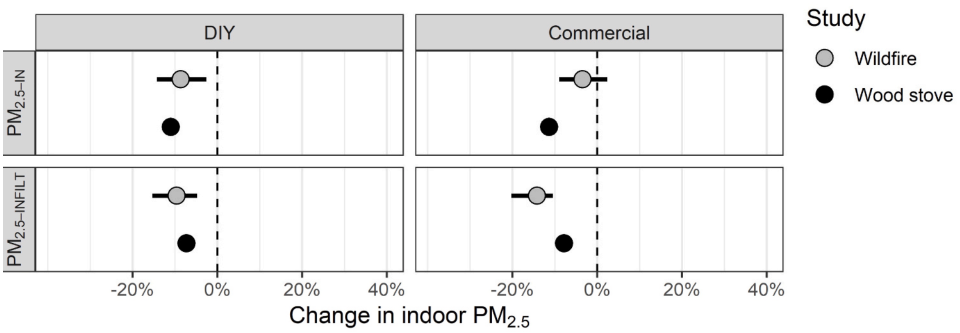
High frequency of PAC usage: Ran PAC ≥8 h for ≥33 % of days in phase (reference: Ran PAC ≥8 h for <33 % of days).

Box 1. Summary of assessment of association between portable air cleaners and indoor $PM_{2.5}$

We evaluated the association between PAC usage and percent reductions in indoor $PM_{2.5}$ using mixed linear models with household as a random effect. PAC usage was a binary predictor defined as "on" if operating for > 50% of a 10-minute window. The outcome measures were indoor $PM_{2.5}$ and infiltrated indoor $PM_{2.5}$, which were averaged at 10-minute resolution. We adjusted for durations that primary doors were open (% of 10-minute period that door was open) and outdoor $PM_{2.5}$ (averaged at 10-minute resolution).

During the wildfire study, DIY PAC usage was significantly associated with a decline in indoor $PM_{2.5}$ (-7.0% [95% CI: -11.3, -2.5]). Commercial PAC usage was negatively associated with indoor $PM_{2.5}$, but the association was not significant (-5.3% [95% CI: -10.4, 0.15]). During the wood stove study, use of both PACs was significantly associated with lower indoor $PM_{2.5}$ (DIY PAC: -9.59 [95% CI: -11.7, -7.43], Commercial PAC:-19.65 [95% CI: -21.84, -17.4]).

In both studies, use of either PAC was associated with reduced $PM_{2.5\text{-INFILT}}$, though estimated reductions were greater during the wildfire study (DIY PAC: -10.8% [95% CI: -15.2, -6.2], Commercial PAC: -18.3% [95% CI: -22.9, -13.5]) than during the wood stove study (DIY PAC: -3.9% [95% CI: -5.9, -1.9], Commercial PAC: -9.2% [95% CI: -11.4, -7.0]).



Detailed description of this analysis can be found in Prathibha et al. [13].

$PM_{2.5\text{-IN}}$: Total indoor $PM_{2.5}$

$PM_{2.5\text{-INFILT}}$: Infiltrated indoor $PM_{2.5}$

There was no discernible pattern of mediation when adding either phase averaged total indoor $PM_{2.5}$ or infiltrated indoor $PM_{2.5}$ to the models, for any health symptom score or PAC type (Tables S5–S12). The lack of evidence of a mediating effect suggests that the small, borderline-significant associations found between PAC usage and health were not attributable to changes in indoor $PM_{2.5}$ concentrations.

Furthermore, outdoor $PM_{2.5}$ concentration (a control variable) was only associated with health symptoms during the wildfire study but not the wood stove study. In the wildfire study, phase averaged outdoor $PM_{2.5}$ concentration was significantly associated with poorer physical and all-cause health in the total effect models (Tables S1 and S3). However, that relationship was not significant when infiltrated and total indoor $PM_{2.5}$ were added to the models (Tables S5, S7, S9, S11). This finding suggests that the association between outdoor $PM_{2.5}$ concentration and health may be at least partially attributable to exposure to infiltrated indoor $PM_{2.5}$ during the wildfire study. In contrast, outdoor $PM_{2.5}$ concentration was not significantly associated with health in any of the wood stove study total effect or mediation models (Tables S2, S4, S6, S8, S10, S12).

