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# A co-created citizen science project on the short term effects of outdoor residential woodsmoke on the respiratory health of adults in the Netherlands

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## Abstract

**Background and aim** Woodsmoke from household fireplaces contributes significantly to outdoor air pollution in the Netherlands. The current understanding of the respiratory health effects of exposure to smoke from residential wood burning is limited. This study investigated the association between short-term changes in outdoor woodsmoke exposure and lung function, respiratory symptoms, and medication use in adults in the Netherlands.

**Methods** This study was co-created with citizen scientists and other relevant stakeholders. A panel study was conducted with repeated observations in 46 adults between February and May 2021 in four Dutch towns. Participants recorded their symptoms and medication use in daily diaries, and conducted morning and evening home spirometry measurements. Woodsmoke exposure was characterized by measuring levoglucosan (most specific marker for woodsmoke exposure), black/brown carbon, fine and ultrafine particulate matter at central monitoring sites. Individual woodsmoke perception (smell) was recorded in daily diaries. Linear and logistic regression models were used to investigate the association between respiratory health and woodsmoke exposure. Models were adjusted for time-varying confounders and accounted for repeated observations within participants.

**Results** Consistent positive associations were found between levoglucosan and shortness of breath (SOB) during rest and extra respiratory medication use. Odds ratios for current day exposure to levoglucosan were 1.12 (95% CI: 0.97, 1.30) for SOB during rest and 1.19 (95% CI: 1.07, 1.33) for extra medication use, expressed per interquartile range of levoglucosan concentrations (69.16 ng/m$^3$). Positive non-significant associations were found between levoglucosan and nasal symptoms, cough and waking up with SOB. No consistent association was found between levoglucosan and lung function. Associations found between woodsmoke markers, SOB during rest and extra medication use remained after the inclusion of $PM_{2.5}$ and UFP in two-pollutant models.

**Conclusions** Adults experienced more SOB during rest, nasal symptoms and used more medication to treat respiratory symptoms on days with higher levels of outdoor woodsmoke concentrations.

**Keywords** Woodsmoke, Levoglucosan, Respiratory health, Panel study, Citizen science

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## Introduction

Outdoor air pollution poses a significant health risk to public health worldwide [54, 55]. While European air quality policies have reduced emissions from industry and transportation, the promotion of renewable fuels and rising fossil fuel prices have elevated wood combustion as a major source of airborne particulate matter in many European regions [14, 17, 35, 45]. The emissions from woodburning, known as woodsmoke, consist of a complex mixture of gases, (semi)volatiles and particulate matter (PM), including carbon monoxide (CO), nitrogen dioxide ($NO_2$), volatile organic matter (VOCs), and polycyclic aromatic hydrocarbons (PAHs) [37]. Exposure to particulate matter in general has been associated with various acute and chronic health effects, particularly cardiovascular and respiratory morbidity and mortality [13, 38, 61]. Even at relatively low levels, $PM_{2.5}$ has been shown to have adverse health effects [11, 59, 72, 57]. While most health studies on $PM_{2.5}$ have focused on urban environments with diverse sources such as traffic and industry, studies examining particulate matter emitted from residential woodburning have revealed similar adverse health effects [61, 63, 68]. As restrictions on traffic and industry-related sources of $PM_{2.5}$ increase, the relative contribution of residential woodburning to ambient air pollution is rising [62]. The World Health Organization (WHO) estimates that residential biomass burning is responsible for approximately 4.2 million premature deaths worldwide, related to indoor and outdoor exposure [71]. In Europe, emissions from residential fireplaces are estimated to contribute to at least 10% of all ambient air pollution-related health effects [8, 9, 55]. In the Netherlands, residential woodburning is estimated to account for approximately 23% of the total national $PM_{2.5}$ emissions and 14% of the life years lost due to outdoor air pollution [26, 50]. With approximately one million active wood stoves and fireplaces, woodsmoke has become a regular nuisance for 32% of the Dutch population [23, 36, 40]. Despite the environmental and human health impacts, there is a lack of policies across Europe regulating residential woodburning compared to other combustion sources [39, 55].

Limited research exists on potential respiratory health effects associated with lower outdoor exposure to woodsmoke from residential woodburning in developed countries [55]. Studies have shown adverse health effects stemming from high and prolonged exposure to woodsmoke in countries where wood stoves are widely used for cooking and as primary heat sources [5, 55]. Additionally, studies have shown associations between biomass smoke from wildfires and respiratory mortality and morbidity [28, 55]. All reviews conclude that well-designed epidemiological studies are needed to address the health effects of woodsmoke in developed countries [21, 22, 49, 55]. A limitation of many epidemiological studies on residential woodsmoke is the difficulty in characterizing the exposure to woodsmoke [28, 67]. Currently, levoglucosan is considered the most accurate chemical marker for woodsmoke [6, 27, 37], although it is not often determined due to the costly nature of the analyses. Therefore, very limited routine monitoring data are available for levoglucosan. Epidemiological studies often rely on proxy exposures such as $PM_{2.5}$ and black carbon to determine the effects of woodsmoke [67].

We conducted an epidemiological study on health effects of outdoor residential woodburning, assessing woodsmoke exposure using levoglucosan measurements as well as other air pollutants. The study was part of the larger European CitieS-Health project, which aimed to conduct co-created citizen science projects in the field of environmental epidemiology [15]. The project involved citizens and relevant stakeholders in all phases of the research project [19, 20]. Woodsmoke was identified as a topic of interest by researchers at the outset of the project due to the significant attention regarding potential health effects of woodsmoke resulting from residential woodburning in the Dutch media. The media highlighted the polarized nature of the debate between individuals experiencing nuisance from woodsmoke and individuals using wood stoves and fireplaces. When co-creating this study with citizens the polarized nature of this topic became even more apparent highlighting the need for a co-created citizen science study to ensure civic trust in the results of this study. Thus, in collaboration with citizens and relevant stakeholders, we investigated the short-term changes in lung function, respiratory symptoms, and medication use associated with short-term woodsmoke exposure in adults.

## Materials and methods

### Co-creation of the study

A group of about 20 people living in the Netherlands, including organized civic communities active in the field of woodburning and health, closely collaborated with researchers from Utrecht University to co-create this study. Stakeholders who also contributed to the co-creation of this study included the National Institute for Public Health and the Environment (RIVM), the Municipal health service of Amsterdam (GGD Amsterdam) and the Netherlands organization for applied scientific research (TNO). Citizens were identified and contacted to engage in this project through a multi-step process: initially, we set up stakeholder meetings with organizations actively dealing with woodsmoke issues, such as GGD Amsterdam, RIVM, TNO, and the Dutch Lung Foundation. These organizations introduced us

to civic actors in the field and flagged areas with high woodsmoke complaint rates. We then started the process of co-identifying the research question which took place between October 2019 and August 2020. Activities included an online call for research questions and subsequent physical (in IJburg) and virtual meetings in areas with high woodsmoke complaint rates. All citizens who responded to the online call for research questions and who were identified as interested parties in earlier stakeholder meetings were invited to the physical and virtual project meetings. We additionally distributed flyers in various neighborhoods. The list of citizens grew throughout the project through word-of-mouth advertisement by parties involved, including groups organized around the woodsmoke theme. During these meetings the research questions and key design aspects of interest to citizens were defined in partnership with researchers. These activities led to the following research question: "What are the health effects associated with short-term exposure to woodsmoke in adults in the Netherlands?". More detailed information regarding the co-creation process can be found in Froeling et al. [20].

