Acute respiratory infection risk associated with exposure to outdoor PM_{10} emissions from domestic heating

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ABSTRACT

AIM: Woodsmoke exposure has known adverse respiratory health effects. However, most studies are based on exposure in developing countries or developed cities. Woodburners are commonly used for domestic heating in New Zealand, and in some areas they impact air quality. We investigated whether woodsmoke exposure at levels encountered in a mid-size township has health effects.

METHOD: We performed a time-stratified case crossover analysis of 1,870 general practitioner (GP) visits for acute respiratory infections (ARI) over five consecutive winters (May–August 2014–2018). Daily air concentrations of particulate matter less than 10 µm (PM_{10}) were obtained from a fixed-site monitoring station. Conditional logistic regression was used to estimate OR and 95%- CI after adjusting for the effects of temperature.

RESULTS: A 10 µg/m^3 increase in PM_{10} concentration was associated with 8% (95% CI 1%–15%) and 20% (95% CI 4%–38%) increases in the odds of a GP visit for an ARI within 24 hours for women and girls, and Māori of both sexes, respectively.

CONCLUSION: Woodsmoke pollution may negatively affect the respiratory health of residents in mid-size towns. However, those most affected by woodsmoke are also likely to be most affected by woodburner phase-out policies. Air quality and housing policies must be integrated to meet a mutual goal of improved health.

Woodburning stoves and fireplaces emit known health-damaging pollutants, including carcinogenic compounds.[1] In New Zealand's South Island, where the coldest winters are experienced, 47% of the population uses woodburners for home heating.[2] Wood has some advantages over electricity, including higher heat output, the ability to scavenge or barter for material, and independence from the power grid. However, in some towns, domestic woodsmoke is the primary driver of winter outdoor air pollution, with daily average concentrations of particulate matter less than 10 µm (PM_{10}) frequently exceeding the 50 µm/m^3 National Environmental Standard for Air Quality.[2,3] Depending on the weather, breaches can occur up to 50 days per winter.[2]

People who routinely experience short-term exposure to high woodsmoke concentrations in winter are potentially at increased risk of adverse health outcomes. Because woodsmoke particles are generally smaller than 1 µm they can be inhaled deep into the respiratory system.[4] Toxicology studies show that short-term woodsmoke inhalation can compromise the respiratory tract's defence systems.[1] Epidemiological studies linking solid fuel combustion exposure to respiratory issues have been carried out for many years, with most evidence coming from developing countries. In these settings, where fuels typically include wood, charcoal, dried animal dung, and agricultural waste, exposure has been linked to acute respiratory infections in children, and chronic bronchitis, tuberculosis, and chronic obstructive pulmonary disease in women.[1,5] Questions remain for exposure in developed countries, where wood is the predominant fuel and better housing conditions and combustion appliances are typically observed.[6] A recent meta-analysis of data from Europe, North America, Australia and New Zealand indicated that exposure to indoor wood burning is associated with an increased risk of respiratory infections.[7] There was insufficient data to draw conclusions about outdoor exposure to woodsmoke from indoor sources.

Within New Zealand, there have been woodsmoke health effects studies in Christchurch, Auckland, and nationally based on modelled data.[3,8–11] In Christchurch, where woodsmoke makes up 90% of ambient outdoor PM_{10},[3] increases in PM_{10} were associated with increased mortality,[10] cardio-respiratory hospital admissions,[3] and respiratory symptoms and medication usage among people with chronic obstructive pulmonary dis-

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ease.[9] In Auckland, exposure to neighbourhoods with higher densities of wood or coal-burning households was associated with increased odds of emergency department visits during early childhood.[8] Limitations of these studies include difficulties in generalising beyond the city environment and their focus on relatively severe outcomes or susceptible populations. It is unclear whether winter woodsmoke pollution in smaller New Zealand towns is associated with respiratory illness to the degree observed in cities, or whether woodsmoke exposure has a potential role in milder health conditions.

Small to medium sized towns in developed countries are ideal for studying woodsmoke health impacts as they are largely free of industrial pollution and road traffic emissions. Acute respiratory infections (ARIs) are common conditions that are better suited for small-population analysis than more severe but less frequent causes of morbidity. We aimed to describe the association between woodsmoke exposure and local general practitioner (GP) visits for ARIs in a mid-sized town with known woodsmoke pollution issues.

