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London wood burning project: air quality data collection

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Table of Contents

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Summary

Main findings from the project include:

- There was evidence of air pollution from stoves and fireplaces inside homes involved in the study, especially when fire lighting and refuelling. However, the contribution of stoves and fireplaces to indoor air pollution was lower than from cooking and cigarette smoking when these activities took place.
- There was clear evidence that wood and solid-fuel burning can cause short-term outdoor pollution peaks in the immediate area, typically around 10m from the chimney and these peaks were mainly linked to fire lighting and refuelling. In cases where peaks were not detected, this may be due to limitations relating to measurement locations and meteorological conditions.
- There was evidence that domestic wood and solid-fuel use was leading to new street-scale air pollution hotspots.
- At a London-wide scale domestic wood and solid-fuel burning is contributing to $PM_{2.5}$. This is mainly during winter evenings and on Friday, Saturday and Sunday. Concentrations attributed to wood and solid-fuel burning were much lower in summer months when indoor burning is rare and outdoor burning is more common.

Domestic wood and solid-fuel burning makes a significant contribution to emissions of particulate matter pollution, estimated at 27% of UK $PM_{2.5}$ emissions in 2020. Both short- and long-term exposure to particulate pollution is associated with a range of adverse health effects. The 'London Wood Burning Project', funded by a Defra Air Quality Grant and led by the London Boroughs of Camden and Islington on behalf of 13 additional London boroughs, seeks to improve scientific understanding and increase public awareness of this pollution source.

The air pollution measurement element of the London Wood Burning Project was carried out by the Environmental Research Group at Imperial College London. It used established measurement methods and calculations and applied these in field-work settings, combined with robust QA/QC procedures to provide information on wood and solid-fuel burning practices on a range of spatial scales.

Ambient concentrations of PM from wood and solid-fuel burning were calculated using measurements from Defra's Black Carbon network using the aethalometer model. The annual mean concentration at two urban background locations in London was 0.76 µg m^{-3} in 2022, making up 8-9% of the total annual mean $PM_{2.5}$ concentration at these locations and is expected to be representative of a wider area. More than half of this was attributed to urban sources of wood and solid-fuel burning within London with a slightly smaller contribution from wood and solid-fuel burning in the regional background (derived from measurements at a rural site upwind of London, unaffected by urban sources).

Portable measurements along two transects highlighted hotspots of wood and solid-fuel burning in north and south London which agreed well with modelled emissions. The aethalometer model was used to calculate concentrations of PM from wood burning from these portable measurements and this enabled differentiation of wood and solid-fuel burning from other sources of black carbon such as traffic. Measurements matched well with locations where wood and solid-fuel burning smells were detected, demonstrating that smell is a reliable indicator of inhaling wood and solid-fuel burning emissions.

Indoor and outdoor measurements from homes with different types of wood and solid-fuel burning appliances or an open fire showed no advantage of burning so-called “smokeless fuels” which are authorised for use in Smoke Control Areas, compared with seasoned wood. Indoor air pollution resulting from use of an open fire was not notably worse than for a Defra-exempt or non-exempt stove. However, improvements in indoor and outdoor air pollution were noted when lighting or adding fuel to a stove with clearSkies Level 5 rating although indoor and outdoor pollution from this appliance was still detected in some circumstances.

Measurements from the Breathe London hyperlocal monitoring network were examined. Temporal similarities between Breathe London $PM_{2.5}$ concentrations and PM from wood and solid-fuel burning were identified using information from Defra’s Black Carbon network. Breathe London measurements may have the potential to identify areas with a greater influence from wood and solid-fuel burning for further investigation.

Efforts to meet the recently updated World Health Organization (WHO) guideline value[1] for $PM_{2.5}$ of 5 µg m^{-3} as an annual mean would benefit from action to reduce emissions from wood and solid-fuel burning. Urban wood and solid-fuel burning sources in London contributed 0.46 µg m^{-3} to London $PM_{2.5}$ concentrations in 2022, which is almost 10% of the total 5 µg m^{-3} WHO guideline limit. Ambient pollution concentrations are influenced by a variety of factors, including local emissions, long range transport and meteorology. Around half of London’s $PM_{2.5}$ comes from regional and transboundary (non-UK) sources outside of London[2]. Wood and solid-fuel burning is currently the second biggest source of $PM_{2.5}$ emissions in London and is one of the main components of ambient concentrations that can be influenced on a local level.

The evidence from this study suggests that newer wood and solid-fuel burning appliances, highly rated for efficiency and low emissions, may have some advantages for air quality compared with older appliances although indoor and outdoor pollution was still detected from the newer appliances. In our experiments, the use of authorised and exempt fuels does not appear to have benefits for indoor or outdoor air quality compared to burning seasoned wood. Participants also found these fuels difficult to light or producing a limited heat output in some cases which could lead to more indoor air pollution due to increased interactions with the fire or stove. Portable measurement methodology developed through this project and earlier pilot studies provides useful information that agrees well with air quality modelling of wood and solid-fuel burning emissions. This method could be used to identify locations or further investigate areas where wood and solid-fuel burning is a concern.

[1] World Health Organisation, 2021. WHO global air quality guidelines: particulate matter (PM2.5 and PM10), ozone, nitrogen dioxide, sulfur dioxide and carbon monoxide. World Health Organization, Geneva. https://apps.who.int/iris/handle/10665/345329

[2] Greater London Authority, 2020. Air quality in London 2016-2020 https://www.london.gov.uk/sites/default/files/air_quality_in_london_2016-2020_october2020final.pdf

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1 Introduction

Air pollution is the largest environmental risk to public health in the UK. It is linked to between 28,000 and 36,000 deaths annually, with a cost to the NHS and social care system estimated at approximately £200m per annum[3]. Both short- and long-term exposure to particulate pollution, PM_{10} and $PM_{2.5}$, is a key concern due to the evidence of associated adverse health effects[4]. These include cardiovascular and respiratory disease, lung cancer and there is growing evidence that PM contributes to the development of diabetes and dementia. Even at relatively low concentrations $PM_{2.5}$ pollution has been found to have a significant burden on population health[5]. There is currently no evidence of a threshold level below which adverse health effects cannot be observed [6,7,8]. These effects are a particular problem for some of society's most vulnerable populations, including those with chronic conditions, children and the elderly[9]. As a result, the World Health Organisation (WHO) recently cut the guideline annual mean PM_{10} concentration from 20 to 15 μgm^{-3} and the annual mean $PM_{2.5}$ concentration from 10 to 5 μgm^{-3} (WHO, 2021). This increases the onus on national and local government to take further action to improve air quality.

An important target for reducing particulate pollution, especially $PM_{2.5}$, is emissions from home burning of solid-fuels. A 2017 study estimated that wood burning was the source of between 23 and 31% of the urban derived $PM_{2.5}$ measured in London and Birmingham[10]. In 2020 home solid-fuel burning accounted for 16% of PM_{10} and 27% of $PM_{2.5}$ UK emissions, with almost twice as much $PM_{2.5}$ emitted from home burning of solid-fuel than from road transportation (Defra, 2023). The latest London Atmospheric Emissions Inventory (LAEI) estimated that 569 tonnes of $PM_{2.5}$ were emitted by domestic biomass/wood burning in the Greater

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[3] Department of Health & Social Care (DHSC), Office for Health Improvement & Disparities (OHID), 2022. Guidance. Air Pollution: Applying all our Health. DHSC, London.

[4] Department for Environment Food & Rural Affairs (Defra), 2023. National Statistics. Emissions of air pollutants in the UK – Particulate matter (PM10 and PM2.5). Defra, London

[5] Brauer, M., Christidis, D., Crouse, A., Erickson, R., Martin, A., Pappin, L., Pinault, M., Tjepkema , S., Weichenthal, R., Burnett, M., 2019. Mortality–air pollution associations in low exposure environments, Environmental Epidemiology. Volume 3 - Issue - p 41

[6] WHO, 2021. WHO global air quality guidelines: particulate matter (PM2.5 and PM10), ozone, nitrogen dioxide, sulfur dioxide and carbon monoxide. World Health Organization, Geneva. https://apps.who.int/iris/handle/10665/345329

[7] Papadogeorgou G, Kioumourtzoglou MA, Braun D, Zanobetti A. Low Levels of Air Pollution and Health: Effect Estimates, Methodological Challenges, and Future Directions. Curr Environ Health Rep. 2019 Sep;6(3):105-115. doi: 10.1007/s40572-019-00235-7. PMID: 31090042; PMCID: PMC7161422.

[8] Air quality in Europe 2022. Health impacts of air pollution in Europe, 2022. https://www.eea.europa.eu/publications/air-quality-in-europe-2022/health-impacts-of-air-pollution

[9] Fuller, G.W., Friedman, S., Mudway, I., 2023. Impacts of air pollution across the life course – evidence highlight note. https://www.london.gov.uk/sites/default/files/2023-04/Imperial%20College%20London%20Projects%20-%20impacts%20of%20air%20pollution%20across%20the%20life%20course%20%E2%80%93%20evidence%20highlight%20note.pdf

[10] Font, A., Fuller G.W., 2017. Airborne particles from wood burning in UK cities. https://uk-air.defra.gov.uk/assets/documents/reports/cat05/1801301017_KCL_WoodBurningReport_2017_FINAL.pdf

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London area, representing 17% of total $PM_{2.5}$ emissions[11]. Most of this comes from burning wood in closed stoves and especially in open fires, which incompletely combust the fuel due to their low combustion temperature which causes relatively high emissions[12]. Furthermore, emissions from residential solid-fuel burning include toxic components. Black Carbon (BC), formed by the incomplete combustion of fossil fuels, wood, and other biomass, contains known toxic constituents such as carcinogens. In urban areas BC is considered a better indicator of harmful particulate substances from combustion sources than either PM_{10} or $PM_{2.5}$ (WHO, 2012). Other types of particles produced by wood burning, such as polycyclic aromatic hydrocarbons (PAHs) have mutagenic and/or carcinogenic properties[13].

This 'London Wood Burning Project' was funded through the Defra Air Quality Grant Scheme 2021-22 and is being led by London Borough of Camden and London Borough of Islington on behalf of 13 additional London boroughs. The overall aims of the project are to improve scientific understanding of the air quality effects of solid-fuel burning, including from different fuel and appliance types, to improve understanding of the health impact risk from these activities and to improve and enhance public awareness and engagement, with the long-term ambition to improve air quality and reduce health damage from solid-fuel burning in London. The first research phase of the project comprises three elements:

- Element 1 - residents surveys around domestic solid-fuel burning
- Element 2 - air quality data collection
- Element 3 - health impacts evaluation

Imperial College Projects Ltd was contracted to provide Element 2 via the expert services of the Environmental Research Group (ERG) at Imperial College London. This report details the methodology, results, analysis and conclusions of the air quality data collection.

2 Aims and objectives

Element 2 of the study aimed to quantify solid-fuel burning emissions in different exposure settings, both indoors and outside.

Targeted measurements sought to quantify indoor and outdoor concentrations from the use of different solid-fuel burners and fuel types. This aimed to improve the scientific understanding of emissions and impacts from different appliance types and fuels. Portable and fixed outdoor measurements aimed to quantify ambient concentrations of PM from solid-fuel burning and provide information on temporal and spatial variation within London. Analysis of ambient PM and solid-fuel burning measurements from

[11] Greater London Authority. 2021. London Atmospheric Emissions (LAEI) 2019 https://data.london.gov.uk/dataset/london-atmospheric-emissions-inventory--laei--2019. Accessed May 2023.

[12] World Health Organisation, 2015. Ambient (outdoor) air pollution – Newsroom/Fact sheets/Detail. https://www.who.int/news-room/fact-sheets/detail/ambient-(outdoor)-air-quality-and-health

[13]Abdel-Shafy, H. and Mansour,M., 2016. A review on polycyclic aromatic hydrocarbons: Source, environmental impact, effect on human health and remediation. Egyptian Journal of Petroleum, 25, 107–123

established measurement resources aimed to provide context, giving a perspective from indoor to London-wide.

These aims will inform and feed into the wider aims of the project to increase understanding about current domestic solid-fuel burning practices and improve public awareness and engagement with a long-term ambition to reduce air pollution and health damage from solid-fuel burning in London.

3 Approach

Four approaches were used to investigate different aspects of wood and solid-fuel burning emissions and exposure. These combined new targeted measurements with the use of existing measurement resources. This provided new insight at four spatial scales:

- In homes where solid-fuel is burned
- Immediately outside homes where solid-fuel is burned
- In selected London streets
- Across London and southeast England

Full details of the methods and QA/QC procedures are provided in section 4. An overview of the methodology and the purpose of each part of the analysis is as follows:

Part 1 Emissions from four categories of solid-fuel burning appliances were investigated, both inside and outside homes using MA300[14] and MA350[15] micro-aethalometers to measure BC and UV absorption, and Sidepak AM520[16] instruments to measure $PM_{2.5}$. Each home burned five fuel types, where possible in their appliance, on separate evenings over an approximately one-week period.

These instruments have been successfully used in previous studies involving portable or short-term measurements. When suitable QA/QC procedures are applied data quality compares well to $PM_{2.5}$ reference measurements or BC and UV absorption measurements from full-sized AE33 aethalometers, the instrument used on Defra's black carbon network.

This method provides information on emissions from different types of solid-fuel burning appliances and an open fire and how these affect indoor and outdoor air quality. The method provides information on variations in emissions for the tested fuel types. The measurements also provide information on other activities that affect air quality in the home and the relative magnitude of this effect compared to indoor solid-fuel burning.

[14] https://aethlabs.com/microaeth/ma300/overview

[15] https://aethlabs.com/microaeth/ma350/overview

[16] https://tsi.com/products/aerosol-and-dust-monitors/aerosol-and-dust-monitors/sidepak%e2%84%a2-am520-personal-aerosol-monitor/

Part 2 Portable measurements were made along two transects, one in north London and one in south London using a micro-aethalometer to measure BC and UV absorption and a Sidepak AM520 to measure $PM_{2.5}$. Ten walks were carried out for each route.

The same instruments and QA/QC procedures were used as for Part 1. The portable measurement method builds on previous pilot studies carried out by ERG that mapped wood and solid-fuel burning hotspots for London boroughs. Previous studies focused on smaller areas whereas for this study, measurements were made on transects through multiple boroughs where a range of wood and solid-fuel burning emissions were predicted from the LAEI.

This method provided information on wood and solid-fuel burning hotspots across transects in north London and south London. The results were compared to modelled wood and solid-fuel burning emissions to identify areas where the measurements match well with predictions or where measurements may provide evidence of solid-fuel burning that were not predicted by the model.

Part 3 Measurements from AE33 aethalometers that are part of Defra's black carbon network[17], managed and operated by Imperial ERG in collaboration with the National Physical Laboratory (NPL), were used to calculate concentrations of PM from wood and solid-fuel burning and the contribution from London sources. AE33 measurements from the Honor Oak Park site were examined in detail.

This part of the work used an established measurement method and QA/QC procedures, along with methodology for calculating wood and solid-fuel burning that has been used, tested and developed over several years.

This method provided context about solid-fuel burning in London and information on how much of this comes from sources within or outside the London urban area. It provided information on the temporal and meteorological factors that affect solid-fuel burning emissions and concentrations

Part 4 $PM_{2.5}$ measurements from the Breathe London[18] hyperlocal monitoring network were examined for evidence of locations that may be more affected by wood and solid-fuel burning emissions.

This relatively new source of $PM_{2.5}$ measurements has not previously been examined in detail for evidence of solid-fuel burning. The methodology was developed for this study using the relationship between $PM_{2.5}$ at the Breathe London sites and wood and solid-fuel burning PM concentrations calculated from fixed aethalometer measurements.

The Breathe London $PM_{2.5}$ measurements do not directly provide information about solid-fuel burning. Comparison with solid-fuel burning concentrations from fixed aethalometer measurements can help to identify similarities in timing (time of day and time of year) of increased $PM_{2.5}$ concentrations and solid-fuel burning concentrations. This may help to highlight areas where solid-fuel burning has a greater influence on $PM_{2.5}$ concentrations using the dense

[17] https://uk-air.defra.gov.uk/networks/network-info?view=ukbsn

[18] https://www.breathelondon.org/

measurement network. This evidence should not be used in isolation but as a potential indicator of where further research could be carried out. Measurements such as those used in part 1 or part 2 could be carried out to confirm whether solid-fuel burning emissions are affecting these areas.

4 Methods

4.1 Part 1: Measurements of BC, UV absorption and $PM_{2.5}$ from solid-fuel burning inside and outside homes

4.1.1 Recruitment

The Imperial College London Science, Engineering and Technology Research Ethics Committee (SETREC)[19] reviewed and approved the recruitment process, advert, participant information sheet, consent form and protocol, along with other details provided regarding methodology, data protection, health and safety and environmental impact. The documents are provided as an appendix.

Participants were recruited by placing an advert[20] in the News section of the Imperial ERG managed Londonair website which hosts air quality data and supporting information for London and surrounding areas. This advert was also shared with the public using social media, i.e., Twitter and circulated to ERG's organisational contacts, who include technical, managerial and public-health staff at local authorities and other organisations dealing with air quality in London and south-east England. Participating boroughs also shared and "re-tweeted" the advert to relevant contacts.

The following solid-fuel burning appliances were sought for testing:

- Open fire
- Defra-exempt stove
- non-Defra-exempt stove
- clearSkies Level 5 certified stove

Other inclusion requirements were that the main contact in the home must be over 18 and that volunteers living in a Smoke Control Area (SCA) must be using a Defra-approved appliance. Where applicable, the appliance should be suitable for burning multiple fuel types. Details of appliance type and location were collated, and potential participants were short-listed.

A questionnaire was circulated to short-listed participants to gather further information on appliance type, property details and burning practices. One volunteer from each of the required categories who met criteria for appliance type and location, along with other practical considerations, was contacted. Participants with solid-fuel burning experience, who regularly utilized their open fire or appliance, to the manufacturer's instructions were selected. They were provided with a participant information sheet and consent form to ensure that they fully understood the procedures and requirements. Subsequently a visit

[19] https://www.imperial.ac.uk/research-ethics-committee/committees/setrec/

[20] https://www.londonair.org.uk/LondonAir/general/news.aspx?newsId=2zyCGOtrFPnz7sZgFfGADc

was arranged to set up the measurement equipment at their home and to provide firelighters, kindling material and fuels for testing.

4.1.2 Measurement methodology and scaling

In total three Sidepak AM520 instruments were used to measure $PM_{2.5}$ and four micro-aethalometers, MA300 and MA350, were used to measure BC and UV absorption. Particles that absorb in the UV range (370 nm) can be considered as an indicator of organic components of wood and solid-fuel smoke particles. The main difference between MA300 and MA350 is the design of the casing. The MA350 has a more robust casing design so was the preferred model for use outdoors.

The Optimized Noise reduction Averaging (ONA) algorithm[21] was used to post-process all one minute, and 30 second data from the micro- aethalometers as a first step prior to any other data processing or analysis. The ONA method was used to resolve the noise of real-time data from the micro aethalometer, while maintaining the highest possible time resolution.

The instruments were co-located at the Honor Oak Park urban background supersite in south-east London and at the Marylebone Road kerbside supersite in central London, for scaling purposes. Where possible, an instrument co-location was carried out before and after the measurements in the homes, but in some cases the pre-measurement co-location was not possible due to instrument faults. Co-locations were carried out for approximately five days each at the two contrasting location types in order to include a range of concentrations for scaling. Co-location dates are shown in Table 4-1.

The $PM_{2.5}$, BC and UV absorption measurements were plotted against the reference $PM_{2.5}$ and AE33 seven-wavelength aethalometers respectively. There is no reference method for BC or UV absorption but the AE33 aethalometer is the chosen measurement method for Defra's black carbon network, of which these instruments are part. The reduced major axis (RMA) regression method was used on hourly averaged data to derive the relationship between the small sensor measurements and the reference or black carbon network measurements. The RMA method was chosen to account for the uncertainty in the measurements of both dependent (sensor) and determinant (reference) variables[22]. The RMA relationship was used as a correction factor to adjust or scale the $PM_{2.5}$, BC and UV absorption sensor measurements to the reference or black carbon network measurements. Co-located instruments are shown in Figure 4-1. Results of RMA regression analysis for $PM_{2.5}$, BC absorption and UV absorption are shown in Table 4-1, Table 4-2 and Table 4-3. Site codes HP1 and HP3 relate to the $PM_{2.5}$ and AE33 aethalometer respectively at Honor Oak Park and MR9 and MS3 relate to the $PM_{2.5}$ and AE33 aethalometer at Marylebone Road.