#### Study design

We conducted a panel study with repeated observations in 46 adults between February and May 2021. Because of COVID-19 related contact restrictions, we could not start the data collection earlier in the winter. The study was done in four areas within the Netherlands: Bergen, De Meern (Utrecht), IJburg (Amsterdam), and Zutphen, each with varying population sizes (Fig. 1). Zutphen has approximately ~ 48,500 inhabitants, IJburg ~ 24,500, Bergen ~ 30,000, and De Meern ~ 22,000 people [12]. Participants had staggered starting dates, but each participated continuously for three months. Participants were asked to perform home spirometry measurements in the mornings and evenings, and record their symptoms and medication use in a daily symptom diary throughout the study. Woodsmoke exposure was characterized by measuring levoglucosan and other air pollutants at central monitoring sites selected at each study location and through individual woodsmoke perception (smell) recorded in daily diaries. This study design uses the day-to-day variability in neighborhood pollution sources and atmospheric dispersion conditions to better understand the health effects of woodsmoke in the area. The study protocol was approved by the medical ethics committee of University Medical Center Utrecht (application number NL75223.041.20).

#### Air pollution exposure assessment

Our primary woodsmoke marker was the 24-hour average levoglucosan concentrations measured from $PM_{2.5}$ filters, collected by Leckel/KFG samplers at all sites. Levoglucosan levels on quartz filters were measured using a gas chromatography–mass spectrometry (GC–MS) method by Leicester's Department of Chemistry laboratory [16]. In addition, real-time measurements of ultrafine particles (UFP) and fine particulate matter ($PM_{2.5}$) were conducted at all sites. UFP was measured using a DiSCmini-handheld nanoparticle counter that measures particles from 10 to 700 nm; PM was measured using the SidePak AM520 Personal Aerosol Monitor ($PM_{2.5}$), which measures particles from 0.1 to 10 µm. In two areas, IJburg and Bergen, additional real-time black and brown carbon measurements were conducted by aethalometer (AE33 Aerosol Magee Scientific). In this aethalometer, channel 1 estimates the combined brown and black carbon emissions, whereas channel 6 specifically represents black carbon. By subtracting channel 6 from channel 1 (C1-6), we can more accurately estimate brown carbon (BrC) concentrations associated with organic combustion. This allows us to distinguish between woodsmoke emissions and carbon emissions from other sources such as motorized traffic. Measurements were conducted continuously at the central monitoring sites throughout the panel study. Monitoring sites were selected at central background locations in the neighborhoods, at least 100 m away from major roads and individual homes with wood burning, as our aim was to measure community-level woodsmoke.

#### Time-varying covariate data

Meteorological data was collected from the Royal Netherlands Meteorological Institute (KNMI) for the stations closest to each central monitoring site. The data includes daily averages for temperature, humidity, wind speed, wind direction, precipitation, radiation, and air pressure for the entire study period [29]. Berkhout weather station data were used for the location Bergen (24 km apart); De Bilt data were used for the location De Meern (12 km apart); Deelen station data were used for Zutphen (27 km apart) and Schiphol data were used for IJburg (22 km apart). The Medical Faculty of Leiden University (LUMC) provided daily pollen count data from Leiden (the nearest pollen station) which was used for all of the locations (closest neighborhood was De Meern which was 47 km away and the furthest was Zutphen which was 135 km away). The pollen types Corylus, Alnus, Betula, Quercus, Fraxinus, Artemisia and Poaceae were included based on their allergenicity [10]. Poaceae, Corylus, and Artemisia pollen types were excluded from the study as their pollen count was not high enough to cause clinical symptoms during the study period.


**Fig. 1** Map of the Netherlands including the four panel study locations. IJburg is a suburban neighborhood of Amsterdam, separated by water from the city center

### Study population

Participants were recruited via various means of advertisement such as flyers, posters, email promotion from the GGD Amsterdam and through citizen scientists. People, including the citizens scientists active in the study, were eligible to participate if they were 30 years or older, lived within 2 km of a central monitoring site selected for the purpose of this study, did not have/use a fireplace during the study, and did not smoke. Both adults with and without asthma/COPD were included in the study. Participants were excluded from the study if they were currently smoking, had a history of a heart attack within the last three months, had undergone chest/abdominal surgery within the previous three months, or had brain, ear, or eye surgery within the past month. None of the participants lived with individuals who smoked. This study took place during the COVID-19 pandemic and was amended to adhere to the restrictions set at the time, such as virtual meetings instead of home visits. Throughout the study, researchers engaged in three online

sessions with the participants. The first meeting occurred on the participants' first day, a baseline questionnaire was administered, and instructions were provided on how to complete the daily symptom diary and perform lung function measurements. Subsequent meetings were held to address any questions from the participants and track their data collection progress. The baseline questionnaire was used to define population characteristics and identify potential confounders and effect modifiers.

### Health outcome assessment

#### *Respiratory symptoms*

The daily symptom diary was recorded via an online Qualtrics survey (Qualtrics$^{XM}$, London, England). Participants could fill in the diary on their mobile phone, computer or tablet using their personal weblink and password. Participants were asked to fill in the diary every evening just before going to bed. Symptoms recorded during the study included coughing, wheezing, shortness of breath during rest (SOB at rest), shortness of breath during exercise (SOB during exercise), nasal complaints (sneezing, irritation, stuffy nose), insomnia, waking up due to shortness of breath, flu, and fever. The symptoms SOB at rest, SOB during exercise, wheezing, and waking up due to shortness of breath were also combined to create a composite symptom named lower respiratory symptoms (LRS). Symptoms severity was recorded using a 3-point scale, with 0 representing no symptoms, 1 representing minor symptoms, and 2 representing moderate/severe symptoms. In the baseline questionnaire participants were asked if they took any daily respiratory medication. In the daily symptom diaries, participants were asked to record any extra respiratory medication they had taken that day, that was not usually part of their daily medication use. Respiratory medication was defined as any medication whether this was an extra dose of prescribed asthma/COPD medication or over the counter medication to relieve respiratory complaints. Due to the COVID-19 pandemic citizens were asked to record any suspected or confirmed COVID-19 infection in their daily diaries. None of the participants had COVID during the duration of this study. A copy of the daily symptom diary can be found in the appendix (see Appendix 1).