Methods

Study location and population

We compared GP ARI coding among four similarly sized towns in Otago with known woodsmoke pollution issues and selected one as the study location (population < 6000) based on its high number of coded visits and consistency across years. A 2019 Emissions Inventory identified that domestic heating is responsible for 94% of the town's daily winter PM_{10} emissions.[12] The inventory used a household survey to collect information on local domestic heating methods and fuel types. Emission factors were applied to these data to estimate emissions for the area. According to the inventory, 56% of the town's households use woodburners to heat their main living area, burning an estimated 26 tonnes of wood and discharging around 141 kg of PM_{10} on a typical winter's night. Less than 1% of households used coal. Outdoor burning is prohibited within the town during winter months. There is no area that could be considered metropolitan, and the nearest highway is at least 200 m beyond the town's residential boundaries. There is no local power station. Agricultural burning in rural land surrounding the town is not considered to be a significant contributor to air pollution experienced within the urban centre due to distance and prevailing weather conditions. For reference, the town's estimated daily winter PM_{10} emissions were 0.9 kg from motor vehicles and 1.1 kg from industrial and commercial sources.

The study population were residents of all ages who presented to their local GP and were diagnosed with an ARI between 1 May–31 August 2014–2018 (Table 1). Excluded were individuals with a home address outside of the town (i.e., visitors) as their exposure during control periods could not be estimated. Anonymised patient data were provided by the local Primary Health Organisation. ARI visits were identified by Read codes. These are a standardised system of recording patient findings and proceedings across primary care. Of interest were visits coded H00 (acute nasopharyngitis), H01 (acute sinusitis), H02 (acute pharyngitis), H03 (acute tonsilitis), H04 (acute laryngitis and tracheitis), H05 (other acute upper respiratory tract infections) and H06 (acute bronchitis and bronchiolitis). Patient age, sex, ethnicity, geographic unit of home address, consultation date and time, and encrypted National Health Index (NHI) number were obtained. Only the first GP visit per day per person was included in the analysis. Individual consent (at patient level) was not required because patient information was not being requested in a form that could identify the individuals concerned. The University of Otago Human Ethics Committee (HD19/027) approved this study.

Woodsmoke exposure and air temperature

The Otago Regional Council monitors winter PM_{10} and air temperature at a fixed site in the study town and agreed to provide study data. Mean 24-hr PM_{10} concentrations and mean 24-hr air temperature was based on the time frame of an air pollution event—3:00 pm to 2:59 pm the next day.

Woodsmoke exposure in the home neighbourhood was assessed by the number of households per hectare using woodburners as their main heat source based on 2018 Census Statistical Area 1 data, replicating the method of Lai et al.[8] The national interim coverage rate for the 2018 Census was 98.6%, the heat and fuel type questions each had a response rate of 92.3% and a quality rating of "moderate".[13] Geographic unit of home address was converted from 2013 Census Meshblock to 2018 Statistical Area 1 using the 2021 Geographic Areas Table.[14]

Study design

Case crossover study

In the case crossover design statistical inference is based on a comparison of each subject's exposure during a period relevant for the causation of the outcome (the hazard period) and during one or more control periods. We tested three hazard periods: 1) exposure during a 24-hour window from 3:00 pm the day before a GP visit to 2:59 pm on the day of visit ("same day"); 2) exposure during a 24-hour window between 3:00 pm two days before, and 2:59 pm the day before a GP visit (one-day lag); and 3) exposure during a 72-hr window from 3:00 pm three days before a GP visit to 2:59 pm on the day of visit (three-day average). Control periods were seven and 14 days before and seven days after the hazard period, to control for time-varying co-factors that may be associated with the day of the week. Control period length was matched to hazard period length. To reduce potential exposure misclassification, we restricted the case crossover analysis to GP visits made by persons residing in a Census Meshblock that fell wholly or partially within a one km radius of the PM_{10} monitoring station.

Ecological study

We also investigated group-level associations between neighbourhood woodburner density, as a proxy for woodsmoke exposure, and ARI GP visitation rates. Unlike the case crossover approach, the ecological study did not assume equal exposure around the PM_{10} monitoring station. However, causality cannot be implied due to the cross-sectional design.