3.2.1. Sensitivity analyses

Defining PAC usage as percent of the total phase, tertiles of total phase, and at least 33 % of the phase did not yield substantive differences in analyses of the relationship between PAC usage and health, with a couple of exceptions (Supplemental Tables S13–S22). In the wildfire study, primary analyses showed no association between pooled PAC usage and physical health. However, in the sensitivity analysis, the highest tertile of pooled PAC usage (running either PAC at least 26.90 % of the phase) was borderline significantly associated with better health compared to the lowest tertile of use (under 9.46 % of the phase) ($\beta = 0.23$, 95 % CI: 0.01, 0.45, $p = 0.056$) (Table S14). In the wood stove study, primary analyses showed borderline and significant positive associations between DIY usage and all-cause/physical health, but no sensitivity analysis showed that relationship to be significant. Therefore, the definition of usage did sometimes impact the associations between PAC usage and health.

When we ran the wood stove study models using the same covariates as the wildfire study models (i.e., percent door open and time spent home instead of CO_2), we found substantively similar results (Tables S23 and S24). The only difference was that the positive association between DIY PAC usage and all-cause and physical health changed from borderline to fully significant (Table S24).

As a whole, the primary analysis results were not robust to sensitivity analyses.

3.2.2. Association between indoor $PM_{2.5}$ concentrations and health

In the wildfire study, the infiltrated indoor $PM_{2.5}$ was significantly associated with poorer physical and all-cause health symptom