[21] Hagler, G., Yelverton, T., Vedantham, R., Hansen, A., Turner, J., 2011. Post-processing method to reduce noise while preserving high time resolution in aethalometer real-time black carbon data. Aerosol and Air Quality Research, 11: 539–546

[22] Ayers, G.P., 2001. Comment on regression analysis of air quality data. Atmospheric Environment 35, 2423-2425

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Figure 4-1 Portable instrument co-location at Marylebone Rd and Honor Oak Park

Table 4-1 PM2.5 RMA regression co-location results

Sidepak s/n		Site	Start	End	hourly mean n	RMA regression R^2	slope	Slope 95% CI	Intercept	Offset 95% CI
001	Pre	MR9	24/10/2022 12:00	01/11/2022 10:00	190	***0.90***	0.220	0.210-0.230	1.120	0.784-1.440
	Pre	HP1	01/11/2022 15:00	08/11/2022 10:00	163	***0.87***	0.124	0.117-0.131	2.300	2.060-2.530
	Post	HP1	24/03/2023 13:00	30/03/2023 10:00	141	***0.38***	0.227	0.199-0.259	1.076	0.503-1.580
	Post	MR9	31/03/2023 10:00	05/04/2023 10:00	120	***0.72***	0.205	0.186-0.226	-0.353	-0.983-0.220
	Combined				618	***0.75***	0.158	0.152-0.165	2.230	2.040-2.410
004	Pre	MR9	24/10/2022 12:00	01/11/2022 10:00	190	***0.81***	0.195	0.183-0.208	-0.362	-0.930-0.171
	Pre	HP1	01/11/2022 15:00	08/11/2022 10:00	163	***0.85***	0.114	0.108-0.121	0.322	-0.064-0.686
	Post	HP1	24/03/2023 13:00	30/03/2023 09:00	140	***0.24***	0.210	0.182-0.243	1.400	0.82-1.90
	Post	MR9	31/03/2023 10:00	05/04/2023 10:00	120	***0.90***	0.191	0.180-0.202	0.941	0.586-1.280
	Combined				616	***0.64***	0.131	0.125-0.137	1.810	1.57-2.04
0010	Pre	MR9	24/10/2022 12:00	01/11/2022 10:00	190	**0.87**	0.218	0.208-0.230	1.110	0.728-1.47
	Pre	HP1	01/11/2022 15:00	08/11/2022 10:00	163	**0.84**	0.108	0.102-0.116	3.010	2.79-3.22
	Post	HP1	15/02/2023 17:00	21/02/2023 08:00	135	**0.91**	0.201	0.191-0.212	-1.320	-1.63-(-1.03)
	Post	HP1	24/03/2023 13:00	30/03/2023 10:00	141	**0.25**	0.247	0.213-0.285	-0.026	-0.83-0.67
	Post	MR9	31/03/2023 10:00	05/04/2023 09:00	119	**0.91**	0.200	0.190-0.212	0.084	-0.298-0.445
	Combined				752	**0.69**	0.156	0.150-0.162	1.740	1.55-1.92

Table 4-2 BC RMA regression co-location results

Micro-Aeth		Site	Start	End	hourly mean	RMA regression				
s/n					n	R^2	slope	Slope 95% CI	Intercept	Offset 95% CI
MA350-0001	Post	HP3	24/03/2023 21:00	26/03/2023 16:00	28	***0.77***	1.150	0.948-1.390	0.027	-0.011-0.058
	Post	MS3	31/03/2023 09:00	05/04/2023 09:00	120	***0.95***	1.190	1.14-1.23	0.010	-0.018-0.037
	Combined				149	***0.96***	1.180	1.14-1.22	0.014	-0.006-0.034
MA350-0002	Post	HP3	15/02/2023 17:00	21/02/2023 08:00	93	***0.95***	0.495	0.473-0.519	0.016	0.008-0.022
	Post	HP3	25/03/2023 18:00	30/03/2023 08:00	109	***0.93***	0.886	0.842-0.931	-0.012	-0.027-0.002
	Post	MS3	31/03/2023 09:00	05/04/2023 09:00	121	***0.95***	0.919	0.884-0.955	-0.011	-0.040-0.016
	Combined				324	***0.94***	0.927	0.902-0.953	-0.050	-0.063-(-0.038)
MA350-0006	Pre	HP3	07/12/2022 15:00	12/12/2022 14:00	119	***0.97***	1.250	1.21-1.29	-0.121	-0.20-0.041
	Post	HP3	24/03/2023 13:00	30/03/2023 07:00	99	***0.76***	1.051	0.952-1.16	0.040	0.017-0.060
	Post	MS3	31/03/2023 09:00	05/04/2023 09:00	121	***0.93***	1.130	1.08-1.19	0.028	-0.006-0.060
	Combined				341	***0.98***	1.220	1.20-1.24	-0.027	-0.047-(-0.008)
MA300-0017	Pre	HP3	07/12/2022 15:00	12/12/2022 14:00	120	***0.97***	1.180	1.14-1.21	-0.031	-0.104-0.040
	Post	HP3	24/03/2023 16:00	29/03/2023 15:00	61	***0.87***	0.994	0.904-1.09	0.038	0.017-0.057
	Post	MS3	31/03/2023 09:00	05/04/2023 09:00	50	***0.91***	0.956	0.876-1.044	0.115	0.064-0.161
	Combined				241	***0.97***	1.160	1.13-1.18	0.001	-0.030-0.032

Table 4-3 UV RMA regression co-location results

Micro-Aeth		Site	Start	End	hourly mean	RMA regression				
s/n					n	R^2	slope	Slope 95% CI	Intercept	Offset 95% CI
MA350-0001	Post	HP3	24/03/2023 21:00	26/03/2023 16:00	28	***0.88***	1.410	1.23-1.61	-0.011	-0.052-0.024
	Post	MS3	31/03/2023 09:00	05/04/2023 09:00	120	***0.96***	1.340	1.30-1.39	-0.028	-0.057-0.001
	Combined				149	***0.97***	1.330	1.29-1.37	-0.016	-0.037-0.004
MA350-0002	Post	HP3	15/02/2023 17:00	21/02/2023 08:00	93	**0.98**	0.567	0.551-0.584	0.009	0.002-0.016
	Post	HP3	25/03/2023 18:00	30/03/2023 08:00	109	***0.97***	0.978	0.946-1.011	-0.015	-0.029-(-0.003)
	Post	MS3	31/03/2023 09:00	05/04/2023 09:00	121	***0.97***	0.976	0.947-1.006	-0.025	-0.050-(-0.001)
	Combined				324	***0.92***	0.946	0.917-0.975	-0.047	-0.064-(-0.031)
MA350-0006	Pre	HP3	07/12/2022 15:00	12/12/2022 14:00	119	**0.99**	1.570	1.54-1.60	-0.330	-0.42-(-0.23)
	Post	HP3	24/03/2023 13:00	30/03/2023 07:00	99	**0.94**	1.110	1.06-1.17	0.023	0.007-0.038
	Post	MS3	31/03/2023 09:00	05/04/2023 09:00	121	**0.97**	1.200	1.16-1.24	-0.009	-0.034-0.015
	Combined				341	**0.99**	1.540	1.52-1.55	-0.192	-0.217-(-0.171)
MA300-0017	Pre	HP3	07/12/2022 15:00	12/12/2022 14:00	120	**0.98**	1.520	1.49-1.56	-0.253	-0.363-(-0.146)
	Post	HP3	24/03/2023 16:00	29/03/2023 15:00	61	**0.94**	1.230	1.16-1.31	0.011	-0.009-0.030
	Post	MS3	31/03/2023 09:00	05/04/2023 09:00	50	**0.98**	0.961	0.911-1.014	-0.011	-0.052-0.027
	Combined				241	**0.98**	1.510	1.49-1.54	-0.250	-0.295-(-0.205)

The aethalometer model was used to calculate the concentration of wood and solid-fuel burning PM (WBPM) from the scaled BC and UV micro-aethalometer measurements made outside the homes. Please note that the abbreviation WBPM refers to burning of wood and other solid-fuels throughout this report. The method is based on the different light absorption properties of wood and solid-fuel burning aerosols and fossil fuel combustion aerosols from traffic: biomass aerosols absorb more light at shorter wavelengths than fossil fuel aerosols. The method was described in full in Sandradewi et al., (2008)[23] and has been applied, tested and developed in a number of other studies by researchers at Imperial and elsewhere (e.g.

[23] Sandradewi, J., Pr´evˆot, A.S.H., Szidat, S., Perron, N., Alfarra, M.R., Lanz, V.a., Weingartner, E., Baltensperger, U., 2008b. Using aerosol light absorption measurements for the quantitative determination of wood burning and traffic emission contribution to particulate matter. Environ. Sci. Technol. 42, 3316–3323. https://doi.org/10.1021/es702253m.

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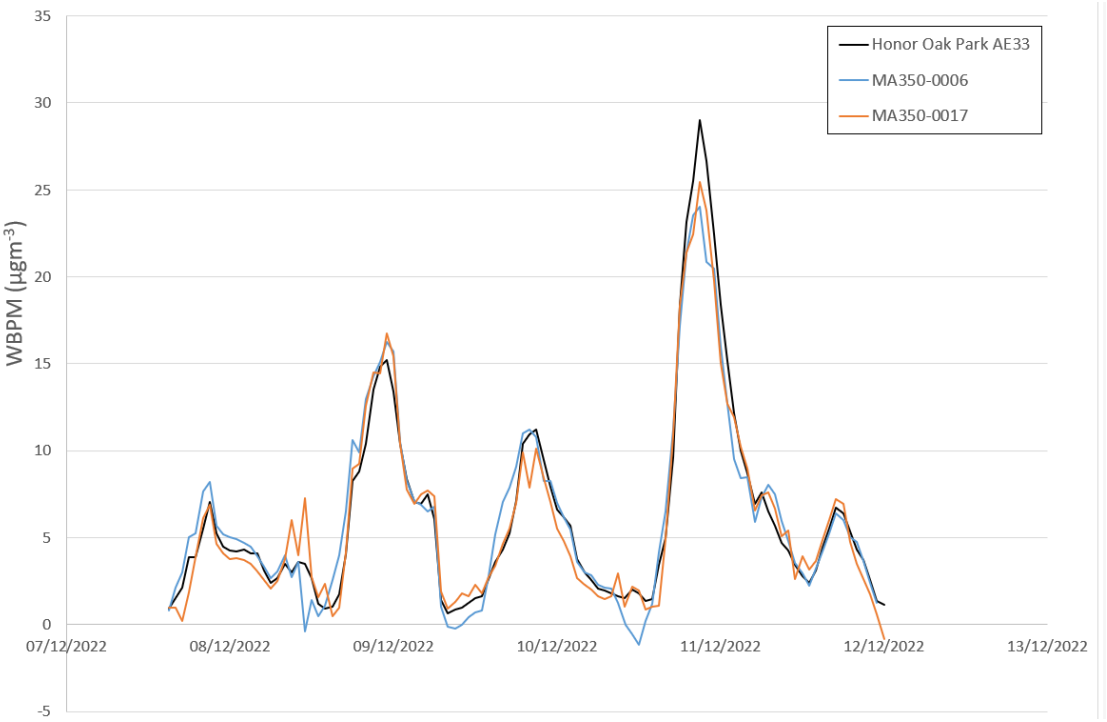
Harrison et al., 2012[24], Fuller et al., 2014[25], Font et al., 2022[26]). The wood and solid-fuel burning PM concentrations in this report were calculated using the method and coefficients which were described and considered in detail in Fuller et al., 2014 and revised in Font et al., 2022. This method is well-established for use with full-sized AE22 or AE33 aethalometers but less so for use with micro-aethalometer measurements. Therefore, the calculated WBPM data from the micro-aethalometers was plotted alongside the calculated WBPM data from the Honor Oak Park AE33 aethalometer during the co-location period to ensure a good comparison. An example of this comparison is shown in Figure 4-2.

Figure 4-2 Comparison of calculated WBPM concentrations for the AE33 aethalometer at Honor Oak Park and from the MA350 micro-aethalometers during the December 2022 co-location period.



The calculation of WBPM was only used for outdoor measurements. It was not considered suitable for the quantification of wood and solid-fuel burning indoors as there are likely to be too many interferences from other organic pollutant sources. In these cases changes in the UV channel of the aethalometer were used as a source indicator only.

[24] Harrison, R.M., Beddows, D.C.S., Hu, L., Yin, J., 2012. Comparison of methods for evaluation of wood smoke and estimation of UK ambient concentrations. Atmos. Chem. Phys. 12, 8271–8283. https://doi.org/10.5194/acp-12-8271-2012.

[25] Fuller, G.W., Tremper, A.H., Baker, T.D., Yttri, K.E., Butterfield, D., 2014. Contribution of wood burning to PM10 in London. Atmos. Environ. 87, 87–94. https://doi.org/10.1016/j.atmosenv.2013.12.037.

[26] Font, A., Ciupek, K., Butterfield, D. and Fuller, G.W., 2022. Long-term trends in particulate matter from wood burning in the United Kingdom: Dependence on weather and social factors. Environmental Pollution, 120105.

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Background $PM_{2.5}$ measurements for context were taken from Defra's UK Automatic Urban and Rural Network (AURN)[27] which is used for compliance reporting against the ambient air quality directives and Environment Act Targets. Measurements from the closest AURN site to each home were used.

4.1.3 Measurements in homes

A pair of instruments, comprising one micro-aethalometer and one Sidepak AM520, was placed inside each home in the room where the solid-fuel burning appliance or open fire was located, except for Home 4 which due to an unusual layout had the monitors on the floor below the stove but with unrestricted airflow between the two. A second pair of instruments was placed in a weather-proof box, outside each property. The location was decided based on security and power supply considerations for the monitors.

Plans of the location of the instruments relative to the open fire or appliance, indoors and outdoors, along with photographs of the instrument set-up, are included for each home in section 4.2.

Five fuel types were burned on separate evenings, where available and where suitable for the appliance. These are shown in Table 4-4. Firelighters, kindling and fuels for each category were selected based on being readily available across several large retail outlets.

Table 4-4 Fuel types burned in each home, where suitable for appliance

Category	Name and brand	Composition
Seasoned/kiln dried wood	 Homefire Premium Hardwood Kiln-Dried Logs	100% wood, kiln dried to <20% moisture content
Non seasoned/non-kiln dried wood	Sourced by participant where available	100% wood with varying moisture content
Smokeless "coal"	Maxibrite Newflame Plus 	Anthracite duff and starch binder 70-80% Petroleum coke 10-15% Bituminous coal 10-15%

[27] https://uk-air.defra.gov.uk/

Authorised manufactured solid-fuel (MSF)	Homefire Ecoal 	Anthracite fines 40-65% Petroleum coke 20-40% Bituminous coal 0-20% Biomass char 0-10% Organic binder up to 20%
Exempt manufactured solid-fuel (MSF)	Bio-Bean Coffee Logs 	Recycled coffee grounds, <12% moisture content
Firelighters and Kindling	Zip firelighters Kiln dried wood kindling 	Kerosene soaked resin. 100% kiln dried wood

Participants were requested to follow a standard protocol for lighting the fire or appliance and to take notes of the timing of lighting, re-fuelling, and other details relevant to the solid-fuel burning. They were also requested to note times and details of any other activities that may be expected to produce emissions of the pollutants being measured, such as cooking, cigarette smoking or use of candles.

Full details of actual fuels tested at each home and further information about instrument placement and burning practices are provided the results section 5.1.

4.2 Part 2: Portable measurements of BC, UV absorption and $PM_{2.5}$ along two transects

4.2.1 Measurement locations

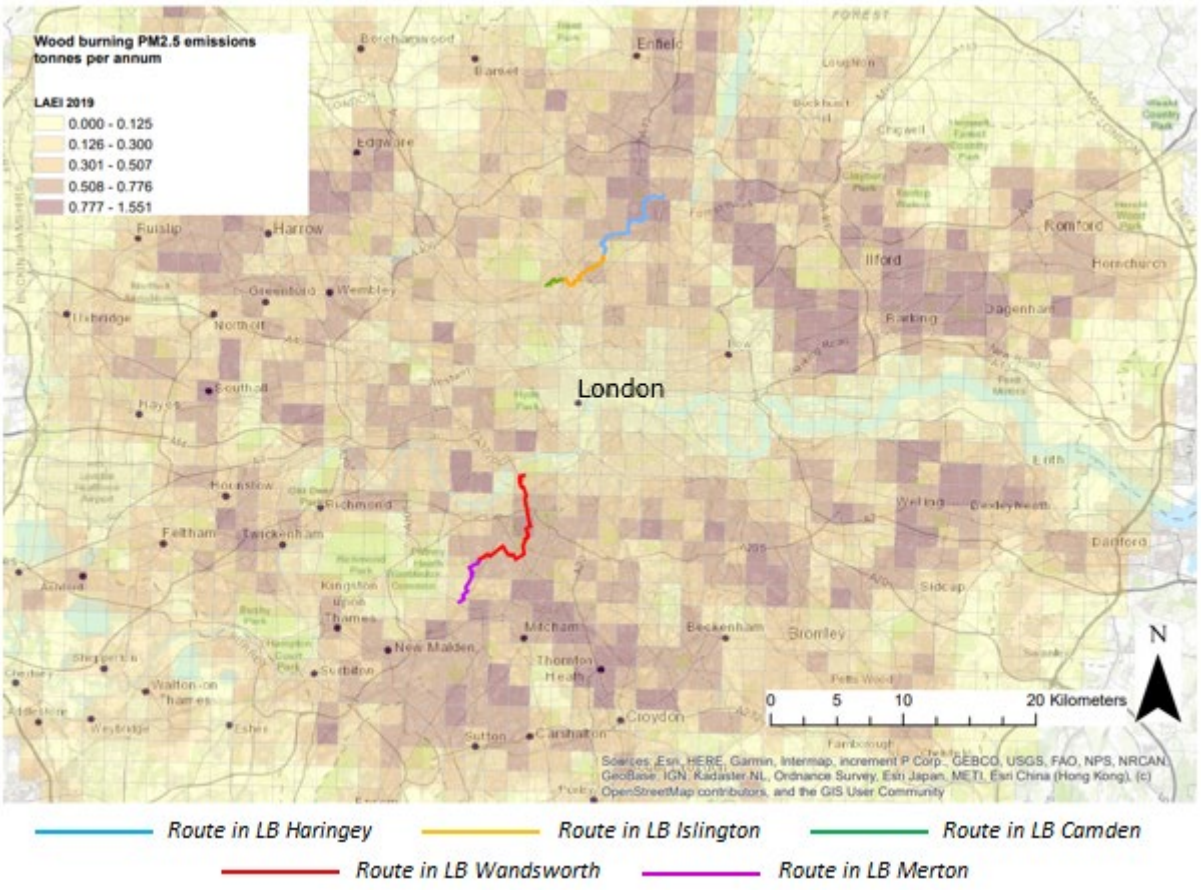
Two transects were chosen by ERG researchers in collaboration with the lead boroughs' project officers and other participating boroughs. The chosen routes were designed to cross through areas with a range of solid-fuel burning emissions, identified using data from the most recent London Atmospheric Emissions Inventory – LAEI 2019 (GLA, 2021). The routes were also chosen to include streets in several participating boroughs whilst maintaining a manageable length for the researchers carrying out the walking measurements.

The north London route was between Bruce Grove Station in Haringey and Glenhurst Avenue close to Gospel Oak station at the southern end of Hampstead Heath in Camden. It measured 10.6 km in length and passed through 61 residential streets & roads in the boroughs of Haringey, Islington and Camden.

The south London route was between Wimbledon and Battersea Park, measuring 10.6 km in length it passed through 53 streets & roads in the boroughs of Merton and Wandsworth.

Both north and south routes are shown in Figure 4-3, on a map of London overlain with modelled LAEI 2019 data of $PM_{2.5}$ emissions from wood and solid-fuel burning.

Figure 4-3: Location map of North and South routes for portable measurements, including modelled wood and solid-fuel burning $PM_{2.5}$ emissions. The route lines are coloured according to London borough.



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The north route is shown in Figure 4-4 with streets and roads listed in Table 4-5. The south route is shown in Figure 4-5 with streets and roads listed in Table 4-6.