Statistical methods

The Dupont method was used to calculate sample size requirements for the case crossover analysis.[15] Based on type I and type II error rates of 0.05 and 0.8, respectively; a 0.12 probability that a case will be exposed to high PM_{10} in the control periods, and a correlation coefficient of 0.2 between hazard and control periods, 599 cases were required to detect an odds ratio (OR) of 1.5. Assuming a higher probability of exposure on control days (0.18) reduces the sample size requirement to 440 for an OR of 1.5. Conditional logistic regression with robust standard errors was used in a complete case analysis to produce risk estimates presented as OR with mean temperature as a covariate. Stratified analyses were conducted by age, sex, and prioritised ethnicity (European, Māori, and all other ethnicities combined). Further stratification into individual disease categories or by year would have resulted in numbers too small for analysis. Goodness-of-fit was tested by plotting the change in Pearson's Chi-squared against predicted probabilities, the link function was tested using a Stata's linktest command, and potential multicollinearity between PM_{10} and mean daily temperature by examining variance inflation factors.

ARI visitation rates were calculated as the number of ARI GP visits divided by the estimated population for the corresponding Statistical Area, multiplied by 1000. The rates were age-standardised using the direct method, with New Zealand's 2018 population as the reference. Multilevel Poisson and negative binomial models were used to identify potential associations between group-level woodsmoke exposure and ARI GP visitation rates at Statistical Area 1 level. Goodness-of-fit was tested using a Chi-squared statistic and Stata's linktest command. All analyses were conducted using Stata 17.0 (StataCorp, Texas).

Results

During the winters of 2014 to 2018, 1,870 ARI GP visits were made by 1,142 individuals. Slightly over half (54.7%) were made by children aged 14 years or younger. More visits were made by women and girls (55.4%) than by men and boys (44.6%). During the same period, mean daily PM_{10} was 34.84 μg/m^3 (range 7.6–97.0 μg/m^3) and mean daily air temperature was 6.5 °C (range -4–17.6°C). The difference between PM_{10} during the same day hazard period and the average concentrations during the three corresponding control periods (the exposure term[16]) had a median of 3.65 μg/m^3 and IQR of 35.87 μg/m^3. The current 24-hr PM_{10} National Environmental Standard for Air Quality[17] of 50 μg/m^3 was exceeded multiple times each year (Table 1).

According to 2018 Census data, the mean number of woodburning dwellings per hectare was 3.4 (range 0.2–7.5). Overall, 546 (28.7%) households were renters, with marked variance in this proportion by Statistical Area (range 3%–50%). Only area-level deprivation quintiles 1 (least deprived) to 3 were represented in the study township. There were no significant differences in woodburner density between the represented deprivation quintiles.

Table 1: Mean PM_{10}, number of National Environmental Standard for Air Quality exceedances*, mean temperature, and number of general practitioner visits for acute respiratory infections by condition, age group, sex, ethnicity, and year for whole study town.

	Winter season (1 May – 31 Aug)					
	2014	**2015**	**2016**	**2017**	**2018**	**Total**
Mean daily PM_{10} (µg/m³), (SD, range)	40.3 (21.3, 10.6–94.2)	32.7 (21.0, 7.6–91.7)	32.3 (23.0, 8.7–94.3)	39.3 (22.5, 9.9–97)	26.9 (16.1, 7.7–80)	34.8 (21.7, 7.6–97.0)
PM_{10} exceedances, n	42	18	29	43	12	144
Mean daily air temp (°C)	5.8 (3.6, -1.3–16.6)	5.5 (4.2, -4.0–15.7)	7.0 (4.4, -1.9–17.6)	6.0 (3.9, -1.5–16.8)	8.3 (3.0, 1.7–15.0)	6.5 (4.0, -4.0–17.6)
GP visits, n (%)						
Total	288	438	396	417	331	1870
Condition						
Nasopharyngitis (H00)	0 (0.0)	9 (2.1)	1 (0.3)	1 (0.2)	2 (0.6)	13 (0.7)
Sinusitis (H01)	31 (10.8)	40 (9.1)	41 (10.4)	44 (10.6)	33 (10.0)	189 (10.1)
Pharyngitis (H02)	19 (6.6)	15 (3.4)	23 (5.8)	28 (6.7)	29 (8.8)	114 (6.1)
Tonsilitis (H03)	30 (10.4)	31 (7.1)	43 (10.9)	16 (3.8)	17 (5.1)	137 (7.3)
Laryngitis & tracheitis (H04)	18 (6.3)	33 (7.5)	20 (5.1)	27 (6.5)	18 (5.4)	116 (6.2)
Other ARI (H05)	158 (54.9)	264 (60.3)	221 (55.8)	226 (54.2)	180 (54.4)	1049 (56.1)
Bronchitis & bronchiolitis (H06)	32 (11.1)	46 (10.5)	47 (11.9)	75 (18.0)	52 (15.7)	252 (13.5)
Sex						
Male	123 (42.7)	198 (45.2)	177 (44.7)	170 (40.8)	166 (50.2)	834 (44.6)
Female	165 (57.3)	240 (54.8)	219 (55.3)	247 (59.2)	165 (49.8)	1036 (55.4)
Age group, years, n (%)						
≤ 14	154 (53.5)	257 (58.7)	198 (50.0)	234 (56.1)	179 (54.1)	1022 (54.7)
15-24	34 (11.8)	29 (6.6)	22 (5.6)	25 (6.0)	24 (7.3)	134 (7.17)
25-44	43 (14.9)	63 (14.4)	78 (19.7)	54 (13.0)	53 (16.0)	291 (15.6)
45-64	38 (13.2)	50 (11.4)	60 (15.2)	67 (16.1)	42 (12.7)	257 (13.7)
≥ 65	19 (6.6)	39 (8.9)	38 (9.6)	37 (8.9)	33 (10.0)	166 (8.9)
Ethnicity, n (%)						
European	259 (89.9)	371 (85.5)	347 (88.1)	335 (80.5)	267 (81.4)	1579 (84.9)
Māori	24 (8.3)	51 (11.7)	38 (9.6)	54 (13.0)	39 (12.0)	206 (11.1)
Pacific Peoples	3 (1.0)	5 (1.2)	4 (1.0)	6 (1.4)	5 (1.5)	23 (1.2)
Asian	2 (0.7)	8 (1.8)	5 (1.3)	21 (5.0)	15 (4.6)	51 (2.7)
MELAA	0 (0.0)	0 (0.0)	0 (0.0)	0 (0.0)	2 (0.6)	2 (0.1)