#### *Lung function measurements*

The home spirometry measurements were performed with Vitalograph Asma-1 spirometers (Vitalograph Inc, Lenexa, USA), which measures forced expiratory volume in 1 s (FEV1) and peak expiratory flow (PEF). FEV1 represents the exhaled volume during the first second of the test, and PEF refers to the maximum airflow rate during the test. This device is widely used in asthma management, previous epidemiological studies and meets the ERS/ATS performance criteria [33, 64–66]. It records the date, time, and measured lung function while automatically conducting quality checks that identifies and disqualifies measurements when any of the following conditions are met: coughing which is classified as a 'bad blow'; the time to PEF exceeds 120 ms; or the extrapolated volume exceeds 5% or 100 ml of $FEV_6$ [33, 64–66]. As a result, participants receive instant feedback on their home spirometry measurement, including notifications regarding errors such as a hesitant start or cough. Participants independently measured their morning and evening lung function at home. Morning spirometry was taken between 06:00–12:00, and evening spirometry was done between 18:00–00:00. Participants were asked to conduct at least three measurements per session, around the same time every day and in the same position (either sitting or standing). Participants were also advised to take any prescribed respiratory medication after the measurements. The system automatically saved the best result from three attempts after each session (morning and evening). During the three online sessions, researchers asked participants to conduct a spirometry measurement during the meeting to ensure they followed the instructions provided.

### Data analysis

Logistic regression using the GEE approach was used to investigate the relation between levoglucosan and other woodsmoke markers and daily symptoms. The results can be interpreted as population-average models. A model with an AR-1 structure did not converge for several symptoms. We did a Quasi-likelihood under the Independence model criterion (QIC) analysis for the different models to determine whether an AR1 correlation structure or exchangeable correlation structure would be better for the symptom models, that did converge. For the majority of the symptoms the exchangeable correlation came out as a better fit. Thus, an exchangeable correlation structure was specified. This assumes that observations are clustered within individuals and that there is no pattern in order of the observations. We analyzed the individual symptoms and a combination of "asthmatic" symptoms defined as LRS. Models were adjusted for time-varying confounders (temperature, humidity, presence of pollen), day of study and accounting for repeated observations within participants. Day of study was included to adjust for potential time trends, e.g. related to the start of the period being from winter and the end of spring. As a sensitivity analysis we adjusted the models for the time-invariant variables age and sex, and in a second step we also included COPD/asthma status.

Morning and evening lung function data were analyzed separately for the daily home spirometry data.

Morning was defined as between 06:00–12:00; evening as between 18:00 and 00:00. The small percentage (10.9%) of observations outside these time windows was not used to avoid potential influence of well-established diurnal variation of lung function. We deleted observations when FEV1 and PEF were three individual standard deviations higher or lower than the individual mean (1.9% of observations). As lung function measurements were unsupervised, we preferred to exclude highly unlikely observations, following previous studies [33, 65]. Associations between daily variation of respiratory health (FEV1 / PEF) and woodsmoke were investigated with population-averaged linear regression models via generalized estimating equations (GEE) accounting for repeated observations within participants. An AR-1 autocorrelation structure was specified. This assumes that observations are clustered within individuals and that observations of subsequent days are correlated. Models were adjusted for time-varying confounders (temperature, humidity, and presence of pollen). As a sensitivity analysis we adjusted the models for the time-invariant variables height, age and sex, and in a second step we also included COPD/asthma status.

We evaluated various time periods for woodsmoke marker concentrations for both the linear and logistic models to allow for delayed effects on all endpoints. These included the 24-hour average concentration (Current day), the previous 24-hour average concentration (Previous day), the 48-hour average concentration (Mean 2 days), the 24-hour average concentration of the present and four previous days (Mean 5 days) and the average concentration between 23:00- 07:00 (Night). For lung function, we also assessed the current hour and the last 2 hours for available woodsmoke marker concentrations for BrC1-6, $PM_{2.5}$, and UFP to potentially assess more acute effects.

As a sensitivity analysis we also adjusted for flu-like symptoms reported by participants. In addition to the single pollutant models, we also specified two pollutant models. Separate models for levoglucosan, adjusting for either $PM_{2.5}$ or UFP were performed to assess whether any associations with woodsmoke markers were confounded by other sources of particulate matter being increased during the same weather conditions. This analysis results in a conservative estimate of the effect of woodsmoke, as $PM_{2.5}$ and UFP are also affected by woodsmoke.

The interquartile ranges (IQR) of all woodsmoke markers were used to express the magnitude of the association of the woodsmoke markers with health outcomes. *P*-values < 0.05 were considered statistically significant. All the analyses were performed with Rstudio, version 4.1.2 [47], using the R packages geepack [24, 73, 74], dplyr [70] and tidyr [69].

## Results

Population characteristics are described in Table 1. The study population consisted of 46 people aged 30 years or older, including 3 citizen scientists who participated in the design discussions. Of the participants 54% were female and 11 participants had asthma and/or COPD. Almost half of the participants came from the Zutphen area due to the strongly established group of citizens who helped with recruitment. Most subjects received post-secondary education.

We observed a large temporal variability for all pollutants including levoglucosan. The distribution of the concentrations of woodsmoke markers analysed over the entire study period is shown in Table 2. The mean levoglucosan concentration was 76.7 ng/m$^3$ (SD = 134.6) over the four study areas. The woodburning season is clearly visible in Fig. 2, which depicts the temporal variation of the 24-h average levoglucosan concentration during the study period per location. The peaks were highest in February and March and then slowly decreased. The concentrations show a wide spread between almost 0 and 400 ng/m$^3$. The levels of levoglucosan were generally highest in Bergen, where the measured peak values are almost a factor two larger than those measured in IJburg.

**Table 1** Characteristics of the study participants

| Characteristic | Panel |
|---|---|
| N | 46 |
| Age, yr (mean (sd)) | 60.2 (9.4) |
| Height, cm (mean (sd)) | 175.5 (9.1) |
| Weight, kg (mean (sd)) | 76.3 (17.2) |
| Female (%) | 25 (54.3) |
| Former smoker (%) | 28 (60.9) |
| Study locations (%) | |
| Bergen | 8 (17.4) |
| De Meern | 7 (15.2) |
| IJburg | 10 (21.7) |
| Zutphen | 21 (45.7) |
| COPD/asthma (%) | |
| Asthma | 8 (17.4) |
| COPD | 2 (4.3) |
| Both | 1 (2.2) |
| Neither | 35 (76.1) |
| Education level (%) | |
| Secondary education | 2 (6.6) |
| Junior college | 5 (11.1) |
| University of Applied Sciences | 23 (51.1) |
| University | 15 (33.3) |

**Table 2** Distribution of the 24-h average measured concentrations (pooled over the four locations) in the period of the health survey (February – May 2021) and their correlation to Levoglucosan

| Pollutant | Mean (SD) | Min | Max | IQR | Correlation to Levoglucosan |
|---|---|---|---|---|---|
| Levoglucosan (ng/m$^3$) | 76.70 (134.59) | 2.74 | 1707.88 | 69.16 | 1.00 |
| BrC C1-6 (µg / m$^3$)[a] | 0.30 (0.47) | 0.01 | 5.67 | 0.28 | 0.94 |
| $PM_{2.5}$ (µg / m$^3$) | 10.91(7.58) | 2.40 | 75.51 | 7.04 | 0.47 |
| UFP (10^3/cm$^3$) | 5.95 (2.56) | 1.31 | 12.88 | 3.82 | 0.37 |

[a] BrC C1-6 refers to subtraction of BC from total carbon measurements from the AE33 channel 1 and 6 measured in IJburg and Bergen

The figure also shows that levoglucosan follows a similar pattern in all four locations. The correlation of levoglucosan between the four locations are moderate to high with a Pearson correlation range of $R = 0.41–0.87$ as seen in Table 3.