Figure 4-4 Location map of North Route for portable measurements, including modelled wood and solid-fuel burning $PM_{2.5}$ emissions

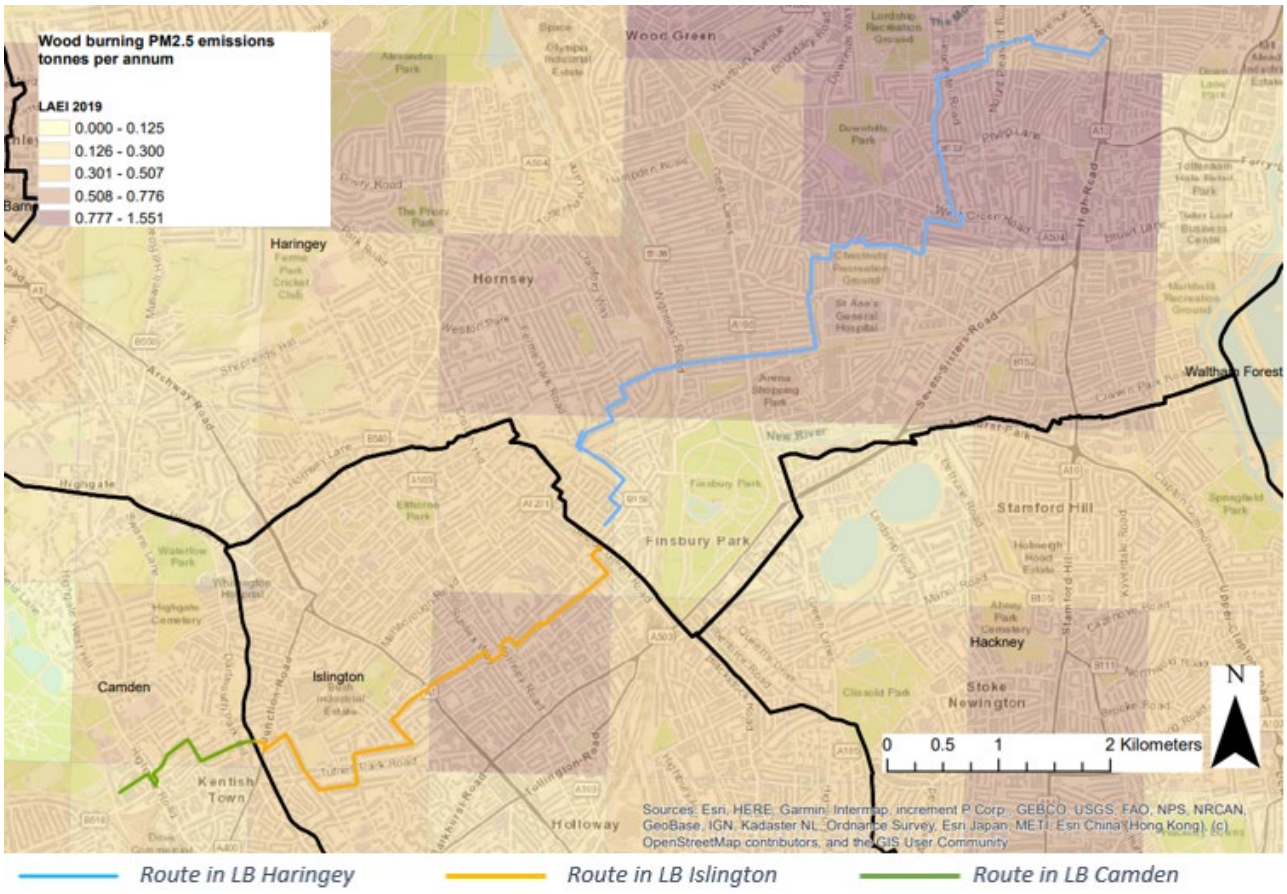

Table 4-5 North route streets, roads, boroughs, and length on route

		m			m			m
Bruce Grove Station			St Ann's Road (B152)	Haringey	25	Hornsey Road (A103)	Islington	47
Moorefield Road	Haringey	132	Warwick Gardens	Haringey	294	Tollington Way	Islington	83
Sperling Road	Haringey	364	Stanhope Gardens	Haringey	390	Sussex way	Islington	63
The Avenue	Haringey	251	Green Lanes (A105)	Haringey	60	Alexander Road	Islington	372
Marden Road	Haringey	67	Burgoyne Road	Haringey	359	Holloway Road (A1)	Islington	230
Higham Road	Haringey	293	Railway Approach	Haringey	128	Tavistock Terrace	Islington	263
Clonmell Road	Haringey	427	Quernmore Road	Haringey	224	Yerbury Road	Islington	174
Summerhill Road	Haringey	348	Oakfield Road	Haringey	66	Mercers Road	Islington	335
West Green Road (A504)	Haringey	50	Addington Road	Haringey	121	Dalmeny Road	Islington	169
Elmar Road	Haringey	249	Albany Road	Haringey	77	St Georges Avenue	Islington	213
Avenue Road	Haringey	191	Stapleton Hall Road	Haringey	358	Huddleston Road	Islington	367
Newsam Avenue	Haringey	95	Florence Road	Haringey	324	Station Road	Islington	135
Gorleston Road	Haringey	102	Osbourne Road	Haringey	130	Junction Road	Islington	43
Falmer road	Haringey	174	Victoria Road	Haringey	68	Wyndham Crescent	Islington/Camden	135
Clarence Road	Haringey	59	Upper Tollington Park Road	Haringey	132	Spencer Rise	Camden	228
La Rose Lane	Haringey	60	Stroud Green Road (A1201)	Islington	5	York Rise	Camden	139
Cranleigh Road	Haringey	69	Tollington Park	Islington	55	Dartmouth Park Road	Camden	278
Etherley Road	Haringey	76	Charteris Road	Islington	135	Grove End	Camden	47
Conway Road	Haringey	105	Moray Road	Islington	493	Chetwynd Road	Camden	22
Ritches Road	Haringey	192	Birnam Road	Islington	229	Higate Road	Camden	63
			Tollington Park	Islington	58	Glenhurst Avenue	Camden	188

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Figure 4-5 Location map of south route for portable measurements, including modelled wood and solid-fuel burning $PM_{2.5}$ emissions

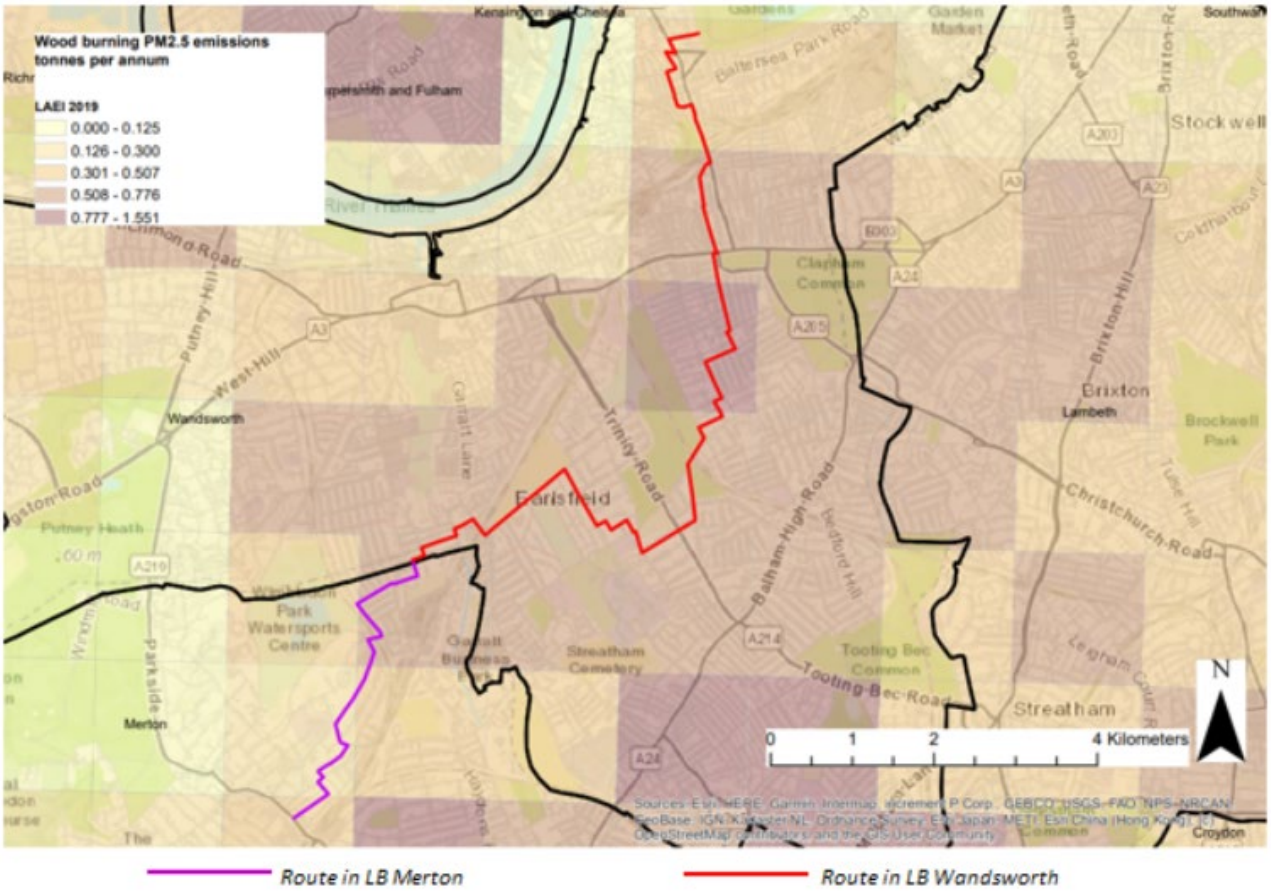

Table 4-6 South route streets, roads, boroughs, and length on route

		m			m			m
Wimbledon			Penwith Road	Wandsworth	156	Broomwood Road	Wandsworth	245
Compton Road	Merton	315	Garratt Lane	Wandsworth	147	Wroughton Road	Wandsworth	129
Worcester Road	Merton	119	Magdalen Road	Wandsworth	786	Chatto Road	Wandsworth	30
Woodside	Merton	57	Ellerton Road	Wandsworth	491	Leathwaite Road	Wandsworth	591
Glendale Drive	Merton	158	Burntwood Grange Road	Wandsworth	75	Sth Circular Road (A205)	Wandsworth	51
Bernard Gardens	Merton	200	Burntwood Close	Wandsworth	78	Attenburg Gardens	Wandsworth	359
Leopold Road	Merton	212	Collamore Avenue	Wandsworth	137	Dorothy Road	Wandsworth	237
Vineyard Hill Road	Merton	626	Lyminge Gardens	Wandsworth	101	Amies Street	Wandsworth	110
Home Park Road	Merton	99	Burntwood Lane (B229)	Wandsworth	25	Latchmere Road (A3220)	Wandsworth	455
Arthur Road	Merton	96	Beechcroft Road	Wandsworth	161	Abercrombie Street	Wandsworth	108
Melrose Avenue	Merton	308	Brodrick Road	Wandsworth	466	Frere Street	Wandsworth	78
Ashen Grove	Merton	336	St James's Drive	Wandsworth	425	Battersea Park Road (A3205)	Wandsworth	21
Havana Road	Merton	166	Bellvue Road (B237)	Wandsworth	237	Stanmer Street	Wandsworth	185
Lucien Road	Merton	124	Bollingbroke Grove (B229)	Wandsworth	88	Shuttleworth Road	Wandsworth	65
Mount Road	Wandsworth	94	Granard Road	Wandsworth	193	Bridge Lane	Wandsworth	144
Acuba Road	Wandsworth	61	Hendrick Avenue	Wandsworth	130	Surrey Lane	Wandsworth	62
Ravensbury Road	Wandsworth	279	Thurleigh Road	Wandsworth	66	Battersea Bridge Road (A3220)	Wandsworth	100
Ravensbury Terrace	Wandsworth	56	Montholme Road	Wandsworth	296	Petworth Street	Wandsworth	225

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4.2.2 Measurement methodology and scaling

The same measurement and scaling methodology was used for the portable measurements as that used for the measurements in homes, as described in section 4.1.2. WBPM concentrations were also calculated for the portable measurements using the same method. It should be noted that the WBPM concentrations can be subject to subject to large uncertainty in locations that are dominated by diesel traffic. The routes were therefore chosen to avoid busy roads where possible and wood and solid-fuel burning PM concentrations should be considered with caution where the routes cross main roads.

The micro-aethalometer and Sidepak AM520 were carried in a backpack. The sample tubes were fed through a gap in the bag zip and held in place with a clip. The instruments were run outdoors for a period up to an hour prior to the start of the sampling. Measurements were made ten times along each route during December 2022 and January and February 2023. These were carried out during weekday evenings or on weekends when domestic solid-fuel burning is most likely to be taking place. Days when low temperatures and light winds or calm conditions were forecast were preferred as this improves the likelihood of detecting emissions due to less pollutant dispersion. The dates and times of the walks along with weather conditions are reported alongside the results in section 5.2.

Figure 4-6 Monitoring backpack with sample lines protruding

4.2.3 Data analysis and mapping

Although final concentration data from the Sidepak and micro-aethalometer gave an overview of $PM_{2.5}$, BC and wood and solid-fuel burning PM measurements along the walking route, a method was required to standardise data so that readings on different days, obtained during different meteorological and background pollution conditions could be directly compared. For each walk a Z-score was calculated for every $PM_{2.5}$, BC and Delta-C measurement. The Z-score indicated the deviations between a measurement and the overall mean for all measurements on a walk, expressed in terms of the standard deviation.

The basic Z-score formula is:

$$z = (x - \mu) / \delta$$

Where x is a 30 second averaged species measurement on a walk, μ is the mean of all measurements of that species on the walk and δ is the standard deviation of measurements of that species on a walk. The use of z-scores standardised measurements across different days, allowing direct comparison of relative $PM_{2.5}$, BC and wood and solid-fuel burning PM measurements across a study area over all days walked.

Standardised z -scores were used to create maps and display spatial variation in $PM_{2.5}$, BC and wood and solid-fuel burning PM along both route walks, with separate maps created for each species. Each 30 second Z-score data point was mapped and classified based on its value. A standard deviation classification was applied to each species Z-score datasets. The classification ranged from multiples of the standard deviation below average, signifying less pollution (negative Z-score value) to multiples of the standard deviation above average, signifying more pollution (positive Z-score value). Z- score data points were coloured according to their class, from dark to light representing high to low z- score value or relative concentration. The use of standardised values allowed direct comparison of each individual route walk's measurements. By overlaying each walk's z-scores, a composite map was created displaying relative levels of each species, along each route. Mapping standardised scores allowed visualisation of how different relative concentration levels of tracers for solid-fuel and actual woodburning particles were spatially distributed along a route. Also, identifying clusters of higher relative measurements or 'hotspots' for solid-fuel and wood and solid-fuel burning emissions along each route.

4.2.4 Smell mapping & smell frequency tables

Solid-fuel burning smells were noted and their location recorded during each walk. An overall solid-fuel combustion smell hotspot map for each route walk was created by mapping each solid-fuel combustion smell event.

4.3 Part 3: Fixed aethalometer measurements

The concentration of PM attributable to wood and solid-fuel burning was calculated at two background locations in London: Honor Oak Park and North Kensington and a rural site in Chilbolton, using measurements from AE33 aethalometers, capable of measurements at seven wavelengths. These instruments were part of Defra's black carbon network, managed and operated by Imperial ERG in collaboration with the National Physical Laboratory (NPL). The measurements are publicly available on the UK-Air website.

The aethalometer wood and solid-fuel burning model was used to calculate WBPM, as described in section 4.1.2.

The analysis for this project focuses on the contribution of wood and solid-fuel burning to PM in London and south-east England for the years 2020 to 2022, adding to the period covered by previous studies and avoiding any potential issues due to instrument changes on the black carbon network. This provides context and an overall perspective for the more targeted local measurements carried out in parts 1 and 2. The measurement instrumentation on Defra's Black Carbon network was upgraded in 2019 from the dual wavelength Magee Scientific aethalometer AE-22, capable of measuring at two wavelengths, to the Magee Scientific aethalometer AE-33, capable of measurements at seven wavelengths. Potential effects of this change were considered in Font et al. 2022, although there was no evidence of a step change in measurement. For information on trends prior to 2020, please refer to Font et al., 2022 where long-term trends in PM from wood and solid-fuel burning between 2015 and 2021 were examined.

Annual mean concentrations of wood and solid-fuel burning PM were calculated for each site using measurements with at least 75% data capture in each hour. Annual mean concentrations of $PM_{2.5}$ and PM_{10} were downloaded from Defra's UK-Air website which hosts data from the UK AURN.

4.4 Part 4: $PM_{2.5}$ Breathe London measurements

The Breathe London sensor network measures NO_2 and $PM_{2.5}$ at around 400 locations across London. The network provides measurements at local and hyperlocal scales using a unique network scaling approach based on the relationship between each Clarity sensor and reference site measurements, applied on a continuous basis. This enables examination of a relatively high density of $PM_{2.5}$ measurements in some areas, compared to the availability of reference measurements. The Breathe London measurements do not include pollutants that can be directly used to derive concentrations of PM from wood and solid-fuel burning (i.e. BC, UV absorption or levoglucosan) as this is beyond the scope of the network. Therefore, the $PM_{2.5}$ measurements were examined, alongside evidence of wood and solid-fuel burning from other sources, namely fixed aethalometer measurements from Defra's black carbon network as described in section 4.3.

$PM_{2.5}$ measurements from selected participating boroughs were extracted from the Imperial ERG Breathe London database for the period 1st November 2021 to 8th March 2023. Due to the large number of Breathe London sites it was not possible to analyse measurements from all sites. The number of black carbon measurement locations for comparison is also limited. Measurements from the London Boroughs of Croydon, Richmond-upon-Thames and Sutton and were selected because of their large number of Breathe London sensors, for their relative proximity to the Honor Oak Park black carbon measurement site and because these participating boroughs were not covered by the other parts of the air quality data collection

work. Many Breathe London sites were installed during 2021 so the earlier part of the year was not considered, in order to limit the effects of site changes whilst still covering the main 2021 to 2022 winter period. Only sensors that operated before 1st July 2022 and continued until at least 1st January 2023 were selected.

4.5 Meteorological measurements

Meteorological data in this report was obtained using the worldmet package in R, which imports data from the National Oceanic and Atmospheric Administration (NOAA) Integrated Surface Database. Measurements from the closest meteorological measurement site to the air quality measurement location were used. For London, including all walking measurements, the meteorological data was taken from London City Airport. For the measurements from homes, meteorological data from London City Airport, Cardinham, Bodmin and Southend was used.

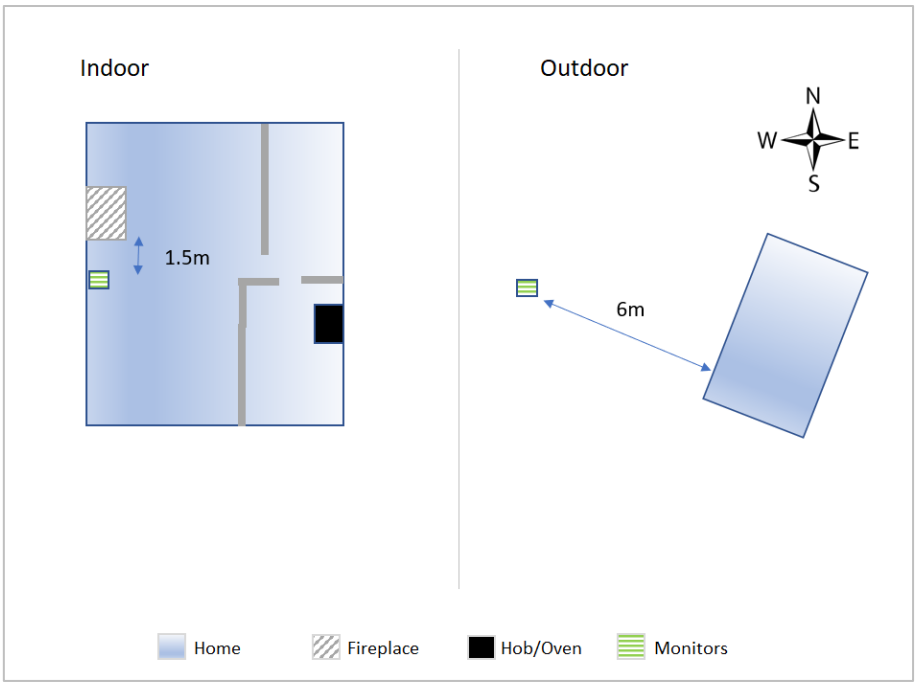
5 Results and discussion

5.1 Part 1: Measurements of BC, UV absorption and $PM_{2.5}$ from solid-fuel burning inside & outside homes

5.1.1 Home 1 – Open Fire

Home 1 was a semi-detached suburban property in Essex with neighbouring houses on all sides and a garden. The home was not in a smoke control area (SCA). It was approximately 300m north of an A route which ran in a SE NW direction. The monitoring station was set-up in the garden, approx. 6m in a NW direction from the house and approx. 1m in height from the ground. Indoors, the monitors were set-up in the living room 1.5m from the open fire. The hob/oven located in the kitchen area had open access to the monitors through a doorway. A plan of both indoor and outdoor monitoring is shown in Figure 5-1.