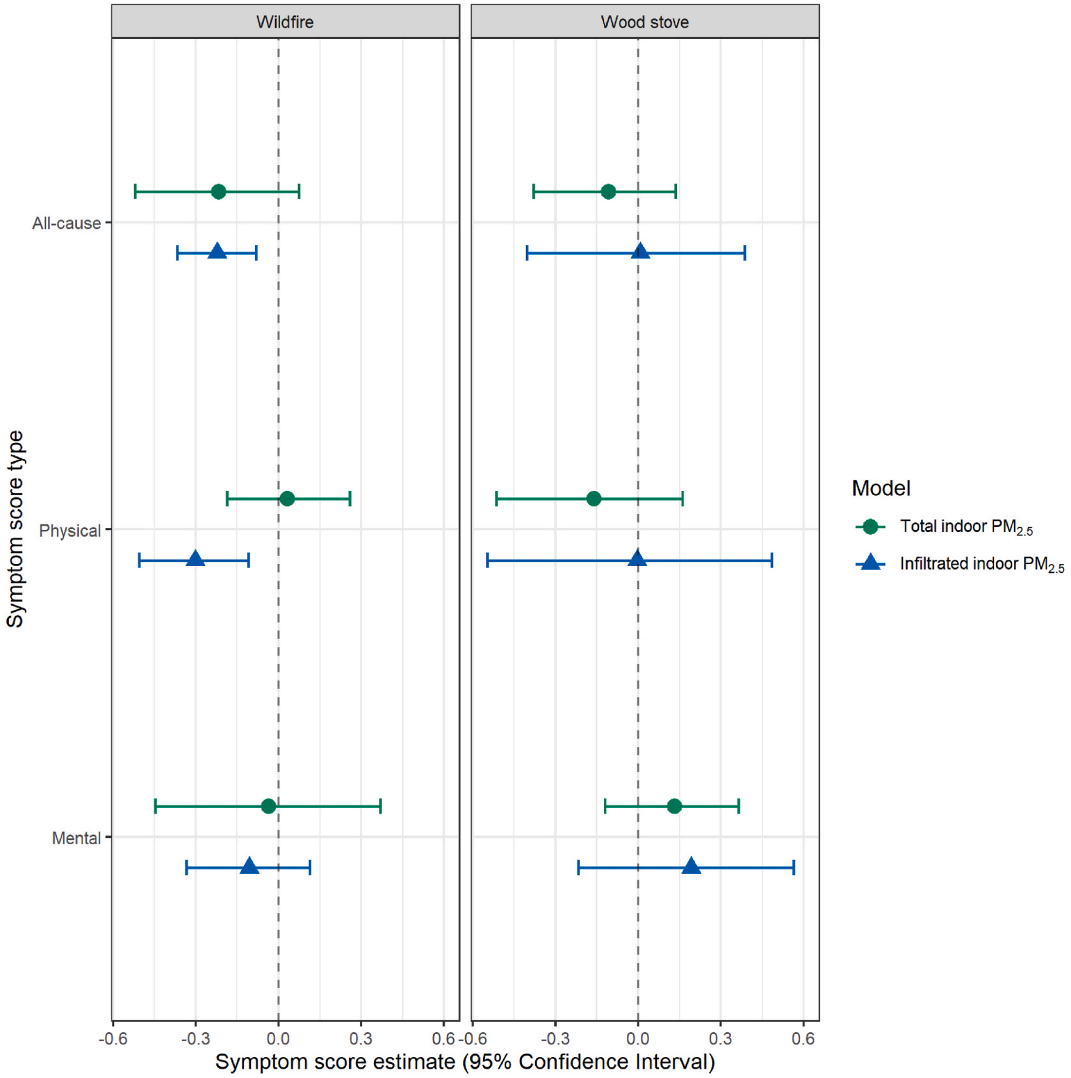


Fig. 3. Forest plot of symptom score estimates associated with indoor $PM_{2.5}$ during wildfire and wood stove studies.

scores (Fig. 3, Table S25). However, total indoor $PM_{2.5}$ concentration was only significantly negatively associated with those measures of health in the unadjusted models (Table S26). In the wood stove study, there were no significant associations between infiltrated or total indoor $PM_{2.5}$ and symptom scores (Tables S27 and S28).

A symptom score estimate greater than 0 indicates improvement in health (measured by self-reported symptoms), and less than 0 represents a decline in health.

Adjusted for log10 phase averaged outdoor $PM_{2.5}$, time spent at home (wildfire study) or log10 phase averaged CO_2 (wood stove study). Phase averaged indoor $PM_{2.5}$ is log10 transformed.

Wildfire study: N = 10 participants and 40 observations in total indoor $PM_{2.5}$ model, N = 8 participants and 32 observations in infiltrated indoor $PM_{2.5}$ model.

Wood stove study: N = 16 participants and 63 observations in both models.

$PM_{2.5}$: Fine particulate matter.

3.3. Health-related barriers and facilitators to PAC use

The primary barrier to use of the DIY PAC was the loud noise of operation, while the quiet operation of the commercial PAC was a facilitator to its use. While almost all participants across studies were frustrated by the loud noise, the majority of participants stated that they would use the DIY PAC if necessary, such as if the air were very smoky, or that they would use the DIY PAC in another room. Thus, perception of poor air quality was one facilitator to use of the DIY PAC. Additionally, participants reported using the DIY and commercial PACs outside of study instruction in reference to protecting elders' health or because a household member was sick, with specific reference to children being sick and to COVID-19. Therefore, protecting the health of elders and children and protection against COVID-19 were facilitators to use of both PACs. Smells or fumes (e.g., smoke, fume from kerosene stove) and the use of the fans for cooling or drying laundry were also reasons people used both PACs. The cooling effect of the DIY PAC was a barrier to use in the wood stove study (wintertime) and a facilitator of its use during hotter periods.