The correlation between levoglucosan and $PM_{2.5}$ and UFP was moderate to low ($R = 0.47$ and 0.37 respectively). The correlation between levoglucosan and the brown carbon marker C1-6 was high ($R = 0.94$).

**Table 3** The correlation of the 24-h average measured concentrations of levoglucosan between the different study locations:

| Correlation to levoglucosan | IJburg | Bergen | De Meern | Zutphen |
|---|---|---|---|---|
| IJburg | 1.00 | 0.87 | 0.69 | 0.41 |
| Bergen | 0.87 | 1.00 | 0.67 | 0.49 |
| De Meern | 0.69 | 0.67 | 1.00 | 0.82 |
| Zutphen | 0.41 | 0.49 | 0.82 | 1.00 |

The 24-hour average concentration of exposures correlations with levoglucosan per location, shown in Table 3, are in line with the pooled correlation findings. The biserial correlation of perception of individual woodsmoke through smell (Smelt woodsmoke) for both the current and previous day with levoglucosan was very low (0.19 and 0.15).

### Respiratory symptoms

In the three-month study period, the total number of days with symptom presence/absence reported by all participants was slightly more than three thousand. The average number of days reporting symptom presence / absence per person was 71. Table S1 shows the number

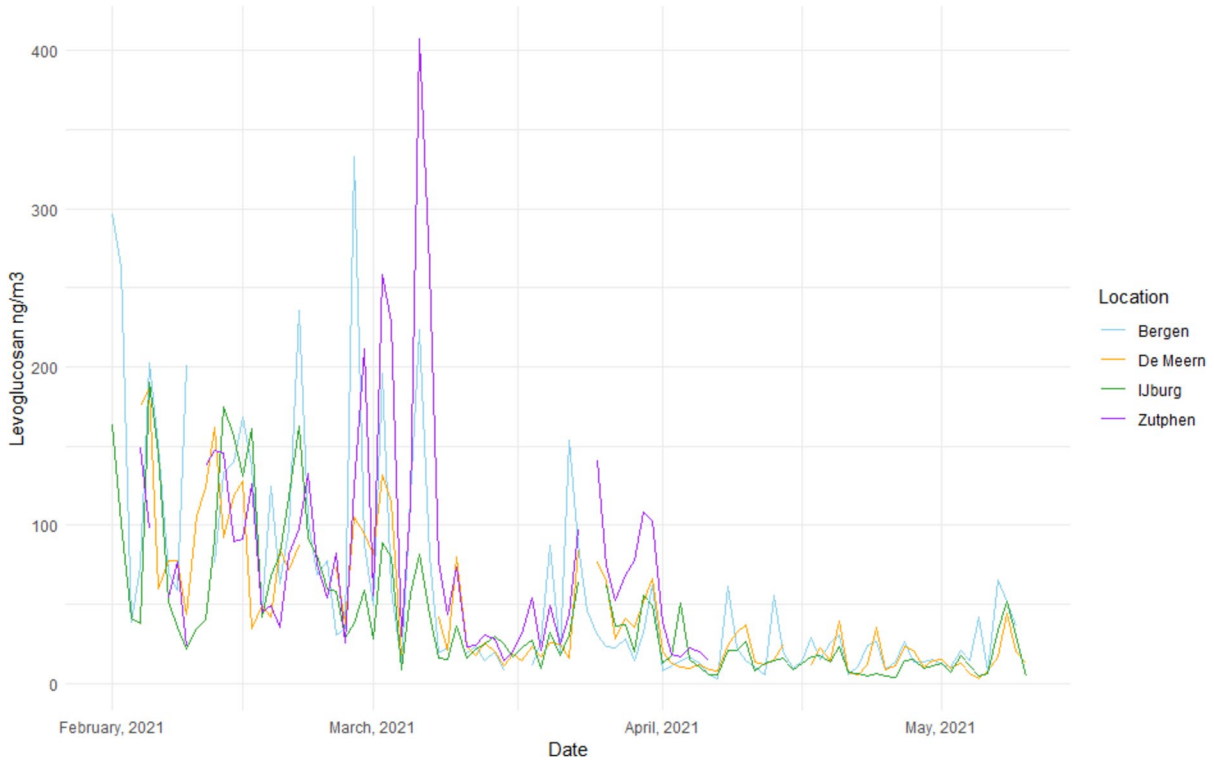


**Fig. 2** Temporal variation in daily levoglucosan per location during the study period

and percentage of symptoms reported by the participants in the daily diary. The most reported symptom was nasal complaints (14.2%) followed by cough (7.1%), combined lower respiratory symptoms (LRS) (6.6%), SOB after exercise (5.2%) and SOB at rest (2.5%). Tables 4 and S2 show the associations between air pollution measured at the central sites and daily respiratory symptoms. The odds ratios (ORs) were usually higher than 1 for levoglucosan for all analyzed respiratory symptoms, indicating more symptoms on days with higher levoglucosan levels. For example, an IQR increase in average levoglucosan concentration of the same day and reported extra medication use, indicated 19% more medication use to treat respiratory complaints (OR = 1.19, (95% CI 1.07, 1.33)).

The associations found between levoglucosan, SOB at rest and additional respiratory medication use (Table 4) were consistent throughout the studied time-lags. When looking at the brown carbon marker C1-6 (measured at two locations) we also found multiple positive associations for SOB at rest and extra medication use. For the subjectively reported smell of woodsmoke the ORs for SOB at rest and extra respiratory medication use showed a less clear pattern with much wider confidence intervals. No clear associations were found with $PM_{2.5}$. The associations with UFP were also consistent for both outcomes. Further adjustment for self-reported "Flu" and "Fever" in the diary did not changed the effect estimates.

Levoglucosan and BrC C1-6 were also positively associated with cough, nasal complaints and the combination LRS (Table S2), however less consistently and with broader confidence intervals including unity. Smelt woodsmoke was not consistently associated with symptoms. For more information on the remaining symptoms see Supplement tables S3 & S4.