Figure 5-1 Plan of indoor & outdoor monitoring at Home 1



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Fuel burning tests were carried out over five 24-hour periods, from 06:00 in the morning to 06:00 the following morning, between 23rd December 2022 and 5th January 2023. On each of the Days 1-5, a different fuel was burned in the open fire. Fuel burning typically took place from the afternoon or evening, to later in the evening of the same day. Table 5-1 lists which fuel was burned each day.

Table 5-1 Test dates and fuel burned at Home 1

Date	Day	Fuel Type	Brand
Fri 23 Dec 2022 06:00 - Sat 24 Dec 2022 06:00	**Day 1**	Seasoned/ Kiln Dried Wood	Homefire Kiln Dried Logs
Mon 26 Dec 2022 06:00 - Tue 27 Dec 2022 06:00	**Day 2**	Exempt MSF	Bio-Bean Coffee Logs
Thurs 29 Dec 2022 06:00 - Fri 30 Dec 2022 06:00	**Day 3**	Authorised MSF	Homefire Ecoal
Mon 02 Jan 2023 06:00 - Tue 03 Jan 2023 06:00	**Day 4**	Unseasoned Wood	-
Wed 04 Jan 2023 06:00 - Thurs 05 Jan 2023 06:00	**Day 5**	Smokeless "Coal"	Maxibrite Newflame Plus

Photos of monitors in situ, and of the open fire are shown in Figure 5-2. Meteorological data from Southend Airport, Essex, for Days 1-5 is presented in Table 5-2.

Figure 5-2 Photos of Indoor monitors, outdoor monitoring and kiln dried wood burning in the open fire at Home 1

Table 5-2 Meteorological data for monitoring Days 1-5 at Southend Airport Essex

	Day 1																							
Time (h)	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	1	2	3	4	5
Temp (Deg C)	8	8	8	8	8	9	9	12	13	12	12	11	10	11	9	8	8	8	8	8	7	NA	7	7
Wind Direction (deg)	**170**	**140**	**102**	**95**	**100**	**70**	**230**	**240**	**246**	**240**	**246**	**240**	**240**	**240**	**235**	**240**	**240**	**240**	**250**	**250**	**230**	**NA**	**226**	**233**
Wind Speed(m/s)	1.8	2.1	1.8	3.1	3.9	3.1	2.3	4.6	5.9	5.7	7.0	8.0	7.2	7.7	6.5	4.6	4.9	3.1	3.1	5.7	4.1	NA	4.4	4.6
	Day 2																							
Time (h)	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	1	2	3	4	5
Temp (Deg C)	7	6	6	6	7	8	8	8	8	7	7	7	6	6	6	6	6	5	5	5	5	5	5	4
Wind Direction (deg)	**300**	**280**	**280**	**260**	**250**	**265**	**250**	**254**	**255**	**240**	**245**	**245**	**246**	**240**	**240**	**240**	**240**	**240**	**240**	**240**	**240**	**240**	**240**	**224**
Wind Speed(m/s)	6.0	4.1	4.9	4.6	4.6	5.4	5.1	5.4	7.0	5.2	4.9	6.0	5.2	4.6	4.4	4.9	5.4	4.9	5.2	4.4	4.6	4.1	3.4	2.1
	Day 3																							
Time (h)	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	1	2	3	4	5
Temp (Deg C)	10	9	9	9	9	9	10	9	9	9	8	7	7	6	7	6	6	6	5	5	NA	NA	8	8
Wind Direction (deg)	**234**	**244**	**240**	**235**	**230**	**240**	**240**	**240**	**235**	**240**	**240**	**230**	**235**	**230**	**235**	**230**	**221**	**205**	**210**	**190**	**NA**	**NA**	**170**	**165**
Wind Speed(m/s)	8.8	7.5	7.0	7.5	7.7	9.1	9.1	8.0	8.8	8.3	6.2	6.5	6.2	6.2	6.7	6.0	5.4	4.9	5.1	2.6	NA	NA	6.7	7.0
	Day 4																							
Time (h)	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	1	2	3	4	5
Temp (Deg C)	7	6	7	7	8	8	9	9	8	8	6	4	2	2	1	0	-1	-2	-1	0	1	5	6	6
Wind Direction (deg)	**220**	**224**	**225**	**255**	**265**	**270**	**260**	**291**	**260**	**269**	**284**	**254**	**241**	**212**	**215**	**230**	**230**	**NA**	**90**	**120**	**NA**	**150**	**170**	**180**
Wind Speed(m/s)	3.1	2.4	2.9	3.4	3.4	3.6	4.1	3.4	3.9	3.6	2.4	1.8	1.8	1.8	1.5	1.5	0.5	0.0	1.5	1.5	0.0	2.6	2.1	2.9
	Day 5																							
Time (h)	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	1	2	3	4	5
Temp (Deg C)	13	13	13	13	14	14	14	14	14	13	13	13	12	12	11	11	11	11	11	11	10	NA	10	10
Wind Direction (deg)	**225**	**230**	**230**	**235**	**240**	**240**	**240**	**250**	**245**	**245**	**240**	**250**	**250**	**250**	**250**	**246**	**240**	**240**	**240**	**240**	**240**	**NA**	**240**	**240**
Wind Speed(m/s)	9.0	10.1	9.0	7.7	8.2	8.8	10.1	10.1	9.3	8.8	8.2	9.6	7.2	7.2	7.2	6.2	5.2	6.5	5.9	6.2	5.7	NA	5.7	5.9

5.1.1.1 Home 1, Day 1 - Seasoned/Kiln dried wood

Indoor high resolution one-minute $PM_{2.5}$, BC and UV monitoring data from Day 1 is presented in Figure 5-3. Initially the $PM_{2.5}$ concentration indoors was 7 µg m^{-3}. A huge $PM_{2.5}$ peak of 125 µg m^{-3} was measured after the grill was used for cooking at 18:07. There was a small BC and UV signal of 1 µg m^{-3} and 7 µg m^{-3} respectively associated with this large cooking increase. Kiln dried/seasoned logs were the fuel used for the open fire on Day 1. When the fire was lit with firelighters and kindling at 19:54 and fuel added at 19:58, immediately afterwards there was an increase in $PM_{2.5}$ from 12 µg m^{-3} to 18 µg m^{-3}. No corresponding increase in BC or UV was measured. Further interventions with the fire over the course of the evening did not result in any increase in $PM_{2.5}$, BC or UV indoors. $PM_{2.5}$ levels stabilised overnight at 3 µg m^{-3}.

High resolution outdoor $PM_{2.5}$, BC and wood and solid-fuel burning PM data on Day 1 is shown in Figure 5-4. Also included in the outdoor plot is hourly background ambient $PM_{2.5}$ measurements from the nearest UK AURN suburban background monitoring site. From approx. 12:00 when monitoring began on Day 1 the wind direction was between 230 and 250 degrees, from a SW direction. This was an un-favourable direction from the point of view of the monitors picking up emissions from Home 1 which was downwind of the monitors.

By the time the fire was lit at 19:54 the background $PM_{2.5}$ concentration was similar to $PM_{2.5}$ levels outside the home. Over the course of the day there was little evidence that any emissions from Home 1 were detected by the outdoor monitors. A possible exception was noted at 21:03 when an increase in $PM_{2.5}$ from 10µg m^{-3} to 13 µg m^{-3} corresponded with fuel added to the fire. A corresponding increase in BC from 0.4 to 1.9 µg m^{-3} and WBPM up to 2 µg m^{-3} was also noted.

Figure 5-3 Home 1 Indoor measurements when Homefire kiln-dried logs were burned, annotated with activities that may be expected to affect pollutant concentrations

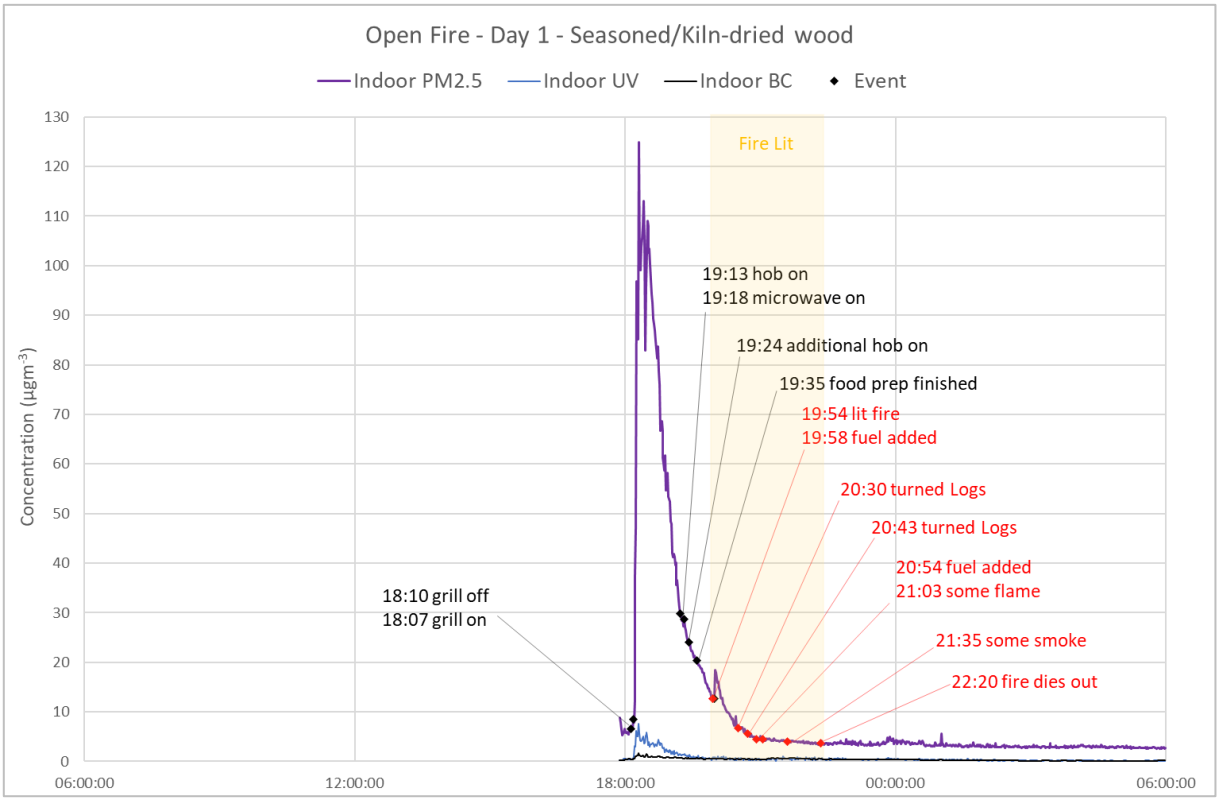
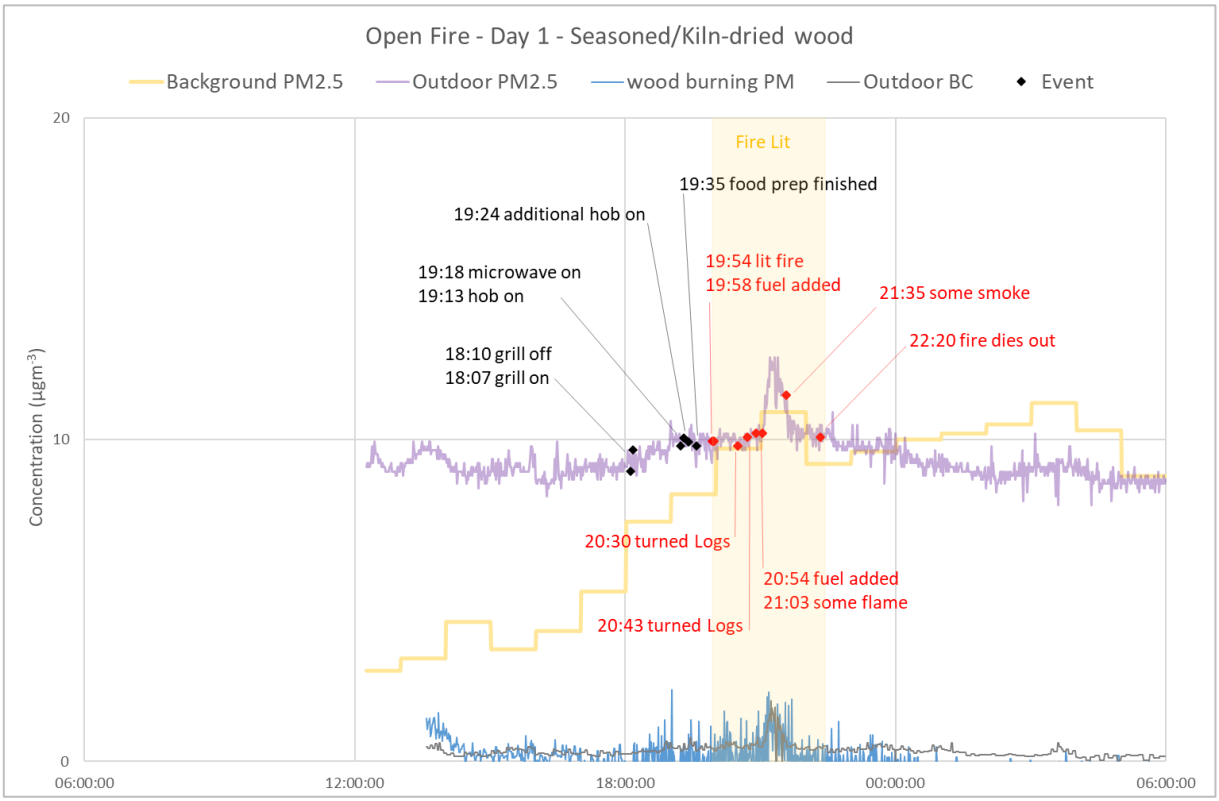


Figure 5-4 Home 1 Outdoor measurements when Homefire kiln-dried logs were burned, annotated with activities that may be expected to affect pollutant concentrations



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5.1.1.2 Home 1, Day 2 - Coffee Logs

Measurements from Day 2 indoor monitoring are shown in Figure 5-5. Large increases in $PM_{2.5}$ corresponded to cooking events. At 09:52 $PM_{2.5}$ increased from 3 µg m^{-3} to 223 µg m^{-3} twenty minutes after the grill and toaster were switched on. $PM_{2.5}$ levels began to reduce immediately after use of both stopped. $PM_{2.5}$ increased from 7 µg m^{-3} to 63 µg m^{-3} following grill and hob use at 12:47. The $PM_{2.5}$ increase to 22 µg m^{-3} from 17:46 appears to be most likely related to the use of the sandwich maker, as it began to decrease once the device was switched off at 18:16. No increases in measurements were noted when the fire was lit with firelighters and kindling and soon after Coffee Logs were added, or afterwards on three separate occasions when Coffee Logs were added.

Outdoor measurements from Day 2 are shown in Figure 5-6. The breeze was gentle to moderate all day at 4-6 m s^{-1}, NW changing to SW by mid-day. Similarly, to Day 1 this was unfavourable for picking up solid-fuel burning emissions from Home 1. Ambient temperature on Day 2 was low, at 5-7° C and this may have increased the solid-fuel burning in general in this residential area. The $PM_{2.5}$ outside the house was approx. 6 µg m^{-3} higher than background $PM_{2.5}$ which may also indicate higher emissions in general in this residential neighbourhood. Small spikes in $PM_{2.5}$ of up to 2 µg m^{-3}, and in WBPM of up to 2 µg m^{-3} were evident before and after the fire was lit throughout the day.

Figure 5-5 Home 1 Indoor measurements when Coffee Logs were burned, annotated with activities that may be expected to affect pollutant concentrations

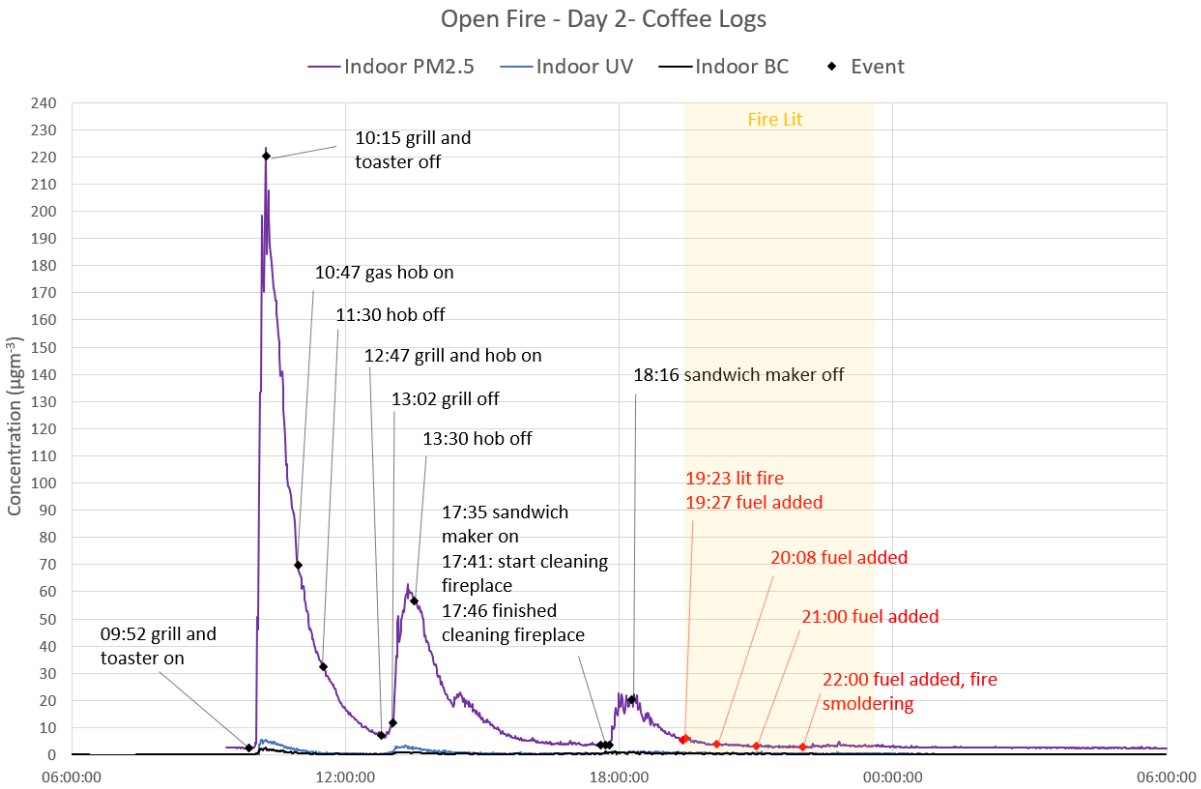

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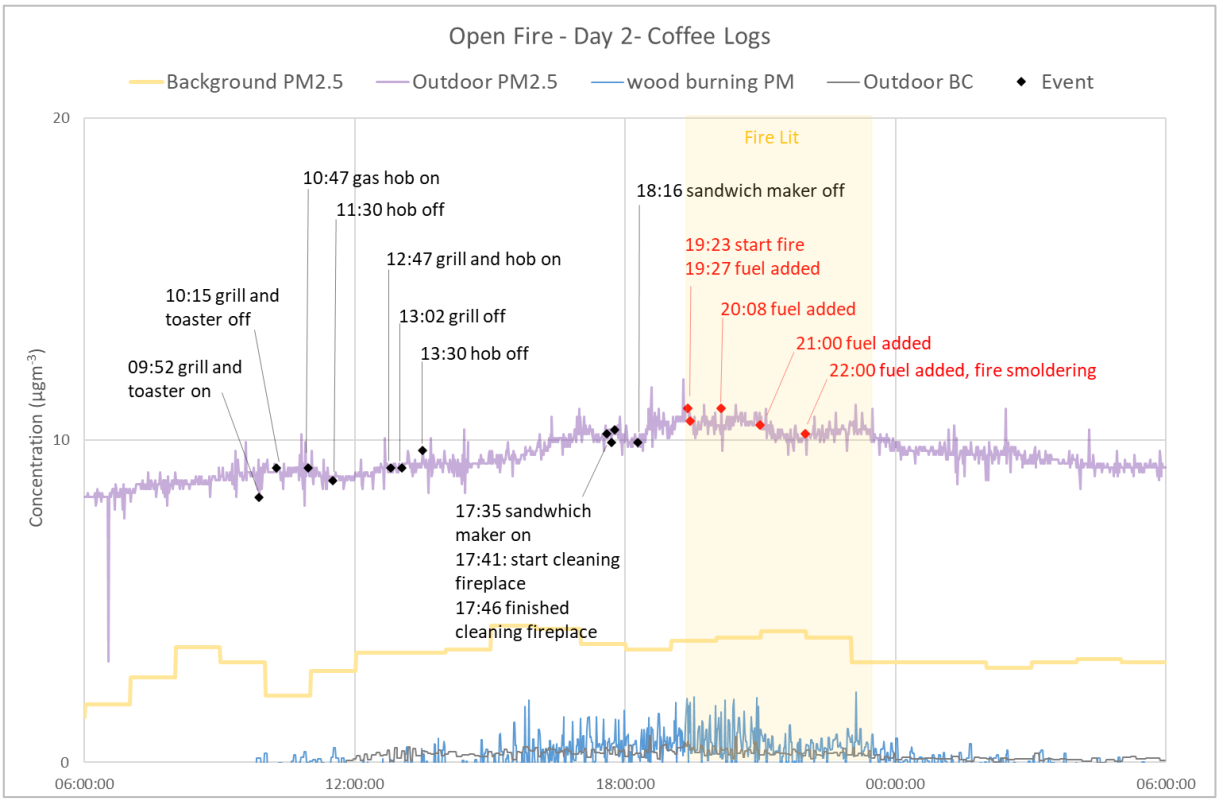
Figure 5-6 Home 1 Outdoor measurements when Coffee Logs were burned, annotated with activities that may be expected to affect pollutant concentrations



5.1.1.3 Home 1, Day 3 - Ecoal

Day 3 indoor measurements are presented in Figure 5-7. Initially, large increases in $PM_{2.5}$ from 16:00, peaking at 51 µg m^{-3} and at 42 µg m^{-3}, coincided with cooking events and the use of both oven and hob. By the time the fire was lit at 19:51, $PM_{2.5}$ levels had fallen to 4 µg m^{-3}. An initial spike in $PM_{2.5}$ from 3 to 22 µg m^{-3} was observed one minute before the fire was lit. When the fire was lit at 19:51, using firelighters, kindling and Ecoal, $PM_{2.5}$ increased again from 7 to 15 µg m^{-3} over the next 20 minutes. Small increases of UV and BC of approx. 0.2 µg m^{-3} were observed. At 21:00, 70 minutes after the fire was lit, $PM_{2.5}$ levels in the living room had returned to 4 µg m^{-3}. There was a small $PM_{2.5}$ peak at 21:02 but this did not correspond to fuel being added to the fire which happened at later at 21:24, by which time $PM_{2.5}$ was already elevated.