4. Discussion

These pilot studies tested the feasibility of investigating the effect of DIY PACs on health during periods of wildfire and wood burning smoke exposure in homes within the Hoopa Valley Indian Reservation. The primary goal of the studies was to pilot test the design, implementation, and analysis of a study investigating the efficacy of DIY PACs in protecting health in a real-world, residential setting. We cannot draw conclusions about causality based on these results. In the samples of 10 and 17 participants, we observed largely null associations between DIY PAC use and self-reported symptoms, and we did not find evidence that any impacts were attributable to changes in indoor $PM_{2.5}$ concentrations. We observed that DIY PAC use was lower than requested among study participants and that the primary barrier to DIY PAC use was the loud noise of operation. Finally, we learned many lessons from these pilot studies that may inform future research on this topic.

While we did not observe robust evidence of an association between PAC usage and self-reported health symptoms, an analysis by Prathibha et al. on the indoor air quality in study homes did observe both PACs to be associated with reductions in indoor $PM_{2.5}$ concentrations (mean declines in 10-min averages ranging 4–20 % μg/m^3) [13]. We suspect that the primary reasons that we did not observe an association between PAC use and symptoms, despite observing reductions in indoor $PM_{2.5}$ concentrations, were that the sample size was too small to detect a health signal, and that the health measure (self-reported symptoms) was not sensitive enough to the small changes we observed in air quality. Other reasons for the mostly null health results likely differ between study periods. In the wildfire study, the phase averaged outdoor $PM_{2.5}$ concentrations during the intervention phases were low (3.58–9.46 μg/m^3) because the wildfire smoke that was present in the initial phase had cleared by the time we implemented the interventions. The phase averaged infiltrated $PM_{2.5}$ was also low (4.43–6.91 μg/m^3), and the indoor sourced $PM_{2.5}$ raised the phase averaged total indoor $PM_{2.5}$ concentration to 13.73–15.59 μg/m^3. Thus, the PACs were cleaning relatively clean air, with most of the $PM_{2.5}$ due to short term spikes from indoor sources. Those indoor sources (e.g., cooking emissions) may cause a different health response than outdoor $PM_{2.5}$ sources. We did observe that during the wildfire study, outdoor $PM_{2.5}$ and *infiltrated* indoor $PM_{2.5}$ were associated with poorer health. However, this analysis pooled exposure and outcome data across all study phases; those associations were probably due to outdoor and infiltrated $PM_{2.5}$ being higher during the initial phase when there was wildfire smoke, resulting in health symptoms. Those symptoms improved in the following weeks, but this may have been due to wildfire smoke clearing outside—and therefore indoors—rather than PAC usage.

During the wood stove study, again, small sample size and the lack of sensitivity of the health measure were likely the primary reasons for largely null results. However, other reasons that reductions in indoor $PM_{2.5}$ from PAC use did not robustly translate to health-protective effects are likely different from the wildfire study. Outdoor $PM_{2.5}$ concentrations were consistently high during the wood stove study (phase averaged mean ranging 45.28–73.74 μg/m^3), infiltrating indoors. Additionally, indoor sources (e.g., wood stoves) coupled with poor ventilation further increased the indoor $PM_{2.5}$ concentrations. During this study period, we did not find any significant associations between outdoor or indoor $PM_{2.5}$ concentrations and symptoms. We suspect that the reason for this lack of association was that the outdoor $PM_{2.5}$ concentrations did not vary enough to see symptom differences at different concentrations. In addition, indoor $PM_{2.5}$ phase averages ranged 17.82–36.37 μg/m^3 and did not decrease in enough households to concentrations at which we would expect to see health improvements. Another wintertime study of PAC use in rural homes using wood stoves for heat also found improved, but persistently elevated concentrations of $PM_{2.5}$ in homes [27]. In the EldersAIR study, homes using a commercial air cleaner had mean indoor $PM_{2.5}$ concentrations of 30.5 μg/m^3 compared to 41.6 μg/m^3 in the previous winter (pre-intervention). PAC usage data was not reported for this study; continuous use was requested of participants. Use of both the DIY and the commercial PAC used in the present studies was measured by power logging devices. Based on these data, the lack of significant symptom improvement with PAC use is likely due, in part, to the fact that PAC usage was lower than necessary to achieve meaningful reductions in $PM_{2.5}$ during the wood stove study.