For both SOB at rest and medication use, the associations with $PM_{2.5}$ were less clear than with levoglucosan. When we corrected for $PM_{2.5}$ all the associations observed with levoglucosan remained (Table S5). When we corrected for UFP, though the associations observed with levoglucosan remained, they did become weaker

**Table 4** Associations between measured air pollution and self-reported smell of woodsmoke with shortness of breath at rest and extra respiratory medication use

| | | | Short of breath rest | | | | Extra medication | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Pollutant** | **Time Lags** | **N Obs** | **N cases** | **OR** | **LCI** | **UCI** | **N cases** | **OR** | **LCI** | **UCI** |
| **Levoglucosan** | Current day | 2797 | 70 | 1.12 | 0.97 | 1.30 | 46 | 1.19 | 1.07 | 1.33 |
| | Previous day | 2801 | 68 | 1.15 | 1.01 | 1.32 | 48 | 1.02 | 0.78 | 1.35 |
| | Mean 2 days | 2637 | 63 | 1.20 | 1.04 | 1.39 | 45 | 1.21 | 1.03 | 1.43 |
| | Mean 5 days | 2651 | 67 | 1.15 | 0.65 | 2.03 | 43 | 1.58 | 1.00 | 2.51 |
| **BrC C1-6** | Current day | 1069[a] | 11 | 1.22 | 0.86 | 1.74 | 15 | 1.52 | 0.99 | 2.33 |
| | Previous day | 1069 | 12 | 1.37 | 0.88 | 2.15 | 15 | 1.51 | 0.94 | 2.41 |
| | Mean 2 days | 1049 | 11 | 1.44 | 0.86 | 2.43 | 15 | 2.01 | 0.93 | 4.37 |
| | Mean 5 days | 1067 | 12 | 3.78 | 1.17 | 12.18 | 15 | 5.73 | 1.32 | 24.83 |
| | Night | 1075 | 11 | 1.15 | 0.85 | 1.55 | 15 | 1.45 | 0.98 | 2.15 |
| **$PM_{2.5}$** | Current day | 3028 | 76 | 1.04 | 0.85 | 1.28 | 47 | 1.04 | 0.77 | 1.41 |
| | Previous day | 3042 | 76 | 0.93 | 0.78 | 1.10 | 48 | 0.96 | 0.74 | 1.24 |
| | Mean 2 days | 3024 | 76 | 0.98 | 0.80 | 1.21 | 47 | 1.01 | 0.77 | 1.32 |
| | Mean 5 days | 3084 | 76 | 1.05 | 0.75 | 1.48 | 49 | 1.07 | 0.71 | 1.60 |
| | Night | 2993 | 75 | 0.95 | 0.73 | 1.22 | 47 | 0.98 | 0.76 | 1.27 |
| **UFP** | Current day | 2190[b] | 46 | 1.52 | 1.14 | 2.04 | 34 | 1.15 | 0.62 | 2.14 |
| | Previous day | 2202 | 46 | 1.05 | 0.77 | 1.43 | 35 | 1.03 | 0.71 | 1.50 |
| | Mean 2 days | 2106 | 46 | 1.36 | 1.03 | 1.81 | 34 | 1.06 | 0.67 | 1.65 |
| | Mean 5 days | 2416 | 46 | 1.50 | 1.19 | 1.91 | 35 | 1.54 | 1.06 | 2.23 |
| | Night | 1981 | 46 | 1.30 | 0.96 | 1.76 | 33 | 0.91 | 0.59 | 1.41 |
| **Smelt woodsmoke** | Current day | 3055 | 76 | 1.22 | 0.44 | 3.38 | 50 | 1.43 | 0.55 | 3.73 |
| | Previous day | 2680 | 68 | 0.96 | 0.55 | 1.70 | 48 | 1.09 | 0.53 | 2.24 |

Time Lags = Time intervals of exposures studied (Mean 2 days = average of the same day and previous day; Mean 5 days = mean of the same day and the previous four days; Night = average between 23:00- 07:00). N obs = number of observations present for exposure and symptoms. N differs because of missing values in exposure and symptom reporting. BrC measured at two of four sites. N cases = number of participant-days reporting the symptom. *OR* Odds ratio, *LCI* Lower confidence interval limit, *UCI* Upper confidence interval limit, Associations adjusted for temperature, relative humidity, pollen count and duration of study participation

[a] Smaller N because measured in two towns only

[b] Smaller N is due to missing exposure data

(Table S6). These calculations reinforce the associations between increased woodsmoke exposure and respiratory complaints. We found subtle differences in the results with the sensitivity analysis adjusting the models for the time-invariant variables age, sex and COPD/asthma status. However, these results did not impact the main findings seen between SOB at rest, extra respiratory medication and levoglucosan (Table S7).

### Lung function measurements

Table S8 lists the number of successful lung function tests and the participants' mean ± SD lung function measurements. There were more than 5,600 valid pulmonary function tests in this study, slightly more in evening ($n=3182$) than in the morning ($n=2439$). The average number of valid lung function tests per person was 69 and 53 days. Tables 5 and 6 contain the associations between daily woodsmoke markers measured at the central monitoring sites and daily FEV1 and PEF measurements for morning and evening respectively. Supplementary Tables S9 & S10 contain the associations between hourly exposures measured at the central monitoring sites and daily FEV1 and PEF measurements. Further adjustment for self-reported "flu" and "fever" did not change the effect estimates. For example, the effect estimates in Table 5 show that the woodsmoke marker levoglucosan had an estimated decrease of -3.21 ml/s (95% CI -13.53, 7.11) for FEV1. The sensitivity analysis adjusting the models for time-invariant variables height, age, sex and COPD/asthma status only subtly impacted associations but did not change the findings with lung function measurements (Table S11).

This implies that an interquartile range (IQR) increase in levoglucosan was associated with a decrease in FEV1 of 3.21 ml/s though with a confidence interval including 0.

For the morning and evening lung function measurements, both positive and negative effect estimates can be seen for levoglucosan and the other exposure variables, suggesting no clear association between lung function and the woodsmoke markers. In contrast to lung function measurements in the morning, almost only non-significant positive associations were observed between PEF and FEV1 and BrC C1-6 in the evening. The marker for the presence of woodsmoke at the individual level ("Smelt woodsmoke") and its time lags also had both

**Table 5** Associations between air pollution and morning lung function measurements

| | Morning: All locations | | | PEF (L/min) | | | FEV1 ( mL/s) | | |
|---|---|---|---|---|---|---|---|---|---|
| **Pollutant** | **Time Lags** | **No Obs** | **N** | **B** | **LCI** | **UCI** | **B** | **LCI** | **UCI** |
| **Smelt woodsmoke** | Current day | 1987 | 46 | -1.75 | -4.88 | 1.38 | 6.58 | -8.75 | 21.92 |
| | Previous day | 1778 | 46 | 1.09 | -3.08 | 5.27 | -0.52 | -19.62 | 18.57 |
| **Levoglucosan** | Current day | 1845 | 46 | -0.64 | -2.76 | 1.47 | -3.21 | -13.53 | 7.11 |
| | Previous day | 1836 | 46 | 0.67 | -0.92 | 2.26 | -0.99 | -12.30 | 10.31 |
| | Mean 2 days | 1730 | 46 | 0.10 | -1.94 | 2.15 | -5.26 | -19.23 | 8.71 |
| | Mean 5 days | 1745 | 46 | 1.97 | -3.58 | 7.51 | -5.19 | -30.84 | 20.46 |
| **BrC C1-6** | Current day | 692 | 18 | -0.52 | -3.74 | 2.71 | -1.21 | -13.52 | 11.09 |
| | Previous day | 692 | 18 | -3.36 | -6.97 | 0.25 | 18.46 | -3.22 | 40.13 |
| | Mean 2 days | 677 | 18 | -3.81 | -8.72 | 1.11 | 24.09 | -3.66 | 51.84 |
| | Mean 5 days | 689 | 18 | -3.32 | -14.75 | 8.11 | 32.99 | -33.32 | 99.31 |
| | Night | 696 | 18 | -0.25 | -1.93 | 1.43 | 8.85 | 1.42 | 16.29 |
| **$PM_{2.5}$** | Current day | 1977 | 46 | -0.18 | -2.13 | 1.77 | -8.30 | -16.19 | -0.41 |
| | Previous day | 1989 | 46 | 0.89 | -0.79 | 2.58 | -3.80 | -15.46 | 7.86 |
| | Mean 2 days | 1976 | 46 | 0.44 | -1.21 | 2.08 | -9.36 | -20.63 | 1.90 |
| | Mean 5 days | 2015 | 46 | 0.83 | -1.20 | 2.86 | -0.35 | -12.94 | 12.24 |
| | Night | 1958 | 46 | 0.59 | -1.08 | 2.25 | -7.30 | -17.28 | 2.67 |
| **UFP** | Current day | 1514 | 46 | 0.70 | -2.26 | 3.65 | 5.37 | -8.42 | 19.15 |
| | Previous day | 1516 | 46 | -0.46 | -3.22 | 2.30 | -7.25 | -25.74 | 11.24 |
| | Mean 2 days | 1463 | 46 | -0.31 | -3.71 | 3.09 | -6.25 | -23.94 | 11.43 |
| | Mean 5 days | 1652 | 46 | -0.42 | -5.10 | 4.26 | 2.79 | -17.50 | 23.07 |
| | Night | 1385 | 46 | -0.33 | -2.49 | 1.83 | -4.67 | -18.42 | 9.09 |