Measurement data from Day 3 outdoors is shown in Figure 5-8. A moderate SW breeze throughout the day was an unfavourable direction for the monitor to pick up emissions from the home. Very small increases in $PM_{2.5}$ of 1-2 µg m^{-3} were observed but generally unrelated to any events with the open fire. WBPM measurements increased > 1 µg m^{-3} from 17:30 but as with $PM_{2.5}$ it was difficult to attribute any changes directly to Home 1 emissions. $PM_{2.5}$ and WBPM measurements outdoors on Day 3 were most likely in the main due to neighbouring properties located to the SW.

Figure 5-7 Home 1 Indoor measurements when Ecoal was burned, annotated with activities that may be expected to affect pollutant concentrations

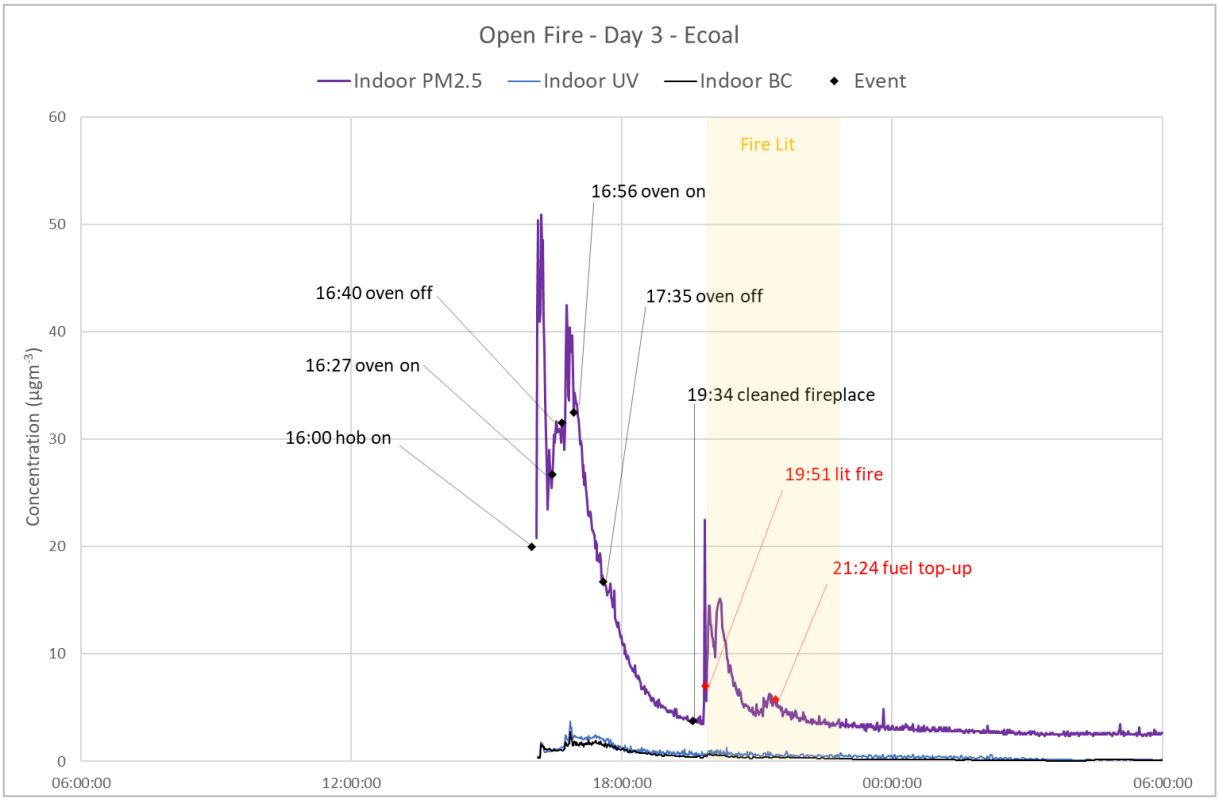


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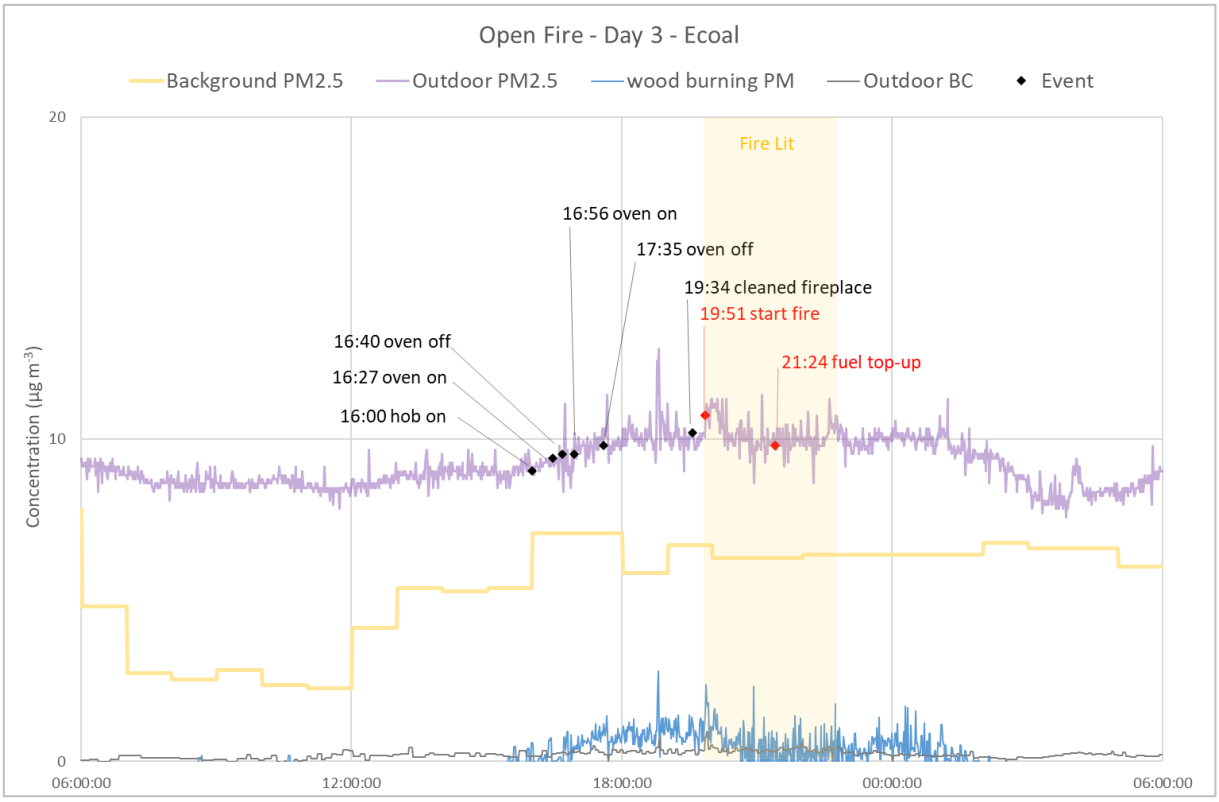
Figure 5-8 Home 1 Outdoor measurements when Ecoal was burned, annotated with activities that may be expected to affect pollutant concentrations



5.1.1.4 Home 1, Day 4 - Unseasoned wood

Day 4 indoor measurements are shown in Figure 5-9. As with previous days the largest $PM_{2.5}$ increase indoors was associated with cooking and use of the oven. $PM_{2.5}$ levels increased from 11 µg m^{-3} to 76 µg m^{-3} soon after the oven was turned on at 19:40. An increase in $PM_{2.5}$ was observed at 21:46 when the fire was lit. The $PM_{2.5}$ increase from 16 µg m^{-3} to 29 µg m^{-3} included unseasoned wood being added to the fire at 21:51. A corresponding very small increase in both UV and BC was measured at < 1 µg m^{-3}. Despite additional unseasoned wood being added at 22:06, logs being turned at 22:10, and additional firelighters being added to get the fire to take hold at 22:16, no changes to $PM_{2.5}$ concentration were detected for any of these events and $PM_{2.5}$ continued to decrease through the evening to 4 µg m^{-3} overnight.

Day 4 outdoor measurements are shown in Figure 5-10. A SW or NW light breeze eased during the day and temperatures dropped to freezing by late evening. The wind direction was again from an unfavourable direction for the monitor to pick up emissions from the home. However, the breeze became very light by evening, at 1-2 m s^{-1}. $PM_{2.5}$, BC and WBPM outdoors were all at the highest levels measured over the five test days. $PM_{2.5}$ concentrations outside the home increased from 19 µg m^{-3} to approx. 24 µg m^{-3} around 30-40 minutes after the fire was lit and unseasoned wood was added. An increase in WBPM of 5 µg m^{-3}, possibly indicated that unseasoned wood and solid-fuel burning emissions contributed to this increase. No increase in BC was observed over this time period. After approx. three hours both $PM_{2.5}$ and WBPM concentrations outside the home began to decrease.

Figure 5-9 Home 1 Indoor measurements when unseasoned wood was burned, annotated with activities that may be expected to affect pollutant concentrations

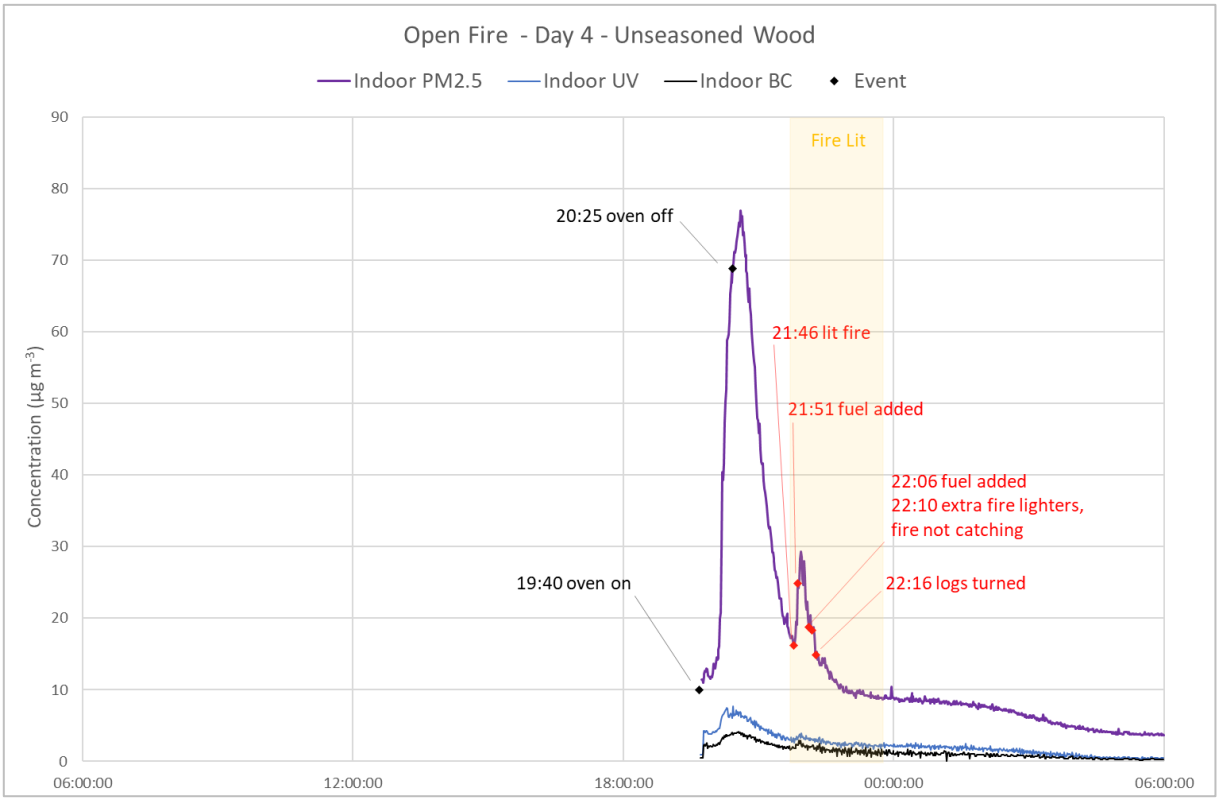
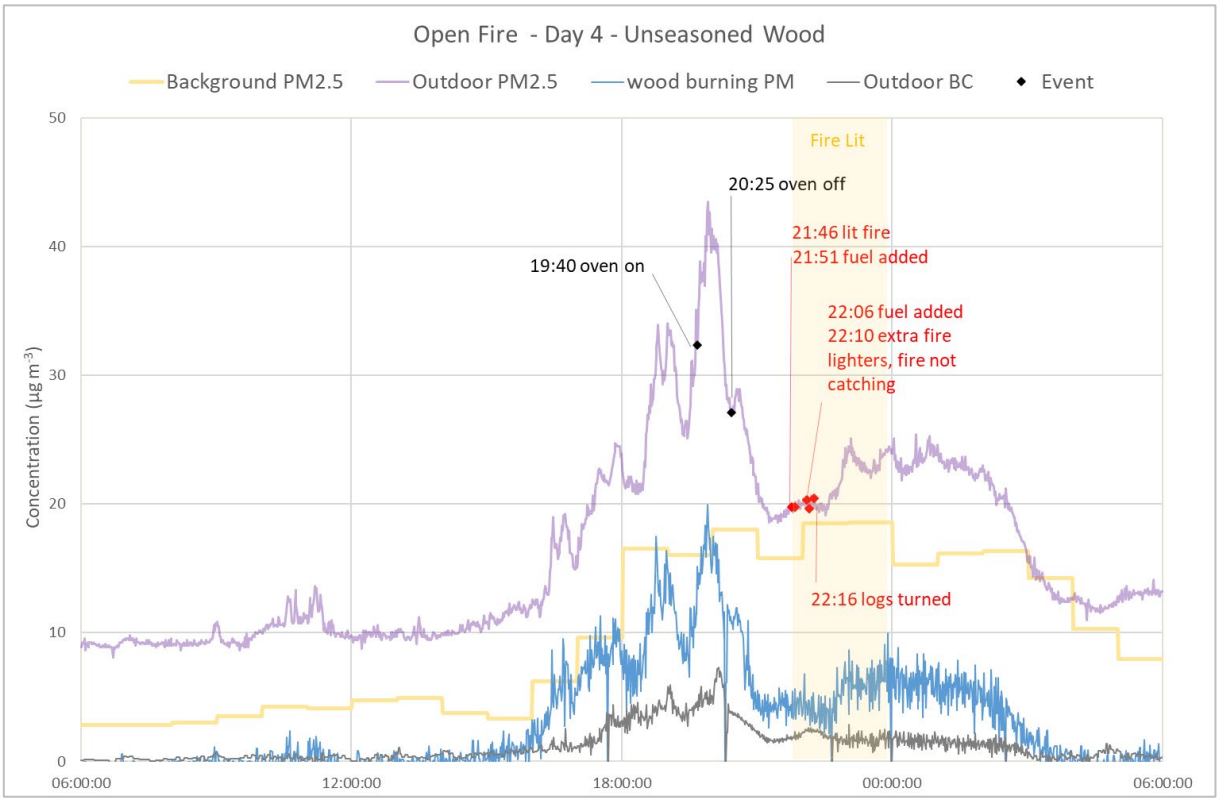


Figure 5-10 Home 1 Outdoor measurements when unseasoned wood was burned, annotated with activities that may be expected to affect pollutant concentrations



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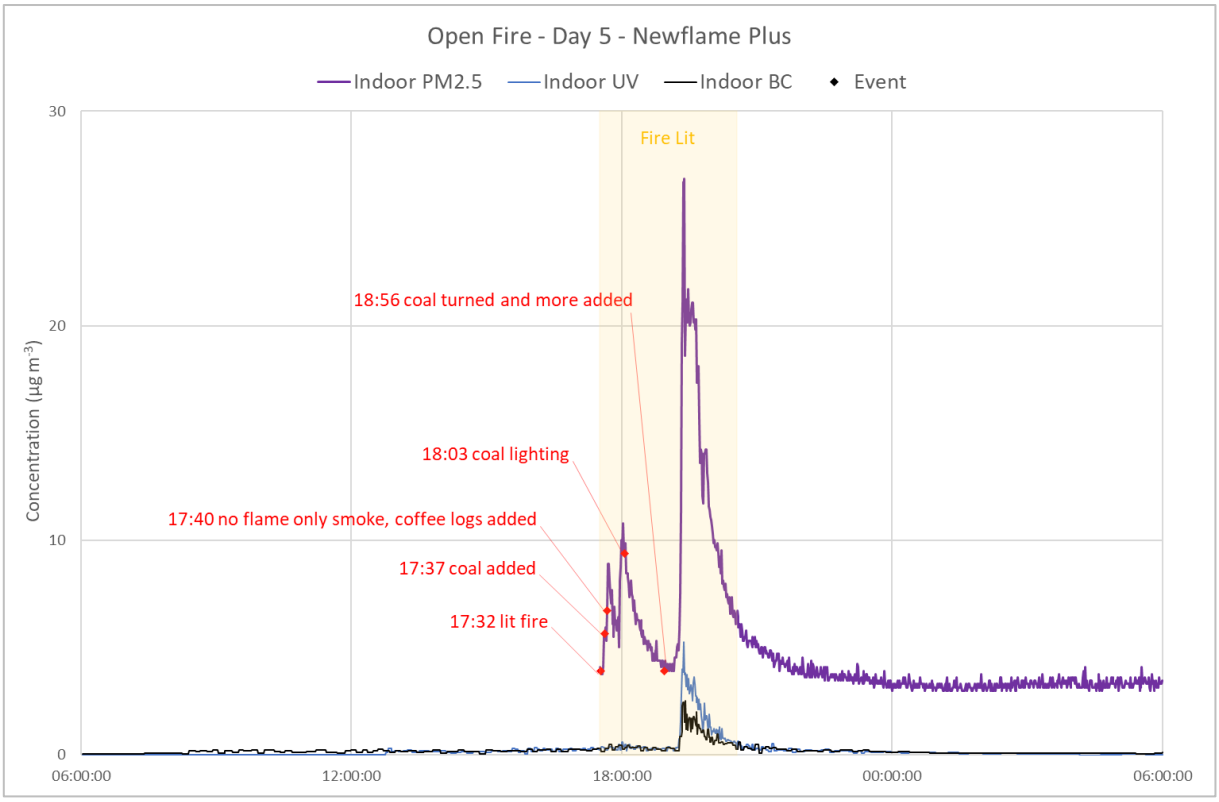
5.1.1.5 Home 1, Day 5 – Newflame Plus