To our knowledge, the two pilot studies presented in this paper are the first to examine the relationship between *DIY* PAC usage and health, so a direct comparison of the results of the present studies to other research efforts is difficult. Additionally, as previously noted, the results should be interpreted with caution due to the small sample size. However, there is a growing number of studies on the association between commercial PAC usage and health in the settings of ambient air pollution, wildfire smoke, and wood stove emissions, with variable findings. The largely null results from the studies we present are consistent with some other studies' findings, including some with larger sample sizes. A 2020 systematic review of commercial PAC use and effects on indoor air quality and health outcomes [3] analyzed 22 studies, 16 of which included a health outcome measure. While all studies showed reduced $PM_{2.5}$ concentrations in indoor air, the health findings were less consistent than the indoor air quality results. Five of the studies in the systematic review assessed the association between PAC use and respiratory outcomes. Despite strong epidemiologic evidence for increased respiratory morbidity with air pollution and wildfire smoke exposure [28,29], only one of the five studies reviewed observed a significant increase in a measure of lung function, the forced expiratory volume in 1 s (FEV_1), associated with PAC usage [30]. Studies of commercial PAC use and cardiovascular health endpoints also showed mixed results. Of ten studies of commercial PAC use and blood pressure, six found no significant association while four found a significant decrease in systolic blood pressure, diastolic blood pressure, or both [3].

While the present studies did not include children, numerous studies have examined commercial PAC use and children's respiratory health, often for children with asthma. Some studies have included children in rural settings. For instance, the KidsAIR randomized trial examined the effect of commercial PAC use or education alone versus control (sham or no filtration) on rates of lower respiratory tract infection (LRTI) in 461 children younger than age 5 in rural U.S. homes heated by wood stoves. Although an exposure-response analysis demonstrated an increased risk of LRTI with increasing concentrations of $PM_{2.5}$ measured in air inside the homes, no significant difference in LRTI incidence was seen between the PAC, education, and control groups over the 2 study winters [27]. Additionally, in a 2022 U S. study of 75 children with poorly controlled asthma exposed to ambient air pollution in an agricultural area of Washington State, subjects were assigned to an educational intervention alone or education plus HEPA PACs in their bedroom and living room. There was no statistically significant change in the Asthma Control Test (ACT) score for the intervention group compared to the control group in primary analyses. Secondary analyses did show a reduced risk of unscheduled clinical visits and fewer asthma symptom days in the previous two weeks. A statistically significant difference between intervention and education-alone groups was seen when a repeated measures analysis excluded data from subjects whose caregivers reported turning off the HEPA PAC more than 3 days in the previous month, emphasizing the importance of user behavior [31].

4.1. Limitations

The present studies had a few limitations. First, the small sample size limited the ability to detect both significant associations between PAC usage and health and the mediation pathway. The small sample also required us to aggregate the outcome variable (self-reported health symptoms) instead of examining specific health symptoms separately, such as cardiovascular, respiratory, neurological, or mental health symptoms. The limited sample size may have been due in part to this study taking place during the COVID-19 pandemic and to community members' lack of trust of researchers and/or the federal government—a challenge common to studies in AI/AN communities [32]. Having a strong community partner helped us reach the individuals who did agree to participate, but we suspect that distrust and lack of perceived benefit may have prevented others from participating. Inevitably, people who are inclined to participate likely do not represent the community as a whole and may be more amenable to public health guidance and interventions than the general population.