Time Lags = Time intervals of exposures studied (Mean 2 days = average of the same day and previous day; Mean 5 days = mean of the same day and the previous four days; Night = average between 23:00- 07:00). N obs = number of observations present for exposure and lung function. N = number of participants. Effect estimates (B) and 95% CI (LCI, UCI). Lung function is presented as FEV1 (amount of air exhaled in 1 s in mL/s and maximum expiratory velocity (PEF in L/min). All associations were corrected for temperature, relative humidity, pollen and duration of study participation

**Table 6** Associations between air pollution and lung function measurements in the evening

| | Evening: All locations | | | PEF (L/min) | | | FEV1 (mL/s) | | |
|---|---|---|---|---|---|---|---|---|---|
| **Pollutant** | **Time Lags** | **N Obs** | **N** | **B** | **LCI** | **UCI** | **B** | **LCI** | **UCI** |
| **Smelt woodsmoke** | Current day | 2661 | 46 | -1.30 | -4.60 | 2.00 | -0.99 | -16.47 | 14.49 |
| | Previous day | 2357 | 46 | -3.30 | -6.57 | -0.03 | -8.18 | -23.31 | 6.95 |
| **Levoglucosan** | Current day | 2435 | 46 | 0.23 | -1.47 | 1.92 | -1.24 | -7.15 | 4.68 |
| | Previous day | 2434 | 46 | -1.24 | -3.06 | 0.57 | 2.18 | -7.32 | 11.69 |
| | Mean 2 days | 2291 | 46 | -0.95 | -2.75 | 0.84 | 2.66 | -8.52 | 13.84 |
| | Mean 5 days | 2313 | 46 | -1.53 | -4.87 | 1.82 | 2.04 | -15.78 | 19.86 |
| **BrC C1-6** | Current day | 965 | 18 | 2.25 | -0.01 | 4.52 | 2.60 | -4.68 | 9.89 |
| | Previous day | 966 | 18 | -0.90 | -3.55 | 1.75 | -0.64 | -10.35 | 9.06 |
| | Mean 2 days | 947 | 18 | 1.71 | -0.94 | 4.36 | 4.27 | -6.32 | 14.86 |
| | Mean 5 days | 965 | 18 | 2.44 | -3.08 | 7.97 | -27.14 | -59.87 | 5.60 |
| | Night | 970 | 18 | -0.89 | -2.45 | 0.67 | -2.85 | -10.49 | 4.78 |
| **$PM_{2.5}$** | Current day | 2636 | 46 | 0.17 | -1.61 | 1.95 | 2.63 | -5.68 | 10.94 |
| | Previous day | 2652 | 46 | 0.13 | -1.26 | 1.51 | -0.34 | -8.01 | 7.33 |
| | Mean 2 days | 2633 | 46 | 0.06 | -1.67 | 1.79 | 1.61 | -6.40 | 9.63 |
| | Mean 5 days | 2689 | 46 | 0.88 | -1.54 | 3.30 | -2.16 | -15.14 | 10.82 |
| | Night | 2606 | 46 | -1.26 | -3.04 | 0.53 | -0.33 | -8.91 | 8.25 |
| **UFP** | Current day | 1952 | 46 | 2.33 | -1.09 | 5.75 | -2.20 | -14.65 | 10.25 |
| | Previous day | 1960 | 46 | -0.04 | -2.40 | 2.32 | 13.01 | 2.97 | 23.05 |
| | Mean 2 days | 1875 | 46 | 2.25 | -1.25 | 5.75 | 7.13 | -6.42 | 20.67 |
| | Mean 5 days | 2136 | 46 | -0.26 | -5.81 | 5.30 | -7.27 | -28.28 | 13.73 |
| | Night | 1768 | 46 | 1.50 | -1.17 | 4.18 | 7.11 | -4.32 | 18.53 |

Time Lags = Time intervals of exposures studied (Mean 2 days = average of the same day and previous day; Mean 5 days = mean of the same day and the previous four days; Night = average between 23:00- 07:00). N obs = number of observations present for exposure and lung function. N = number of participants. Effect estimates (B) and 95% CI (LCI, UCI). Lung function is presented as FEV1 (amount of air exhaled in 1 s in mL/s and maximum expiratory velocity (PEF in L/min). All associations were corrected for temperature, relative humidity, pollen and duration of study participation

positive and negative effect estimates for PEF and FEV1 in the morning and negative effect estimates in the evening). The inconsistencies in effect estimates within and between markers indicative of woodsmoke exposure suggest a consistent association between woodsmoke and lung function measurements could not be substantiated.

## Discussion

We examined the short-term health effects of outdoor woodsmoke exposure using a panel study design in adults. Our results showed consistent associations between concentrations of the specific woodsmoke marker levoglucosan with SOB at rest, and additional respiratory medication use. We also observed weak associations between this woodsmoke marker and cough and nasal complaints. We did not find consistent associations with lung function.