MELAA: Middle Eastern, Latin American and African ethnicities. *Exceedances based on current 24-hr average National Environmental Standard for Air Quality[17] of 50 µg/m³. Note that the World Health Organisation 24-hr guideline was reduced to 45 µg/m³ in 2021.[18]

Table 2: Stratified results of case crossover analysis of PM_{10} by general practitioner visits for acute respiratory infection based on patients residing in a 2013 Census Meshblock within or partially within a 1 km radius of the PM_{10} monitoring station (n = 812).

	Number of GP visits	Same day			24 h lag			3-day average		
		OR*	(95%CI)	p	OR	(95%CI)	p	OR	(95%CI)	p
All (n = 812)	812	1.05	(1.00–1.11)	0.052	1.03	(0.98-1.08)	0.245	1.00	(0.96–1.03)	0.782
Sex										
Male (n = 340/812)	340/812	1.01	(0.93–1.09)	0.838	0.99	(0.92–1.07)	0.793	0.96	(0.91–1.01)	0.116
Female (n = 472/812)	472/812	1.08	(1.01–1.15)	0.016	1.06	(0.95–1.03)	0.064	1.02	(0.98–1.07)	0.306
Ethnicity										
European (n = 646/806)	646/806	1.02	(0.97–1.08)	0.409	1.03	(0.97–1.09)	0.305	0.99	(0.95–1.03)	0.631
Maori (n = 106/806)	106/806	1.20	(1.04–1.38)	0.013	1.10	(0.97–1.25)	0.143	1.03	(0.92–1.15)	0.602
Other (n = 54/806)	54/806	1.11	(0.90–1.36)	0.320	0.93	(0.77–1.12)	0.425	1.00	(0.83–1.20)	0.998
Age										
0-14 (n = 414/812)	414/812	1.06	(0.98–1.13)	0.137	1.04	(0.97–1.11)	0.292	1.01	(0.96–1.06)	0.643
15 + (n = 398/812)	398/812	1.05	(0.97–1.12)	0.211	1.03	(0.95–1.10)	0.500	0.98	(0.93–1.03)	0.425

*OR: Odds ratio based on 10 μg/m³ increase in PM_{10} concentrations, adjusted for air temperature over the same time periods.GP: General practitioner. Lower denominators indicate missing data.