Second, our study design confounded time-varying factors (e.g., meteorological conditions and associated behaviors) with the intervention because every participant received the same intervention at the same time. Thus, any difference in symptoms between intervention periods could have been due, for example, to changes in season or to other exposures. We addressed this limitation in our statistical models by defining PAC usage as the percent of the time the PACs were used during any of the intervention periods, but a randomized study design in which participants were randomized to use a DIY, commercial, or no PAC/sham filtration at different times would be the best way to decrease this potential for bias in a larger study. Third, wildfire smoke was only present during the initial phase of the wildfire study, so the intervention phases were confounded with the smoky air clearing. We thus controlled for outdoor $PM_{2.5}$ and found no significant improvements in health associated with PAC usage, likely because cleaning relatively clean air would not result in changes in health symptoms for most people. The unplanned timing of wildfires is a challenge common to all prospective wildfire studies, and future studies assessing effects of wildfire smoke could benefit from building flexibility into the study timing to improve the chances of capturing wildfire smoke exposure (see Lessons Learned, below). Fourth, most participants in these studies already owned PACs, and we felt that it was unethical to ask participants not to use PACs they already owned. This limitation meant that we could not have a strict control group and that participants may have used personally owned PACs during the initial phases, biasing results toward the null. We controlled for self-reported personally owned PAC usage, but members of the same household differed in reporting how often and how many personally owned PACs they used during each phase, so we know this measure is imperfect. Future studies would benefit by measuring personal PAC usage to account for their impact on indoor air quality, or by excluding people who own PACs. A fifth limitation was recall bias of health symptoms. We asked participants at the end of each phase (ranging 5–14 days) about their health symptoms over that period, and recall error may have biased the results in either direction. Lack of blinding of participants and potential order effects also may have biased the symptom measure. Finally, although most questions about symptoms were informed by validated questionnaires, the outcome symptom measure is not a validated measure of health.

4.2. Strengths

These studies also had several strengths. First, they were closer to real-world conditions than many other studies evaluating the effect of PAC usage on health, some of which have run PACs continuously and have required that doors and windows remain closed during the study period. While we requested that study participants use the PACs at least 8 h a day while awake during the DIY and commercial PAC phases, we gave participants the choice to use either PAC for unspecified durations during the sensor display phase. Participants had the freedom to turn PACs on or off during all intervention phases. Thus, we captured a wide range of "dosage" of PAC use and were able to begin exploring how much usage is necessary to impact health. We found no evidence of a linear relationship between usage and health, but rather that there may be a threshold at which health effects begin to emerge. Future studies with larger sample sizes could better elucidate the levels of usage needed to prevent adverse health effects at different levels of exposure to air pollution. A second strength of these studies was that we measured health symptoms rather than subclinical health effects. Measuring symptoms may be more relevant to public health risk assessment and messaging. However, again, larger sample sizes are likely necessary to capture health symptoms than the present study. Third, we implemented a longer period of exposure measurement than many studies of PAC interventions and we assessed exposure to $PM_{2.5}$ directly in the homes (air quality sensor), and quantified usage of the study-provided PACs with power logging devices.

Fourth, these studies focused on a population that is especially vulnerable to the negative health impacts of smoke—both wildfire and wood burning smoke. The participants of these studies are exposed to smoke year after year, sometimes year-round, from wildfires, burning wood for heat, and burning of debris and garbage. Furthermore, this community experiences social and economic vulnerabilities from a history of settler colonialism and attempted cultural erasure [19], hindering community members' ability to adapt to wildfire smoke exposure. Centering such communities in efforts to protect and promote health in the context of wildfires and other climate change effects is vital to working toward environmental justice.

4.3. Lessons learned

While the results of the analyses presented in this paper must be interpreted with caution, there are several key takeaways from the ASPIRE-Health pilot studies conducted in Hoopa, CA that could inform future studies investigating the association between DIY PACs and health:

1. **Research on wildfire-related health effects requires flexibility and substantial time and resource investment.** The unpredictable nature of wildfires necessitates set-up of a study before the possibility of wildfire smoke (obtaining informed consent from participants, obtaining baseline measurements, and installing equipment) and being prepared to mobilize study personnel (e.g., travel to the study site) and participants (e.g., rapidly scheduling home visits for sample collection) to capture the exposure and outcomes when smoke occurs. With a large sample size, obtaining outcome measures from all study participants, whether through surveys or biological samples, during the unpredictable exposure period requires significant staff time. An additional critical resource need is adequate compensation for study participants who volunteer for a potentially long study duration, while awaiting smoke impacts.
2. **Randomizing participants to intervention(s) and control group(s) is important to avoid bias from time-varying confounders.** This approach could be done either through a case crossover design in which the timing of the intervention is randomized or by simply randomizing participants to an intervention group and a control group during one intervention period. If the research is in the context of wildfire smoke, given the unpredictable nature of wildfire events, the latter is a more realistic design.
3. **A complex study design is required to answer both whether an intervention can effectively protect health *and* whether, how, and how much it is used in real-world settings.** To answer whether a DIY PAC can effectively protect health, sufficient "dosage" (use) of the intervention is required. In this case, dosage is dependent on participant adherence to usage of the PAC. One of the most noteworthy findings of these pilot studies was that participants used the DIY PACs far less than instructed, largely due to their loud operation. To ensure adequate dosage to assess efficacy, incentives to study participants (e.g., compensation bonuses) may be necessary. However, outside of a research study, financial incentives are rarely possible. Instead, factors such as perceived risk/benefit, self-efficacy, and social norms typically affect health behaviors. The field of implementation science could offer insights into answering both research questions.
4. **Excluding people who already own PACs would avoid the ethical dilemma of asking people not to use personally owned PACs.** However, as community organizations and public health guidance increase distribution or encourage uptake of PAC use, this exclusion criterion is becoming increasingly restrictive.
5. **Using the power logger was critical to assessing the dosage of the intervention.** Self-reported usage differed greatly from the usage recorded by the power loggers, emphasizing the importance of measuring usage empirically. However, power loggers did occasionally fail. Capturing both measures of usage, especially over a long intervention period, may be necessary.

5. Conclusion

We did not find robust associations between DIY or commercial PAC use and health symptoms in these studies but draw no decisive conclusions about absence of an association due to small sample size. In addition to small sample size, unfavorable study conditions (i.

e., lack of wildfire smoke during the wildfire study period) and low PAC usage of participants during periods of consistently elevated indoor and outdoor $PM_{2.5}$ concentrations may have been responsible for this lack of associations. Future research on DIY PACs and smoke exposure should prioritize large sample sizes, flexibility in study design to improve chances of capturing periods of smoke exposure, deeper investigation of factors affecting behavior, and randomization of participants to control and intervention arms—-which may require finding study populations in which PACs are not already prevalent to avoid unethical requests to not to use PACs that individuals already own. While researchers hone their ability to measure health impacts of PACs, there is existing evidence that lends support to recommending their use: 1) This research and previous studies have demonstrated that PACs (DIY and commercial) are associated with reduced $PM_{2.5}$ concentrations indoors and 2) there is strong evidence of negative health impacts from exposure to elevated ambient $PM_{2.5}$ concentrations. However, simply distributing PACs will not ensure that individuals undergo the behavior change of using them. More research is needed to understand what factors affect use. Facilitators of use identified by this study included a desire to protect children's and older adults' health, including a perceived reduced risk of infection with COVID-19. An additional facilitator in warm weather was the dual functionality of PACs as both air cleaners and fans that can be used to cool homes. Providing operational instructions and access to replacement filters may be needed to encourage sustained use of PACs. Understanding the ability of PACs to mitigate negative health effects of $PM_{2.5}$, making PACs and replacement filters accessible to all communities exposed to wildfire and wood burning smoke, and identifying factors that influence people to use those PACs during smoky periods are all important steps in protecting the health of the growing numbers of people who are exposed to smoke for increasing periods of time with the changing climate.

Data availability statement

Main datasets available through the EPA Environmental Dataset Gateway.

Disclaimer

The views expressed in this article are those of the authors' and do not necessarily reflect the views or policies of the U.S. EPA, DOE, ORAU/ORISE, or the Hoopa Valley Tribal EPA. Any mention of trade names, manufacturers or products does not imply an endorsement by the United States Government or the U.S. Environmental Protection Agency. EPA and its employees do not endorse any commercial products, services, or enterprises.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.heliyon.2024.e25225.

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