### Associations between woodsmoke and respiratory health

A major strength of the current study was the assessment of exposure to woodsmoke through measurements of levoglucosan. Few previous epidemiological studies have used daily time series of levoglucosan to investigate health effects of short-term exposure to woodsmoke. We found more consistent associations between respiratory symptoms and measured levoglucosan than with self-reported smell of woodsmoke. Participants' smell of woodsmoke was not consistently associated with respiratory complaints. The poor correlation observed between the subjective smell of woodsmoke and the objective marker, measured levoglucosan, suggests that associations of symptoms with levoglucosan are unlikely biased due to reporting more symptoms when woodsmoke was smelt. The low correlation between reported smell of woodsmoke in participants homes and levels of woodsmoke in the community, could be due to participants not smelling the moderate levels of woodsmoke in their communities. Alternatively, the central measuring sites may not have detected individual exposure peaks related to nearby sources. Despite assessment of a specific woodsmoke marker, associations between levoglucosan and health could still be confounded by pollution from other sources if these are correlated in time with similar weather conditions. We did not have daily data on particle concentrations from other sources available. We adjusted the levoglucosan health associations for

$PM_{2.5}$ and UFP measured in the neighborhoods, assuming that the concentrations of these pollutants were affected to a large degree by other sources. The correlations between levoglucosan and $PM_{2.5}$ and UFP were low, likely related to the many sources contributing to $PM_{2.5}$ concentrations. Considering that residential woodburning is estimated to account for approximately 23% of the total national $PM_{2.5}$ emissions in the Netherlands, the weak observed correlation is not surprising. $PM_{2.5}$ is widely recognized as a pollutant affected by regional-scale processes with only modest local source influences. After including $PM_{2.5}$ and UFP as confounding variables in the statistical model, associations with levoglucosan remained. This suggests that other generic sources of fine particulate matter did not materially confound the associations seen with levoglucosan. We recognize that this analysis presents an overadjustment, as woodsmoke also contains fine and ultrafine particles. This overadjustment may be more severe for UFP, as UFP is more affected by local sources than $PM_{2.5}$ and the small study areas were selected away from major traffic sources.

In this study no consistent associations were seen between short-term woodsmoke exposure and morning or evening lung function. This study did find consistent associations with various self-reported symptoms especially with SOB at rest and extra medication use. As previously mentioned the associations with the subjectively reported symptoms, in the absence of an association with the objectively measured lung function, are unlikely a result of reporting bias since the correlation of the symptoms with smelt woodsmoke was low. These findings align with several previous short-term air pollution studies, including a semi-controlled exposure study on barbecue emissions [34] and human controlled exposure studies of woodsmoke [55], which did not find a lung function response to short-term exposure to fine particle concentrations above 100 μg/$m^3$, while documenting increased inflammation markers. Symptoms were generally not increased in these studies, possibly related to the study population of primarily healthy adults. A previous panel study investigating the short-term health effects of aviation-related air pollution in the areas surrounding Schiphol airport in the Netherlands, found clear associations between aviation-related UFP and reported respiratory symptoms but not with lung function measurements [25, 33]. Another controlled exposure study in mild asthmatics also found associations between indoor UFP from candles and cooking with self-reported symptoms and not with lung function [32].

#### Characterizing woodsmoke exposure

Woodsmoke is a complex mixture of gases, vapors, and solids, the composition of which can differ in different burning conditions [51, 53]. In the review by Kocbach Bølling et al. [30] they focused on the physicochemical properties of woodsmoke in different combustion conditions, showing that individual behavior influences woodsmoke emissions considerably. In this study, the concentrations of $PM_{2.5}$, BC, BrC and UFP were measured at central monitoring sites in each study location of the panel study. Unlike previous studies, we did not only use proxy exposures such as fine particles to characterize woodsmoke exposure but also the specific woodsmoke marker levoglucosan. Thus, the associations seen with levoglucosan were considered the most representative for woodsmoke as also suggested by others [6, 27, 37, 41, 42, 46, 56].

When comparing all the proxy exposures with levoglucosan, we saw a good correlation between levoglucosan and BrC C1-6 ($R=0.94$). This supports the idea that BrC C1-6 can accurately estimate brown carbon emissions associated with organic combustion. This is consistent with a study in Canada, reporting correlations higher than 0.95 between BrC C1-C6 and levoglucosan in four sites [67]

Central monitoring sites were used to characterize the woodsmoke exposure at a neighborhood-level. Our study focused on neighborhood exposure rather than individual exposure, as there is currently no low-cost device for measuring levoglucosan levels at each residence. The participants recruited in the study had to live within a 2 km radius from the central monitoring site. Woodburning sources are scattered throughout neighborhoods which can lead to significant exposure level differences among residents in a relatively compact area [60]. To ensure the representativeness of the central monitoring sites, we analyzed the correlation of levoglucosan between the four areas—IJburg, Bergen, Zutphen, and De Meern. A moderate to high correlation was found, indicating that days with elevated levoglucosan levels in one area were often associated with higher levels in the others. This suggests a shared influence of weather conditions, such as cold weather, which likely leads to increased wood burning across all locations. In addition to emissions, dispersion could also play a significant role in the observed patterns, as wind and atmospheric conditions affect how pollutants spread across different areas. Although levoglucosan concentrations varied, indicating local differences, our findings suggest that the 2 km radius around the central monitoring sites was sufficient to capture the general exposure trend. With a single site, we cannot distinguish the contribution of local and more distant residential sources of wood burning. No forest fires occurred during the study period.

### Previous findings regarding woodsmoke and health

Our findings of an association between short-term exposure to woodsmoke and respiratory health are consistent with several previous studies on the health impacts of biomass burning [3, 7, 21, 22, 28, 30, 37, 49, 55]. These reviews have focused on PM emissions, the most commonly studied component. To put our results into perspective, we first discuss the few previous studies on short-term exposure to residential woodsmoke exposure in developed countries. We then use recent reviews to discuss the large body of evidence of studies on indoor and community outdoor exposure in developing countries; studies on biomass from wildfires and human controlled exposure studies.

Published reviews differ in their assessment of consistency of findings of health effects in western countries, ranging from strong evidence [55], evidence for community woodsmoke, but not indoor woodsmoke in children [49], to mostly inconsistent findings [21, 22]. All reviews agree that there is a need for new studies to improve exposure assessment, adjustment for confounders and design. In most reviews, no distinction is made between short-term and long-term exposure studies [21, 22, 49]. The time series and short-term exposure studies included in the systematic reviews, fairly consistently showed associations of woodsmoke markers with respiratory health indicators, including respiratory morbidity and mortality from time series studies [21, 22, 49, 55]. A major issue in time series and panel studies is exposure assessment to be able to evaluate woodsmoke specifically. Very few panel studies have been conducted on short-term exposure to outdoor community level woodsmoke and respiratory health [21, 22, 49, 55]. The evidence base includes studies with $PM_{2.5}$ and $PM_{10}$ as markers conducted in areas where woodsmoke is the dominant source of particles in winter such as in Christchurch New Zealand; Temuco, Chile and several studies in the North of the US and Canada [21, 22, 49, 55]. Time series studies in Copenhagen and California using source-apportionment reported significant associations between biomass-burning particles and respiratory hospital admissions in children [2, 43]. Several intervention studies of reduced woodsmoke in North American communities documented improved community air quality and improved respiratory health [22, 49, 55]. Finally, two panel studies in asthmatic children in Seattle reported significant associations between short-term fine particle and levoglucosan lung function [1, 31].

A large amount of literature exists on the health effects of indoor and outdoor woodsmoke in developing countries, where woodstoves are commonly used for cooking and as a primary source of heat, especially in rural areas. These studies have reported clear respiratory and less cardiovascular health effects related to both short- and long-term exposure [37, 55]. Based on this literature a substantial burden of disease related to household air pollution has been estimated [71]. These studies indicate the potential for woodsmoke to elicit adverse health effects, but due to the lower exposure levels and potentially different composition of the mixture, results cannot be directly transferred to the European setting. In developed countries, the epidemiological evidence for respiratory health effects of indoor woodsmoke exposure is much more limited, related also to limitations in these studies [21, 22, 49].