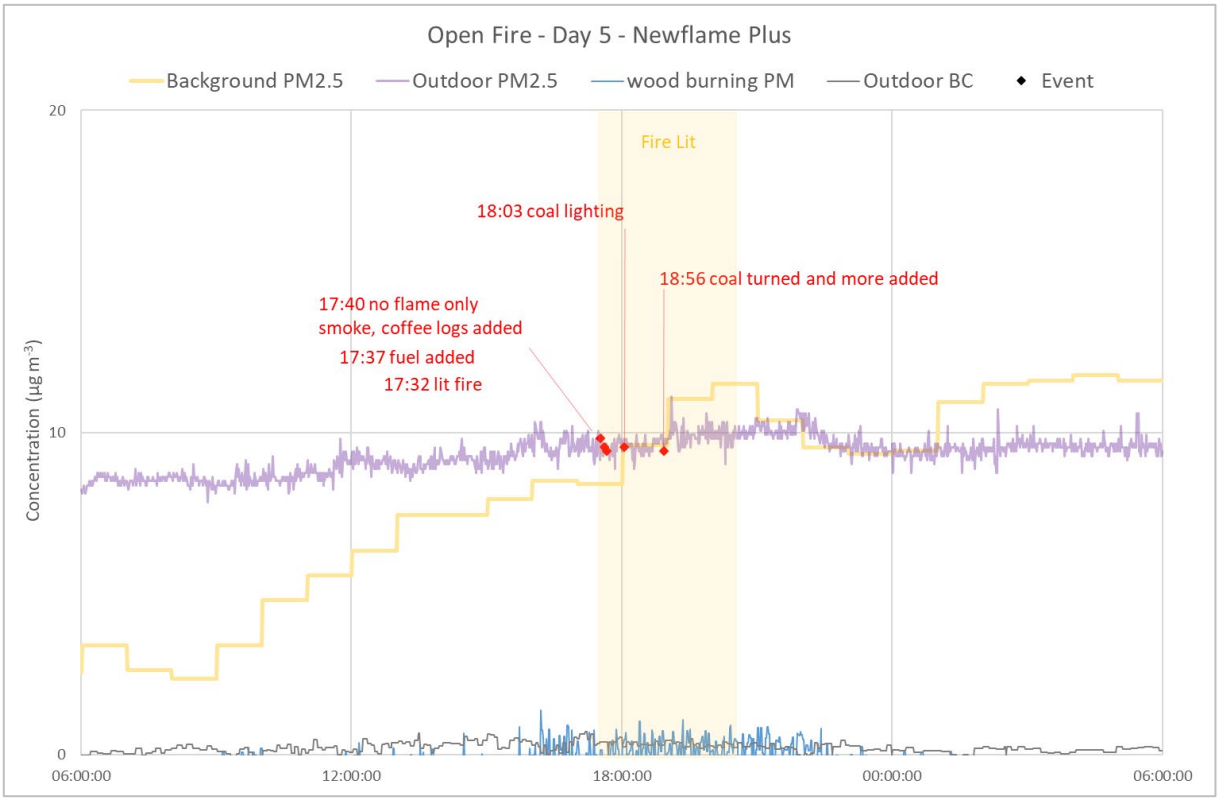
Indoor measurements from Day 5, shown in Figure 5-11, showed $PM_{2.5}$ peaks corresponding to the fire being lit and fuel being added. The fuel on Day 5 was classified as smokeless coal for this project. It had a higher anthracite content than the Ecoal used on Day 3. $PM_{2.5}$ increased from 4 to 9 µg m^{-3} over nine minutes from when the fire was lit a 17:32. Over this time a mix of smokeless fuel and coffee logs were added to the fire as the coal proved difficult to light. A $PM_{2.5}$ peak of 11 µg m^{-3} from 5 µg m^{-3} was observed at 18:01 and soon after at 18:03 it was noted that the fire was alight. Coal was turned and more added at 18:56 and after 30 minutes $PM_{2.5}$ levels began to increase again and reached a peak of 27 µg m^{-3} from 4 µg m^{-3} at 19:23. Corresponding increases in BC of 2 µg m^{-3} and UV of 5 µg m^{-3} were observed. In the absence of any additional notes to the contrary, it must be assumed that these increases were from the fire. $PM_{2.5}$ levels in the living room decreased to 3 µg m^{-3} overnight.

Figure 5-11 Home 1 Indoor measurements when Newflame Plus was burned, annotated with activities that may be expected to affect pollutant concentrations



On Day 5 there was a fresh to moderate breeze of 5 to 10 m s^{-1}, from a SW direction. Outdoor measurements from Day 5 are displayed in Figure 5-12. The wind direction was adverse to picking up emissions directly from the home. Outdoor $PM_{2.5}$ was stable, varying by only 1-2 µg m^{-3} from midday and during the time that the fire was alight. Small quantities of WBPM, up to 1 µg m^{-3} were measured but did not coincide with fire events.

Figure 5-12 Home 1 Outdoor measurements when Newflame Plus was burned, annotated with activities that may be expected to affect pollutant concentrations



5.1.1.6 Home 1 Summary

Overall, the greatest $PM_{2.5}$ concentrations measured inside Home 1 were a result of cooking activities. Over the five days $PM_{2.5}$ peaks of 263 µg m^{-3} corresponded to use of the toaster and grill, 125 and 63 µg m^{-3} to use of grill, 76 and 42 µg m^{-3} to use of the oven, 51 µg m^{-3} to use of hob and 22 µg m^{-3} to use of a sandwich maker. The participant confirmed that for many of the cooking events the extractor fan was not in use.

A summary of all increases in indoor concentrations of $PM_{2.5}$, UV, and BC due to events associated with the open fire, is shown in Table 5-3. On four days an increase in $PM_{2.5}$ was observed when the fire was lit. Lighting the fire involved using firelighters and kindling and the addition of fuel.

Table 5-3 Summary of PM2.5, UV & BC measurement increases indoors at Home 1

Day	Fuel	Lighting Fire	Fuel Add 1	Fuel Add 2	Fuel Add 3	Fuel Add 4
		PM2.5, UV, BC Increase (µg m^{-3})				
1	**Kiln dried wood**	6,0,0	0,0,0			
2	**Coffee Logs**	0,0,0	0,0,0	0,0,0	0,0,0	
3	**Ecoal**	8,0,0	0,0,0			
4	**Unseasoned wood**	13,0,0	0,0,0			
5	**Newflame Plus**	5,0,0*	6,0,0**	23,5,2		

* kiln dried logs also added

** coffee logs also added

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The firelighters used contained Kerosene and it is possible this may have caused an increase in $PM_{2.5}$. On more than one occasion, the participant noted an increase on the $PM_{2.5}$ monitor display when handling the firelighters before any lighting took place. On one occasion on Day 3 an initial spike in $PM_{2.5}$ from 3 to 22 µg m^{-3} was observed one minute before the fire was lit.

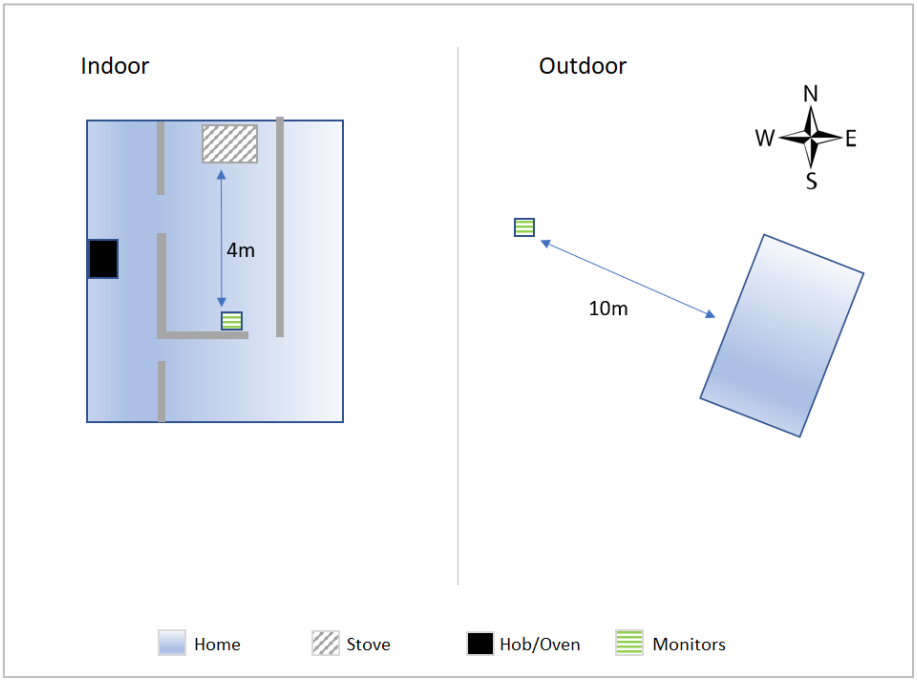
Increases in $PM_{2.5}$ of 6,0,8,13 and 5 µg m^{-3} were observed indoors after the fire was lit on Days 1-5 respectively. The greatest increase in $PM_{2.5}$ concentration measured after the fire was lit was on Day 4 when unseasoned wood was also used to light the fire and there was an increase of 13 µg m^{-3}. There were only two instances over the five days when the addition of fuel to the fire resulted in an increase in $PM_{2.5}$ in the living room. On Day 5 approximately 10 minutes after the smokeless coal Newflame Plus and coffee logs were added to the fire $PM_{2.5}$ increased by 6 µg m^{-3} and later on the same day when Newflame Plus was added and the existing coal in the fire was turned, $PM_{2.5}$ increased by 23 µg m^{-3}. UV and BC indoor concentrations increased by 5 and 2 µg m^{-3} at the same time.

Detection of emissions from the fire outside the property was hindered by the wind direction relative to the location of the instruments outside the home over the five test days. The SW, W and NW breeze would have blown emissions from the fire away from the monitors in the garden, although some very local turbulence may have been present. Wind direction and wind speed measurements were hourly averages so there could have been variations over shorter time periods, which may have affected dispersion of emissions from the home. With this in mind, on Day 1 there was an increase in $PM_{2.5}$ from 10 to 13 µg m^{-3} in the garden immediately after kiln dried logs were added to the fire. Corresponding increases in BC from 0.4 to 1.9 µg m^{-3} and WBPM up to 2 µg m^{-3} were also noted. On Day 2 after the fire was lit and coffee logs were added, although $PM_{2.5}$ levels were generally unchanged, WBPM increased slightly by < 1 µg m^{-3}. On Day 4, in almost calm conditions after the fire was lit and unseasoned wood added, $PM_{2.5}$ measured outside the home increased from 19 µg m^{-3} to 24 µg m^{-3}. A similar increase in WBPM may indicate that unseasoned wood burning emissions were responsible for the increase. In some cases, the measurements indicated possible detection of emissions from neighbouring homes. It is likely that emissions from Home 1 may similarly have resulted in increased pollutant concentrations at the homes of neighbours.

5.1.2 Home 2 – DEFRA Exempt Stove

Home 2 was a semi-detached suburban property in London with neighbouring houses to the northeast and southeast and a garden. It was bordered to the west and south by a train line and beyond that, residential homes. It was approx. 70 m south of an A route which ran in a SW NE direction. Between the A route and the home was a green space. The home was in a smoke control area (SCA) and wood burning was permitted using the DEFRA exempt stove. The monitoring station was set-up in the home's garden, 10m in a NW direction from the house and approx. 1 m off the ground. Indoors, the monitors were set-up in the living room, approx. 4m opposite the stove. The hob/oven in the kitchen area and the room with the monitors were connected by a door. The door was open and closed at different times over the study period, but this was not recorded. A plan of both indoor and outdoor monitoring is shown in Figure 5-13.

Figure 5-13 Plan of indoor & outdoor monitoring at Home 2



Fuel burning tests were carried out over five 24-hour periods from 06:00 in the morning to 06:00 the following morning, between 17th January 2023 and 22nd January 2023. On each of the Days 1-5, a different fuel was burned in the stove. Fuel burning typically took place from the afternoon or evening, to later in the evening of the same day. Table 5-4 lists which fuel was burned on each day.

Table 5-4 Test dates and fuel burned at Home 2

Date	Day	Fuel Type	Brand
Tue 17 Jan 2023 06:00 - Wed 18 Jan 2023 06:00	**Day 1**	Seasoned/ Kiln Dried Wood	Homefire Kiln Dried Logs
Wed 18 Jan 2023 - Thurs 19 Jan 2023 06:00	**Day 2**	Exempt MSF	Bio-Bean Coffee Logs
Thurs 19 Jan 2023 06:00 - Fri 20 Jan 2023 06:00	**Day 3**	Authorised MSF	Homefire Ecoal
Fri 20 Jan 2023 06:00 - Sat 21 Jan 2023 06:00	**Day 4**	Unseasoned Wood	-
Sat 21 Jan 2023 06:00 - Sun 22 Jan 2023 06:00	**Day 5**	Smokeless "Coal"	Maxibrite Newflame Plus

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Photos of monitors in situ and of the stove, including burning of various fuels over the test days, are shown in Figure 5-14. Meteorological data over the test days was taken from London City Airport and is presented in Table 5-4.

Figure 5-14 Photos from Home 2 of Indoor monitors, unseasoned wood burning, coffee logs burning, outdoor monitoring, Ecoal burning and the stove with fans in place.

Table 5-5 Meteorological data for monitoring Days 1-5 at London City Airport

	Day 1																							
Time (h)	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	1	2	3	4	5
Temp (Deg C)	-2	-2	-2	-2	-1	1	1	2	2	2	2	2	1	1	0	0	0	-1	-1	-1	-1	-1	-1	-1
Wind Direction (deg)	**230**	**240**	**NA**	**NA**	**340**	**290**	**355**	**290**	**302**	**300**	**290**	**290**	**280**	**268**	**240**	**240**	**230**	**220**	**226**	**240**	**235**	**240**	**230**	**226**
Wind Speed(m/s)	1.0	1.0	0.5	1.0	1.5	1.0	1.5	1.5	1.8	2.6	2.6	3.1	3.1	2.6	2.6	3.1	3.1	3.1	2.6	2.9	3.6	3.6	3.1	3.6
	Day 2																							
Time (h)	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	1	2	3	4	5
Temp (Deg C)	-1	0	0	1	2	3	4	5	5	5	5	4	4	4	4	3	2	2	2	1	1	0	0	0
Wind Direction (deg)	**240**	**240**	**245**	**230**	**250**	**255**	**269**	**285**	**300**	**285**	**290**	**284**	**265**	**261**	**275**	**234**	**255**	**260**	**252**	**235**	**230**	**235**	**240**	**225**
Wind Speed(m/s)	4.1	3.6	3.9	4.4	3.9	4.1	4.6	5.4	4.9	4.9	3.9	4.6	4.9	3.9	3.9	3.6	3.6	3.4	3.1	3.4	2.9	3.1	3.1	2.1
	Day 3																							
Time (h)	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	1	2	3	4	5
Temp (Deg C)	0	-1	0	1	2	4	4	5	5	5	4	4	3	3	3	3	3	2	2	1	1	1	1	1
Wind Direction (deg)	**215**	**238**	**235**	**235**	**240**	**235**	**240**	**266**	**290**	**300**	**296**	**295**	**285**	**285**	**290**	**280**	**267**	**250**	**250**	**240**	**245**	**250**	**240**	**236**
Wind Speed(m/s)	2.6	2.6	3.6	2.6	2.6	2.9	2.6	3.1	3.6	3.6	3.6	2.9	3.4	3.4	4.4	4.6	4.6	4.4	4.1	4.1	2.9	5.2	3.9	3.6
	Day 4																							
Time (h)	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	1	2	3	4	5
Temp (Deg C)	1	3	3	4	5	5	6	6	6	6	6	5	5	5	4	3	3	3	3	3	3	2	1	1
Wind Direction (deg)	**255**	**272**	**280**	**280**	**285**	**290**	**300**	**289**	**300**	**300**	**305**	**300**	**305**	**325**	**340**	**300**	**320**	**330**	**NA**	**360**	**66**	**60**	**NA**	**100**
Wind Speed(m/s)	3.6	4.7	5.4	4.1	3.9	4.9	5.7	5.2	4.1	4.9	4.9	3.4	2.9	3.1	2.9	2.1	2.1	1.8	0.8	1.0	1.8	1.1	0.5	0.8
	Day 5																							
Time (h)	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	1	2	3	4	5
Temp (Deg C)	1	1	1	2	4	5	6	6	6	6	5	5	3	2	1	0	NA	0	0	-1	-1	-1	-2	-2
Wind Direction (deg)	**57**	**340**	**300**	**NA**	**NA**	**NA**	**130**	**85**	**75**	**80**	**94**	**70**	**NA**	**NA**	**NA**	**NA**	**NA**	**NA**	**NA**	**280**	**NA**	**NA**	**NA**	**280**
Wind Speed(m/s)	2.1	0.8	1.3	0.5	1.0	1.0	1.6	3.1	3.4	2.6	2.3	1.6	0.3	0.0	0.3	0.0	NA	0.0	0.8	0.8	0.3	0.3	0.5	0.5

5.1.2.1 Home 2, Day 1 – Seasoned/Kiln-dried wood

Kiln-dried or seasoned wood was used as the fuel on Day 1. Plots of indoor measurements are displayed in Figure 5-15.

There was a small spike in $PM_{2.5}$, with concentrations increasing briefly, from 12 µg m^{-3} to 15 µg m^{-3} at 18:10 when the stove was lit, and fuel added. A small increase was observed in the UV absorption of 2 µg m^{-3} and BC of 1µg m^{-3}. At 18:18 when the stove door was closed $PM_{2.5}$ increased from 12 µg m^{-3} up to 17 µg m^{-3}. UV and BC did not increase at 18:18. From 18:40 onwards six large distinct $PM_{2.5}$ peaks occurred over the remainder of Day 1. At 18:42 $PM_{2.5}$ increased from 16µg m^{-3} to 27 µg m^{-3} and at 19:46 $PM_{2.5}$ increased from 18 µg m^{-3} to 41 µg m^{-3}. Both these peaks followed events of cigarette smoking and adding fuel to the stove, so it was unclear which event was responsible. However, no significant $PM_{2.5}$ increase was observed when fuel was added at 18:58. Logs were added to the stove at 20:48 and a cigarette was smoked at 20:55. $PM_{2.5}$ increased almost immediately after the cigarette was smoked and over the next 20 minutes from 20 µg m^{-3} to 48 µg m^{-3}. The increase immediately following lighting of the cigarette would suggest that the cigarette smoke was responsible for the peak rather than the addition of fuel. No change to $PM_{2.5}$ was observed when logs were added to the stove at 21:33. $PM_{2.5}$ increased again from 24 µg m^{-3} to 41 µg m^{-3} over 15 minutes at 22:08 after a cigarette was lit. This again suggests that cigarette smoke was responsible for the $PM_{2.5}$ increases rather than fuel being added to the stove. At 23:21 an increase in $PM_{2.5}$ from 22 µg m^{-3} to 32 µg m^{-3} over 10 minutes was observed corresponding to an event when embers in the stove were broken down at 23:20 and a cigarette was smoked 23:21. At 00:50 an increase in $PM_{2.5}$ from 16 µg m^{-3} to 36 µg m^{-3} over 8 minutes, corresponded to cigarette smoking. All the $PM_{2.5}$ peaks on Day 1 had accompanying

increases in the UV signal, which is a tracer species for particulates resulting from biomass burning and would have been expected from burning tobacco and wood. Very small changes in BC were measured corresponding to the larger $PM_{2.5}$ and UV increases observed. It is worth noting that all cigarettes were smoked under the cooker extractor fan in the kitchen, which was switched on.

One cooking event at 20:12, when a stir fry was cooked, was followed immediately by a small increase in $PM_{2.5}$ from 31 µg m^{-3} to 35 µg m^{-3} over 3 minutes, after which $PM_{2.5}$ decreased. There was no change to BC or UV measurements at the time. The cooking event finished at 20:30 by which time $PM_{2.5}$ concentration was at 26 µg m^{-3}. The cooker extractor fan was in use during the cooking event.

Three fans were in operation around the DEFRA exempt stove, two on top and one at floor level in front. These fans are powered by heat from the stove and are popular with stove owners and ensure heat generated by the stove is circulated around the room. When the stove was hot, the fans would have ensured good circulation of air in the room with the monitors, and increased air exchange between rooms adjacent to the living room. The participant commented that there was 'good heat' from the wood logs.