Case crossover analysis

A subset of 812 visits made by residents living within a 1 km radius of the PM_{10} monitoring station with complete PM_{10} and air temperature data was used for the case crossover analysis. For women and girls, a 10 μg/m³ increase in PM_{10} concentration was associated with an 8% increase in the odds of an ARI GP visit within 24 hours (OR 1.08, 95% CI 1.01–1.15, Table 2). For Māori of both sexes, a 20% increase in odds was observed for the same concentration increase and period, but with a wide confidence interval (OR 1.20, 95% CI 1.04–1.38, Table 2). Although a 5% increase in odds was observed for all GP visits, the 95% confidence interval included 1.0 so we cannot rule out a type I error (OR 1.05, 95% CI 1.00–1.11, Table 2). These associations were not sustained across different exposure lag periods. The age-stratified analysis did not indicate any age-related risk differences.

Ecological analysis

The ecological analysis was based on 1,870 visits made by residents of the whole study township. The estimated ARI GP visitation rate per 1,000 people per year was 131.3 (95% CI 126.7–136.1). The lowest rates were observed in the least deprived areas, at 47 per 1,000 people per year. ARI GP visitation rates were significantly higher in deprivation quintiles 2 (145.3 per 1000 people per year, relative risk [RR] 3.1, 95% CI 1.58–6.07) and 3 (171.6 per 1,000 people per year, RR 3.66; 95% CI 1.28–10.49) compared with quintile 1 (least deprived). We found a group level association between woodburner density and ARI GP visitation rate. With each additional woodburning household per hectare, the risk of an ARI GP visit increased by 17% (RR 1.17, 95% CI 1.06–1.30) for people living in that area. The association between deprivation and ARI GP visits was no longer significant after adjustment for woodburner density. Further, there was no evidence of effect modification by deprivation quintile.

Discussion

Woodsmoke exposure may increase ARI risk in the study town. The most affected populations appear to be women and girls, and Māori of both sexes. The magnitude of any woodsmoke effect on these groups is uncertain due to wide confidence intervals around our estimates. Stronger effect sizes for women than men and Māori than non-Māori have been previously reported in air pollution studies.[11,19] It is unlikely that either group has an inherent vulnerability to woodsmoke. Although not directly investigated here, any increased susceptibility of Māori is almost certainly due to underlying imbalances in the social determinants of health and burden of diseases caused and perpetuated by systemic factors. We know that racism in the healthcare system affects access, experience, and outcomes for Māori.[20] Similarly, gender inequality and restrictive norms shape women and girls' environmental exposures and access to care.[21] However, reported sex-based risk differences could be partly due to residence-based exposure estimates being more accurate for women.[19] Potential sex-linked biological differences in risk (such as lung size) are unconfirmed.[19]

Our findings support those reported for other health outcomes in New Zealand. A PM_{10} increase of 10 μg/m^3 was associated with a 4% (95% CI 2%–6%) increase in respiratory mortality in Christchurch,[10] and 7% (95% CI 3%–10%) and 20% (95% CI 7%–33%) increases in the odds of all-cause mortality in adults aged 30–74 years and for Māori nationally.[11] Also in Christchurch, an inter-quartile rise in PM_{10} of 14.8 μg/m^3 was associated with a 3% (95% CI 2%–4%) increase in respiratory-related hospital admissions.[3] For woodburner density, a 7% (95% CI 3%–12%) increase in the odds of non-accidental emergency department (ED) visit before age three years per wood or coal-burning household per hectare was reported in Auckland.[8] We found a much larger effect size of 17% (RR 1.17, 95% CI 1.06–1.30) increased risk of GP visit for ARI per wood or coal-burning household per hectare. This could be due to our inclusion of people of all ages, or to our health outcome of interest being considerably milder than an ED visit. Our linkage of outdoor woodsmoke pollution from indoor sources with respiratory infections somewhat fills the research gap identified by Guercio et al.[7]

Winter woodsmoke pollution could be reduced by strategic intervention. An Australian intervention subsidised woodburner replacement with electric heating, ran education campaigns to improve woodburner use, and fined homeowners who repeatedly emitted excessive woodsmoke.[22] Post intervention, woodburning prevalence fell from 66% to 30% of all households. Mean daily wintertime PM_{10} fell from 44 μg/m^3 during 1994–2000 to 27 μg/m^3 during 2001–2007, and wintertime cardiovascular and respiratory mortality fell significantly. An American intervention exchanged older woodburners with lower emission models.[23] Wintertime mean $PM_{2.5}$ concentrations fell from 27.2 μg/m^3 in the two winters before the intervention to 19.7 μg/m^3 for two winters after. A reduction of 5 μg/m^3 in $PM_{2.5}$ was associated with large reductions in respiratory infections in children, including influenza (52%) and throat infections (45%). Another American intervention included a mandatory no-burn programme when air quality was forecast to be poor, retrofitting with lower-emitting appliances before the transfer and sale of a property, and a limit on the number of woodburning devices allowed in new developments.[24] $PM_{2.5}$ reduced by 3.79 μg/m^3 post intervention. Among people aged 65 years or older, cardiovascular disease hospitalisation rates decreased from 152.2 to 81.1 per 1,000 population, and ischemic heart disease rates from 60.7 to 31.6 per 1,000 population. Although all three studies reported improved air quality and reduced adverse health impacts following an intervention, none addressed the potential issue of cold homes and their associated health impacts.