A sizable number of studies have assessed health effects of wildfires in Europe and North America especially [28, 55]. Collectively, these time series studies have documented respiratory and cardio-vascular mortality and respiratory hospital admissions to be associated with biomass burning exposures [28]. A meta-analysis of nine studies on respiratory hospital admissions reported a pooled excess risk of 4.2% (95% CI 2.9, 5.3). However, wildfire smoke may differ in composition from residential woodsmoke because of different burning conditions [53].

A review of five human controlled exposure studies conducted using various experimental set-ups, collectively showed mild inflammation without an effect on lung function [55]. A more recent review of 12 primary controlled exposure studies, reported inconsistent results across studies based on reporting of statistically significant findings from studies, attributed to major differences in experimental set-ups (e.g. burning conditions, and fuel), evaluated outcomes and time points of outcome assessment [53]. Studies were mostly performed in small groups (10 to 48) of healthy adults with high though realistic woodsmoke exposure, some included exercise. A recent semi-experimental study in the Netherlands reported consistent associations between 1-hour exposure to barbecue fumes and the inflammation marker IL-8 without an association with lung function and symptoms in healthy young adults [34]. Finally, Sigsgaard et al. [55] demonstrated that woodsmoke particles can induce inflammatory responses, oxidative stress and immunosuppression, among others, using in vivo and vitro experiments.

### Co-creating an environmental epidemiology study

Beyond the traditional nature of an epidemiological study, this project stands out for its unique approach in co-creating all the phases of the research project with citizens and relevant stakeholders. Involving citizens in all phases of the study offered several benefits. The research question was socially relevant, and design elements were discussed and tailored to meet the needs of the involved citizens. Citizens also played a significant

role in recruiting participants for the study. The citizen scientists recruited more than half of the citizens involved in the project (mainly from Zutphen). While the study did not require a representative sample of the population, the research team encountered challenges in recruitment despite substantial efforts, likely influenced by the impact of the COVID-19 pandemic. Nonetheless, the study included a substantial panel of nearly 50 participants, which is considered a large-scale study due to the daily observations made on each individual over a three-month period. Consequently, we obtained a rich dataset comprising significant health-related information, enabling a thorough investigation of the relationship between woodsmoke exposure and health outcomes. Citizens also played a major role in the interpretations of findings. Initially, researchers considered investigating neighborhood levels of woodsmoke to be a limitation of this study. However, after discussing the results with citizen scientists, they explained that the associations found between short-term woodsmoke exposure and respiratory symptoms at a neighborhood level across the different locations confirmed that the source of the exposure is not isolated to a single fireplace. Associations found at a neighborhood level suggest that the effects of woodsmoke is not solely an individual problem but a community-wide issue that needs to be addressed.

#### Strengths and limitations

The use of specific woodsmoke markers, particularly levoglucosan, stands out as a major strength, ensuring that associations observed are attributed to woodsmoke exposure rather than other sources. A limitation of the levoglucosan marker is that it was averaged over 24-hour periods, whereas wood burning tends to occur in more restricted time windows. A limitation regarding the specific woodsmoke marker BrC C1-6 is that the AE33 was only placed in IJburg and Bergen, instead of in all four locations. Despite this limitation, the available data showed high correlations between BrC C1-6 and levoglucosan levels. This suggests that BrC C1-6 could be a viable alternative to levoglucosan for woodsmoke research, offering the advantage of generating data with higher temporal resolution. Such a capability is crucial for more detailed investigations into the effects of woodsmoke exposure. By focusing on neighborhood exposures we could measure a larger study area in the Netherlands. The results based on these neighborhood exposures demonstrated that health outcomes from short-term exposure to woodsmoke can be considered a community-wide issue.

Even though we used a spirometer that is widely used in asthma management and epidemiological studies of air pollution, these were unsupervised measurements. Whether this may have influenced the results is questionable. In previous studies, where no association with lung function and woodsmoke were found, a variation of supervised and unsupervised measurements were conducted. In studies done by Sehlstedt et al. and van Kersen et al., they used the same spirometry device as in this study and had the participants conduct and record the measurements themselves [52, 55, 65]. Whereas other referenced studies had a trained professional present during the spirometry measurements [4, 34, 55, 58].

The COVID-19 pandemic impacted the exposure patterns of citizens as participants spent most of their time at home, probably resulting in more accurate exposure assessment. The COVID-19 pandemic may have affected our effect estimates. Fireplaces are typically turned on in the evenings and in the weekends when people are at home, also in non-COVID-19 periods. Therefore, the impact on health effect estimates related to wood smoke is likely limited. We cannot exclude the possibility that our panel participants had a different sensitivity to wood smoke than the average adult population. This may have affected our estimated effect size, not the finding of consistent associations. As we minimized contact with study participants, it seems unlikely that the decision to participate was related to COVID-19 issues. Another implication of the COVID-19 pandemic was that we started the study later than anticipated, resulting in fewer periods with high woodsmoke exposure.

Having citizens as a part of the research team is considered another major strength as citizens were able to help formulate the research question and study design, help with recruitment and help interpret preliminary findings. This also helped citizens gain access to academic knowledge that was being generated in real time. This helped with communicating and accepting findings in a broader context by citizens who have a fireplace themselves, policy makers, and other relevant stakeholders. While we measured a specific wood burning marker, our study could not delve into the nuances of individual fireplace factors, such as appliance type, combustion cycle, user practices, wood type, log size, and moisture content. These factors have been shown to affect magnitude and composition of particle emissions [49, 53, 55]. There are various studies that have investigated the impact of fireplace/woodstove use on indoor air quality. These studies often highlight the importance of proper stove management, maintenance, and education to mitigate health risks associated with indoor air pollution as well as targeted interventions to reduce emissions in households with vulnerable population groups [18, 44, 48].

In summary, this study showed clear associations between the exposure to woodsmoke, shortness of breath

at rest and additional medication use in the Netherlands. The findings highlight the importance of addressing woodsmoke as a community-wide concern and provide a foundation for further investigations into the specific components of woodsmoke that may contribute to health effects.

## Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s12940-024-01124-9.

Additional file 1.

Additional file 2.

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**Authors' contributions**
FF: Conceptualization, Investigation, Writing—Original Draft, Writing—Review & Editing, Visualization. JC; KM; MO; EL: Writing—Review & Editing; Help with Investigation. RV; MGN; JvT; DdJ & PB: Writing—Review & Editing, Funding acquisition. AM; HG; DvD; MC: Writing—Review & Editing. CHARRED Citizen Scientists: Conceptualization, Investigation, Reviewing. GH: Conceptualization, Writing—Review & Editing, Supervision, Funding acquisition.

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**Availability of data and materials**
The datasets generated and/or analysed during the current study are not publicly available due individual privacy regarding health data. But exposure data are available from the corresponding author on reasonable request.

## Declarations

**Competing interests**
The authors declare no competing interests.

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## Publisher's Note