Figure 5-15 Home 2 indoor measurements when Homefire kiln-dried logs were burned annotated with activities that may be expected to affect pollutant concentrations

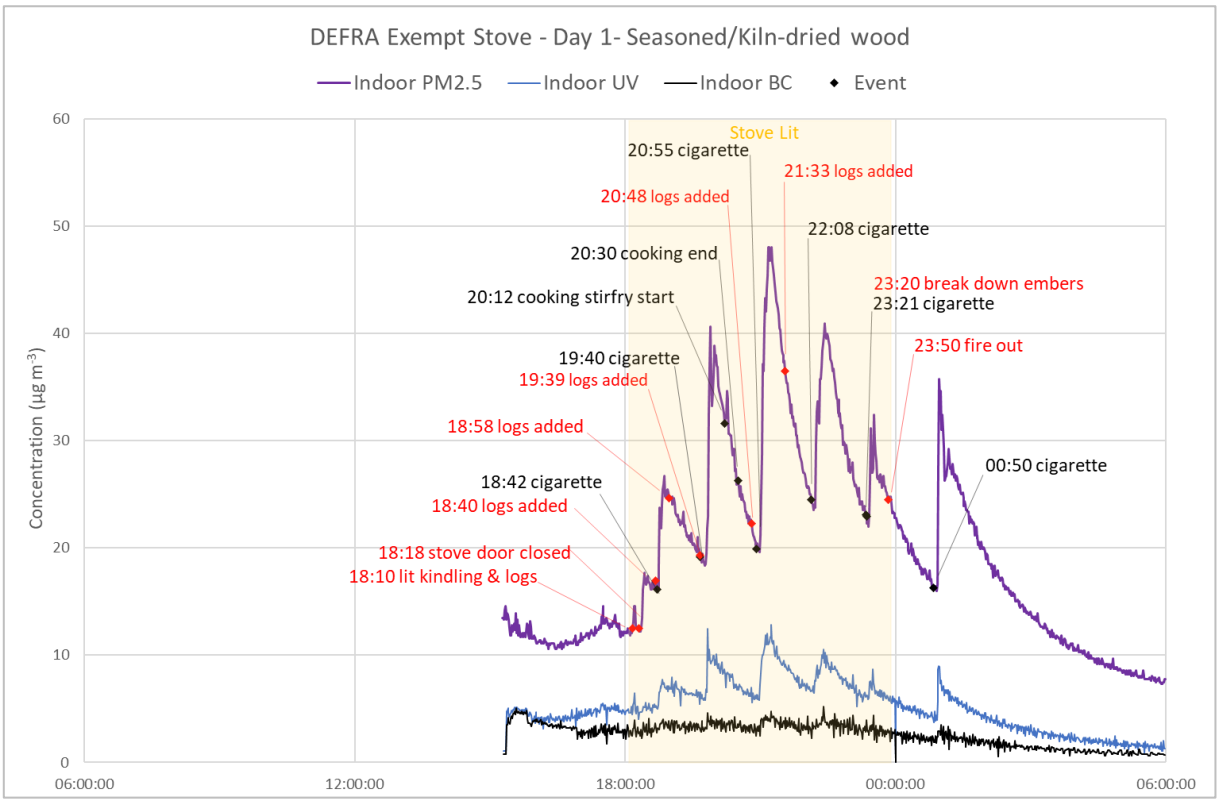

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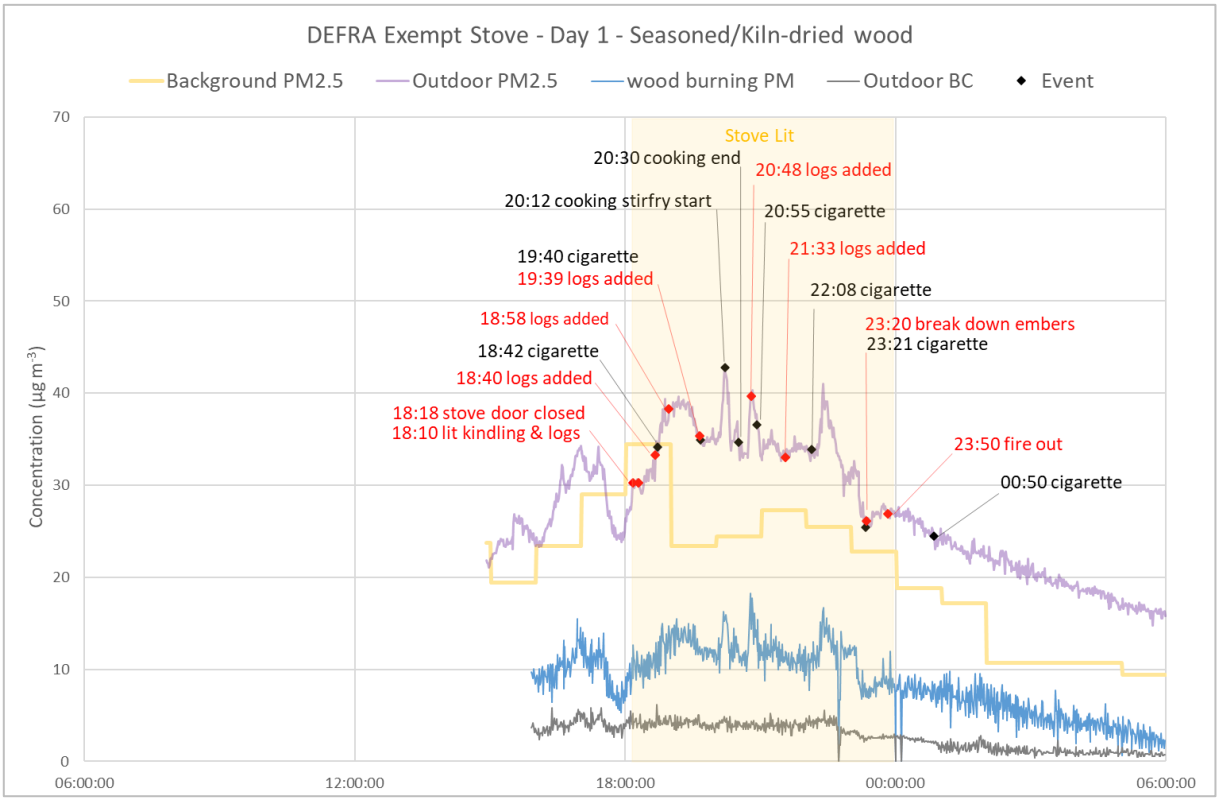
Figure 5-16 Home 2 outdoor measurements when Homefire kiln-dried logs were burned, annotated with activities that may be expected to affect pollutant concentrations



Plots of outdoor measurements at Home 2 on Day 1 are shown in Figure 5-16. The weather was cold with a temperature around freezing all day and a NW light breeze becoming SW. It should be noted with reference to the plan the outdoor monitors for Home 2 in Figure 5-13, that this would not have been a favourable wind direction to pick up emissions from the home on monitors in the garden. Wind from this direction would generally have blown smoke away from the monitors. There may however have been times when emissions from Home 2 could be picked up by the monitors due to a drop in wind activity or a change in circulating air as a result of nearby buildings. Background $PM_{2.5}$ is provided from the closest AURN suburban air quality monitoring site.

In general, there was an increase in $PM_{2.5}$ outside the home in the hours after the fire was lit, compared with background $PM_{2.5}$. Increases in WBPM indicate that solid-fuel and wood burning were significant contributors. This may come from emissions from the stove in Home 2, although it is difficult to point to any one event involving the fire being directly responsible for particular outside measurement increases. Several small $PM_{2.5}$ peaks from approx. 20:00 to 23:00 may have been due to Home 2 stove emissions. During this time kiln-dried logs were added to the stove three times, at 19:39, 20:40 and 21:33. $PM_{2.5}$ increases of 2 to 8 µg m^{-3} and corresponding WBPM increases of 2 to 6 µg m^{-3} were measured. The presence of WBPM would be expected from the burning of kiln-dried logs. The increases in $PM_{2.5}$ and WBPM were not large spikes typically expected when emissions are directly picked up by the monitors but may have been a result of pollutant dispersal around the home. There was no corresponding change to BC concentrations. During other periods on Day 1, it is likely that due to the wind direction, measurements outdoors were reflective of general pollution in the area from neighbouring residential homes.

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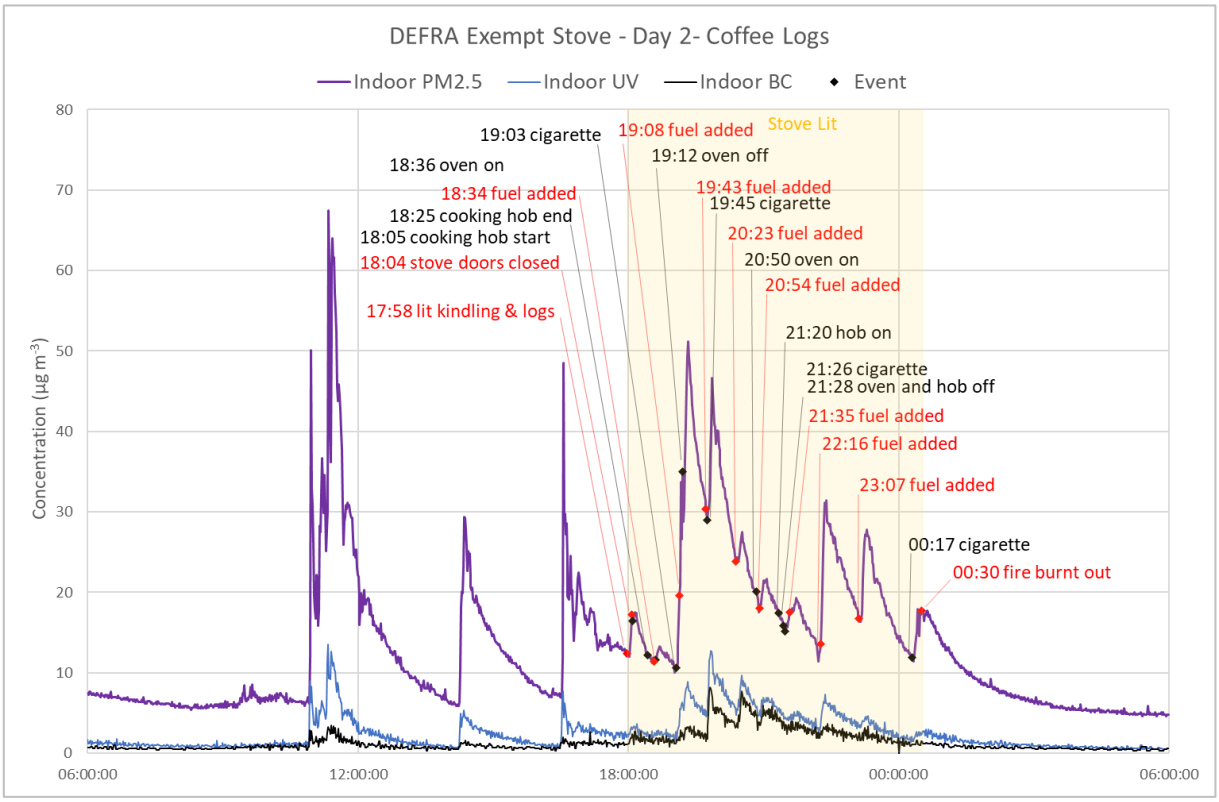
5.1.2.2 Home 2, Day 2 – Coffee Logs

Plots of indoor pollution measurements at Home 2 on Day 2, when Coffee Logs were burned in the stove, are presented in Figure 5-17.

Figure 5-17 Home 2 indoor measurements when Coffee Logs were burned, annotated with activities that may be expected to affect pollutant concentrations

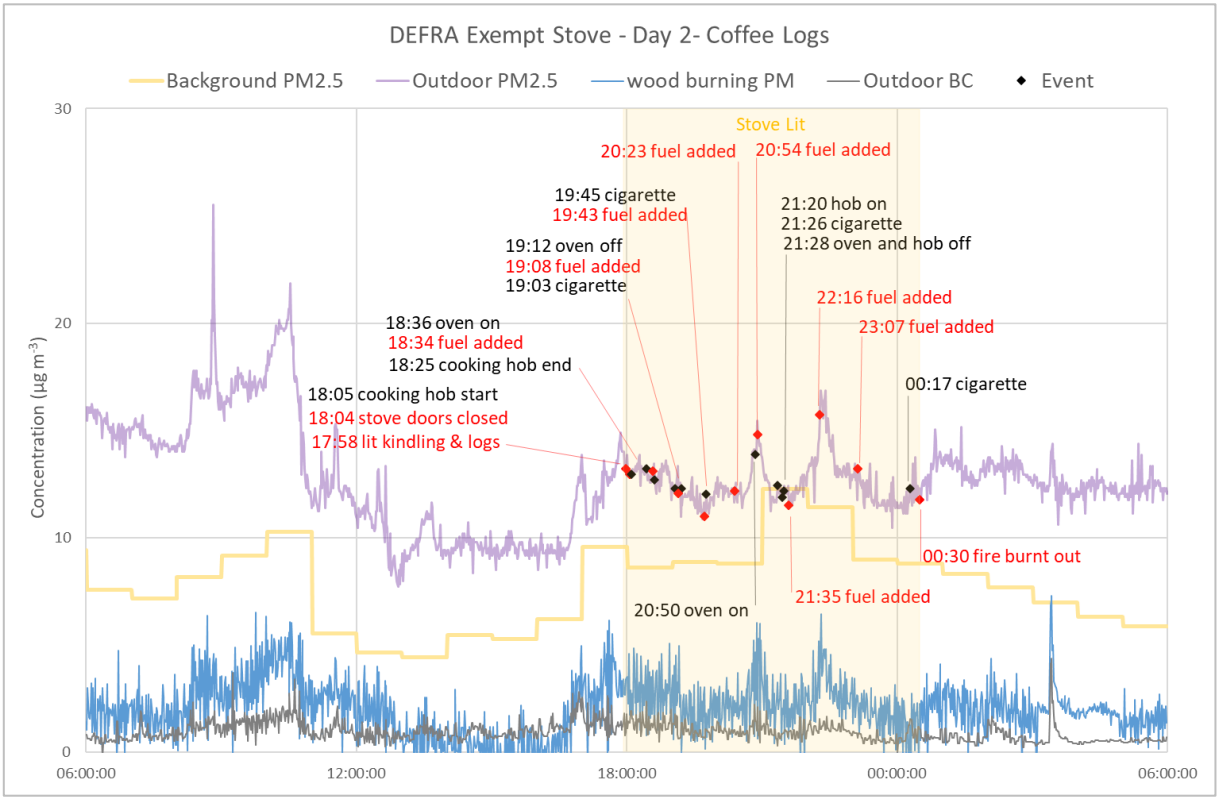


Notes by the participant began when the stove was lit at 17:58, so the source of pollution causing earlier peaks is unknown. At 17:58 when the fire was lit there was an increase in $PM_{2.5}$ of 5 µg m^{-3} and a 1 µg m^{-3} increase in both UV and BC over 6 minutes until the door of the stove was closed. At 18:36 $PM_{2.5}$ increased by 2 µg m^{-3} over 4 minutes with similar small increases in both the UV signal and BC measured, coinciding with the oven being switched on. However, 2 minutes previously at 18:34 fuel was added to the stove and as such it was difficult to confidently attribute this peak to either event. At 19:03 when a cigarette was lit $PM_{2.5}$, UV and to a lesser extent BC began to increase immediately. Concentrations were still increasing when fuel was added to the stove at 19:08 with no evidence that this event had any significant impact on pollution levels. At 19:12 the oven was switched off and presumably the oven door opened. $PM_{2.5}$ which had begun to fall increased immediately again suggesting air from the oven contributed more $PM_{2.5}$. UV data was similarly affected. At 19:43 fuel was added to the stove and at 19:45 a cigarette was lit. $PM_{2.5}$ increased from 29 µg m^{-3} to 46 µg m^{-3} over 6 minutes after the cigarette was lit. Similarly, to Day 1, the increase appeared to be caused by the cigarette rather than the fuel being added. Fuel was added to the stove at 20:23 and $PM_{2.5}$ increased from 24 µg m^{-3} to 27 µg m^{-3} over 7 minutes. UV and BC increased by around 3 µg m^{-3} over the same time period. Four events between 20:20 and 20:35 involving cooking, with the oven and hob, smoking, and adding fuel to the stove appeared to have contributed to increased $PM_{2.5}$ from 15 µg m^{-3} to 19 µg m^{-3} over 13 minutes. At 22:16 fuel was added to the stove, however $PM_{2.5}$ had already begun to increase 3 minutes previously so this may have been caused by an event before that was

not noted. $PM_{2.5}$ continued to rise to a peak of 31 µg m^{-3} from 11 µg m^{-3} over eight minutes with an obvious increase in the UV signal over the same time period. At 23:07 there was a single event when fuel was added to the stove and $PM_{2.5}$ immediately began to increase, reaching a peak of 28 µg m^{-3} from 17 µg m^{-3} over 10 minutes. A UV and BC increase of 2 µg m^{-3} was observed at the same time. At 00:17 a cigarette was smoked and $PM_{2.5}$ increased from 12 µg m^{-3} to 18 µg m^{-3} over 8 minutes. This final event gave a good signature of UV and BC for cigarette smoke with a much higher signal for UV relative to BC.

The participant commented that there was a slight coffee smell whenever the stove door was opened when in use on Day 2, except on one occasion when fuel was added at 22:16. No glowing embers were noted at 00:30 and the fire was considered out at this time. $PM_{2.5}$, UV and BC signals continued to decrease to background levels overnight. The participant noted that the Coffee Logs "burnt quickly, constant refills required, and the heat output was low".

Figure 5-18 Home 2 outdoor measurements when Coffee Logs were burned, annotated with activities that may be expected to affect pollutant concentrations



Outside measurements for Day 2 are shown in Figure 5-18. It was a cold day, the maximum temperature during the day was 5 C and freezing at night. There was a gentle SW to NW breeze up to 5 m s^{-1}. This airflow would have blown emissions from the home away from the outdoor monitors. Generally, although higher, the $PM_{2.5}$ outdoors followed the same trend as background $PM_{2.5}$. There were two notable $PM_{2.5}$ peaks after the fire was lit indoors. Soon after fuel was added at 20:23, $PM_{2.5}$ increased from 12 µg m^{-3} to 15 µg m^{-3} over 15 minutes, accompanied by an increase in WBPM of 3.0 µg m^{-3} and BC of < 1 µg m^{-3}. When fuel was added at 21:35, PM2.5 slowly increased from 12 µg m^{-3} to 17 µg m^{-3} over 50 minutes, accompanied by an increase in WBPM of 4.0 µg m^{-3} and BC of < 1 µg m^{-3}.

5.1.2.3 Home 2, Day 3 – Ecoal

Ecoal was burned in the stove on Day 3. The indoor data plot is shown in Figure 5-19.

Two events, cooking and stove use occurred simultaneously for the first 45 minutes after the stove was lit at 18:10 and it is difficult to discern the precise contribution of either. However, once frying stopped at 18:23, $PM_{2.5}$ began to decrease, falling from 28 µg m^{-3} to 24 µg m^{-3} over 16 minutes, and the decrease was unaffected by the stove door being closed. At 18:35 the participant noted a slight smoke escape when the stove door was opened, and fuel added. Initially $PM_{2.5}$ was unaffected continuing its decrease from 26 µg m^{-3} to 24 µg m^{-3} over 9 minutes before increasing from 24 µg m^{-3} to 27 µg m^{-3} over 8 minutes. This second increase was due to the fuel being added at 18:35 as the stove door remained open. UV and BC increased by 4 µg m^{-3} and 2 µg m^{-3} respectively. When fuel was added at 19:22 the decrease in $PM_{2.5}$ which began 3 minutes earlier was unaffected. A large peak at 20:28 does not correspond to any event in the participant's notes. At 21:08 the decrease in $PM_{2.5}$ from this large peak was unaffected by fuel being added to the stove. At 21:18 when the stove doors were closed there was a slight increase in $PM_{2.5}$ from 45 µg m^{-3} to 48 µg m^{-3} over 1 minute. The increase was most likely due to an escape of smoke from the stove. UV increased by 2 µg m^{-3} at the same time with no change in BC. At 21:29 a cigarette was smoked and $PM_{2.5}$ increased 4 minutes later from 24 µg m^{-3} to 35 µg m^{-3} over 11 minutes. UV increased by 4 µg m^{-3} with no change in BC. At 22:39 fuel was added, no smoke escape was noted by the owner but there was an increase in $PM_{2.5}$ from 21 to 28 µg m^{-3} over 10 minutes, with UV absorption also increasing by 7 µg m^{-3} at the same time and no change observed in BC. There were no note entries to explain peaks seen later in the evening and at 00:49 it was noted that although there were some red embers still glowing in the stove the fire was almost out. It was noted by the participant that this Ecoal burned quite quickly, and the stove needed to be reloaded regularly and that the heat output was not high.