It is important that in our efforts to reduce woodsmoke pollution, we do not compromise people's ability to heat their homes. Living in a cold house was recently associated with poorer mental wellbeing and higher rates of sick days, asthma, mould, colds, and flu among New Zealanders.[25] Some interventions can potentially raise home temperatures as well as improve outdoor air quality and reduce health inequity. For example, retrofitting insulation has been shown to increase home warmth and improve health.[26] A home insulation intervention was recently associated with reduced hospital admissions, with the greatest benefits observed for Māori and Pacific Peoples.[27] Critically, from a woodsmoke perspective, insulated houses need less energy to heat.[28] Retrofitting insulation may contribute to improved air quality through lesser woodburning or greater capacity to rely on clean heat devices, which typically have lower heat outputs and higher running costs. Although an association between increased insulation and improved air quality is speculative, due to the demonstrated health benefits it seems reasonable to argue that the first step in improving air quality is improving the thermal efficiency of homes. Homes inhabited by groups already disadvantaged by unjust systems, policies, and practices should be targeted first.

As the most deprived quintile areas were not represented in our study township, we cannot draw firm conclusions about differential susceptibility to woodsmoke exposure by deprivation status. The association between deprivation quintiles 1–3, and ARI rates was no longer significant after adjustment for woodburner density—despite density not differing between deprivation quintiles. It is possible that more deprived areas have older, less efficient woodburners, or that residents are using lower quality wood. We know from previous work in this community that more deprived households often buy smaller quantities of wood at a time, which tends to have a higher moisture content as winter progresses. Poor combustion efficiency results in higher PM_{10} emissions.[1] It is also possible that poorer housing quality in more deprived areas is facilitating greater infiltration of outdoor air pollution into the indoor home environment or other causes of respiratory illness, such as mould. Due to these potentially confounding factors, woodburner density may not be an appropriate measure when trying to understand whether woodsmoke moderates a pathway between deprivation and ARI or other health outcomes. Other likely effect modifiers include co-morbidities and household crowding. A further issue with our deprivation approach is that we do not know if individual-level socio-economic attributes of Māori or women and children in the study area were aligned with the area-based deprivation measure used. Some individuals may be experiencing significant hardship within a relatively less deprived area.

Like most epidemiological studies of woodsmoke exposure, we do not have personal exposure information. Personal exposure will vary according to individual time and activity patterns and housing characteristics. Using the same day of the week on control days and restricting the analysis to those who live near the PM_{10} monitoring station will attenuate exposure measurement error somewhat. Confounding by fixed factors such as housing conditions and smoking status is controlled for in the case crossover study design. However, within-person confounding is still possible for transient factors that change over time within a participant. The aggregation of ARI GP visits to the statistical area level in our woodburner density analysis may have reduced the effects of intra-individual variance, enabling detection of a stronger association between woodsmoke and ARI.

Unknown completeness of the GP data also affects the internal validity of our study. We do not have information on the proportion of visits coded. More deprived individuals may be less likely to visit their GP due to accessibility and cost. It is possible that adults with ARI are underestimated in our study. The high proportion of children under 14 years in our study may be partly due to GP visits being free for this group.

Relatively few studies have examined the health impacts of woodsmoke in developed countries. Ours adds to this underdeveloped research area, and further indicates that residential wood burning may be associated with adverse respiratory health effects and disproportionately affect women and girls, as well as Māori. The norms, systems, policies, and services supporting inequity must be addressed. Reducing woodsmoke exposure may reduce inequities in ARI risk, but urgent action is required to remove the role of systemic influences. The potential impact of retrofitting home insulation on heating practices and air quality should be investigated in future work. For the sake of our health and the environment, we need to move away from burning wood in high-emissions devices for domestic heating. However, we cannot rapidly do so until our houses have considerably improved thermal efficiency.

COMPETING INTERESTS
Nil

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