Figure 5-20 displays outdoor measurements from Home 2 on Day 3. It was a cold day, freezing overnight and a maximum temperature of 5 C during the day with a gentle SW to NW breeze. Emissions from the home would generally have been carried away from the monitors. $PM_{2.5}$ outside the home followed a similar trend to background $PM_{2.5}$. There was an increase in $PM_{2.5}$ from 13 µg m^{-3} to 22 µg m^{-3} over 40 minutes when fuel was added to the stove at 18:35, however this was also noted in background $PM_{2.5}$ so was probably more coincidental. Over the same time WBPM increased by approx. 5 µg m^{-3} and BC increased by approx. 2 µg m^{-3} indicating a contribution of solid-fuel burning emissions to this widespread peak. Outdoor PM2.5 increased from 20 µg m^{-3} to 25 µg m^{-3} soon after fuel was added at 19:22 with a corresponding increase in WBPM and BC of approx. 3 µg m^{-3} and 2 µg m^{-3} respectively. However, because of the wind direction it is difficult to state with any certainty that the two events were related.

Figure 5-19 Home 2 indoor measurements when Ecoal was burned, annotated with activities that may be expected to affect pollutant concentrations

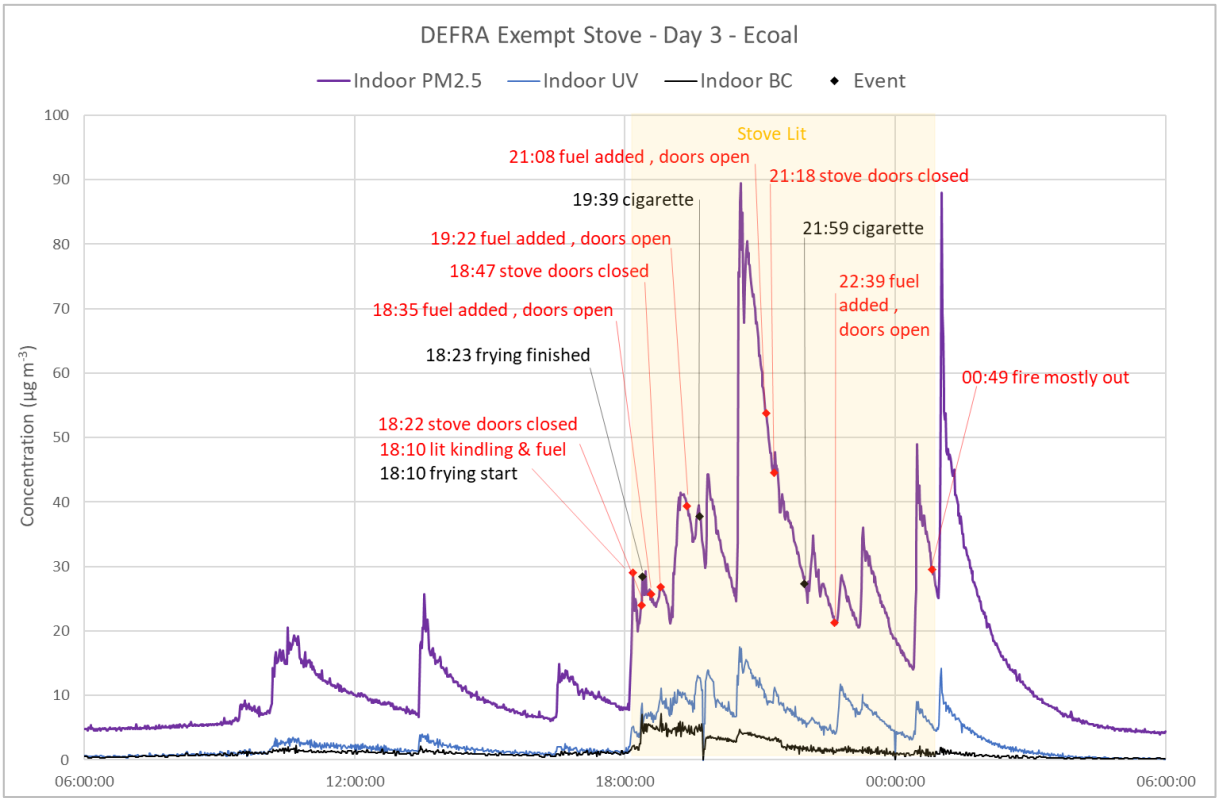
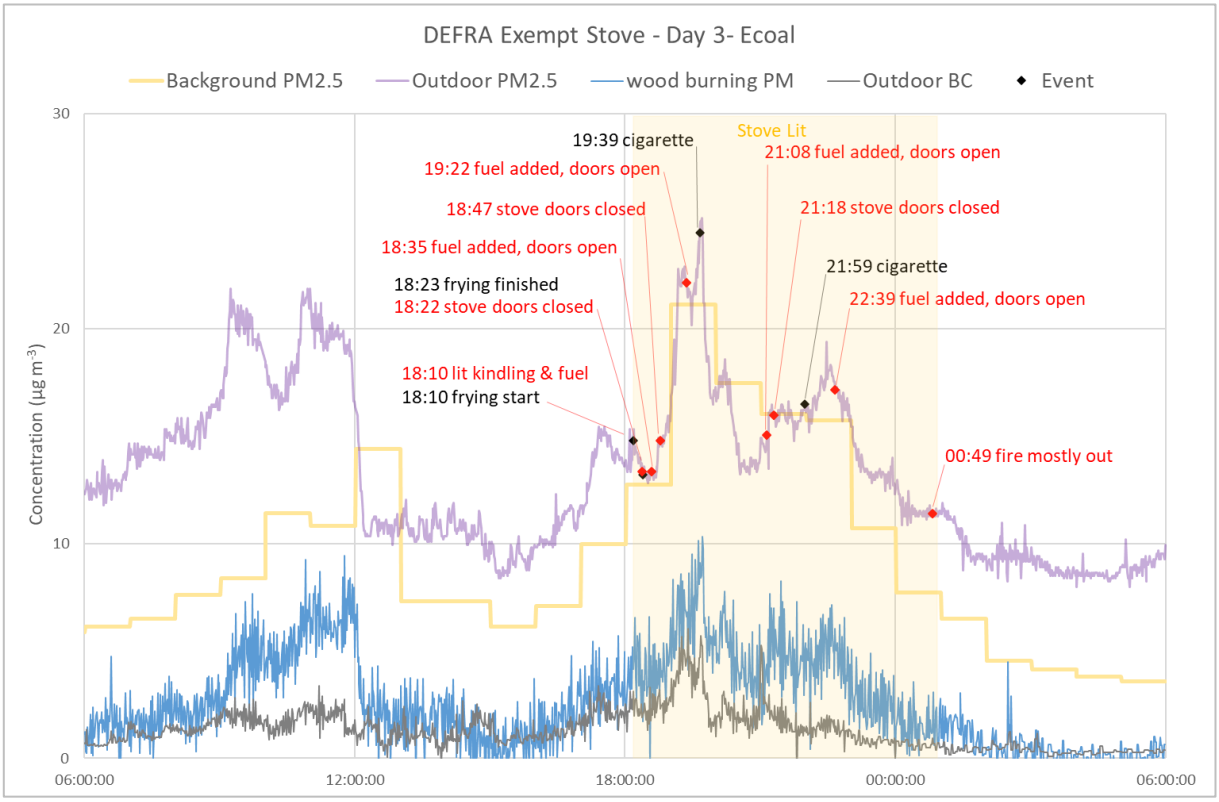


Figure 5-20 Home 2 outdoor measurements when Ecoal was burned, annotated with activities that may be expected to affect pollutant concentrations



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5.1.2.4 *Home 2, Day 4 - Unseasoned wood*

Unseasoned wood provided by the participant, was used as fuel in the stove on Day 4. This wood came from felled trees and branches in the participants garden. The moisture content of the wood was measured by the participant at between 17% and 35%. When the fire was lit and fuel added at 16:40, $PM_{2.5}$ increased from 11 µg m^{-3} to 31 µg m^{-3} over 19 minutes until the stove door was closed. UV and BC increased at the same time by < 1 µg m^{-3}. Fuel was added at 17:45 and again at 18:33 but there was no noticeable change in $PM_{2.5}$, UV or BC levels. At 21:14 there was a single event when logs were added to the stove, $PM_{2.5}$ increased from 15 µg m^{-3} to 25 µg m^{-3} over 13 minutes. At the same time UV absorption increased by 5 µg m^{-3} and BC increased by < 1 µg m^{-3}. At both 20:33 and 21:12 fuel was added to the stove, however a cigarette was lit 5 and 3 minutes later respectively and it was difficult to interpret to what extent each event contributed to the subsequent peak, although there appeared to be a closer match between cigarette smoking than the fuel being added. There were no subsequent notes to explain the $PM_{2.5}$ peaks from midnight and it was observed that the fire was out at 00:15. A slight smoky smell was noticed by the participant each time the stove doors were opened to add fuel, at 17:45 there was a strong smoky smell. It was also noted that the fuel was 'slow to light, but burnt well and had a good high heat output'

The outdoor data plot is presented in Figure 5-22. There was a light NW breeze throughout the day likely to blow emissions from the home away from the monitor. Although $PM_{2.5}$ outside the home was higher, it generally followed the background $PM_{2.5}$ and as a result it is likely most of the outside measurements were due to local neighbourhood pollution. Elevated WBPM and BC pointed to solid-fuel burning emissions contributing. Soon after fuel was added to the stove at 22:12 outdoor $PM_{2.5}$ increased from 13 µg m^{-3} to 17 µg m^{-3} over 15 minutes and WBPM increased by 3 µg m^{-3}. It is possible Home 2 fuel burning emissions contributed, but not certain due to wind direction.

Figure 5-21 Home 2 indoor measurements when unseasoned wood was burned, annotated with activities that may be expected to affect pollutant concentrations

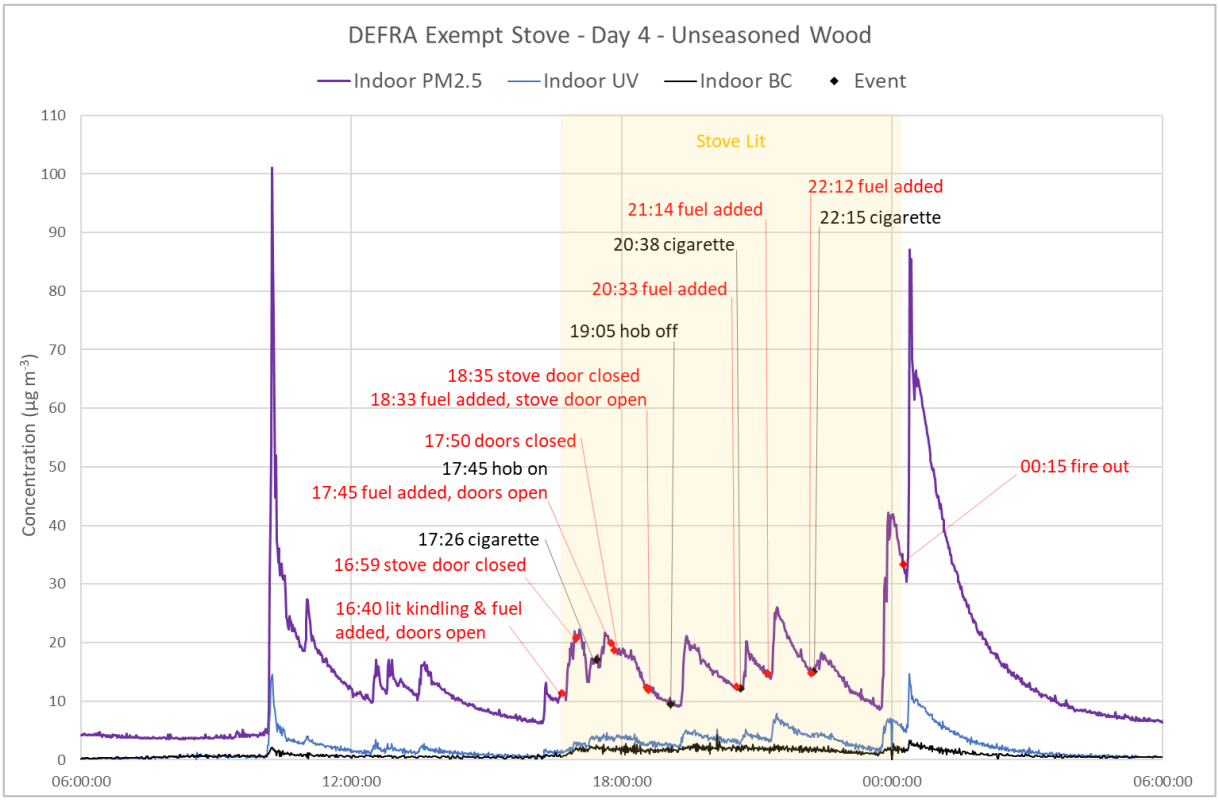

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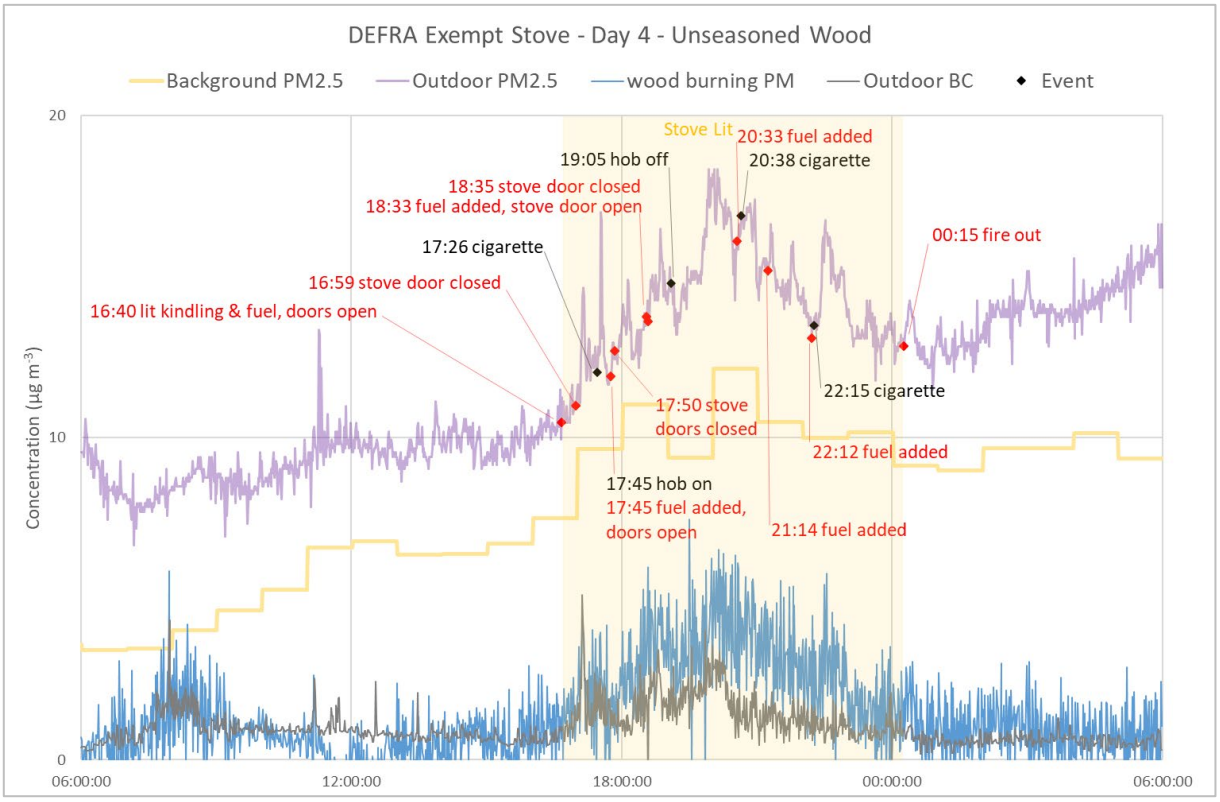
Figure 5-22 Home 2 outdoor measurements when unseasoned wood was burned, annotated with activities that may be expected to affect pollutant concentrations



5.1.2.5 Home 2 Day 5 – Newflame Plus

Newflame Plus was the fuel burned in Home 2 on Day 5. There was poor correlation between events in the home and peaks observed and it was difficult to attribute any event definitively to any change in concentration. Although cigarettes were recorded on previous days, they were not recorded on Day 5 so it is possible this missing information may have helped to identify some of the peaks. The participant commented that the Newflame Plus was very difficult to light and it had 'low heat emission'.

Outdoors at Home 2 on Day 5 there was a very light mostly NE breeze with little or no wind activity for the second half of the day. It is possible that in calm conditions, the monitors could pick up emissions from the stove in Home 2. Temperatures were close to freezing during early morning and evening and below freezing overnight. Outdoor data is shown in Figure 4-24. $PM_{2.5}$ outside the home and background $PM_{2.5}$ increased steadily from 17:00 corresponding to the onset of still and cold conditions leading to poor dispersion. This caused a widespread pollution episode with a contribution from solid-fuel affecting London which started on the evening of these measurements and can also be seen in Figure 5-64 in section 5.3 which provides details of measurements from fixed aethalometer sites.

High WBPM > 30 µg m^{-3}, BC >10 µg m^{-3} and outdoor and Background $PM_{2.5}$ > 70 µg m^{-3} were observed. We would expect measurement of the home's emissions to be characterised by sharp increases in levels and this was observed on two occasions. At 17:10 when the fire was lit, $PM_{2.5}$ increased from 20 µg m^{-3} to 26 µg m^{-3} over 6 minutes, WBPM increased by 1 µg m^{-3}. Also, at 17:30 when $PM_{2.5}$ increased from 21 µg m^{-3} to 36 µg m^{-3} over 10 minute, accompanied by an increase in the WBPM concentration of 4 µg m^{-3}.

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Figure 5-23 Home 2 Indoor measurements when Newflame Plus was burned, annotated with activities that may be expected to affect pollutant concentrations

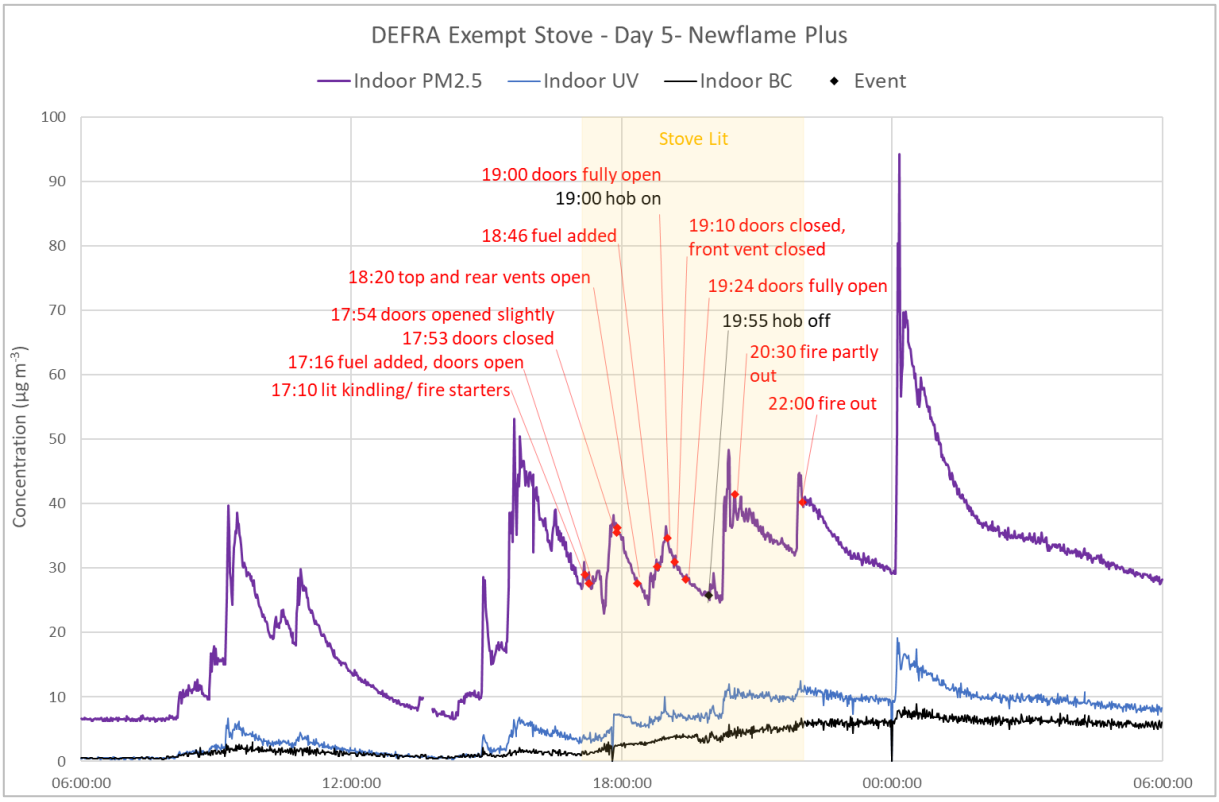
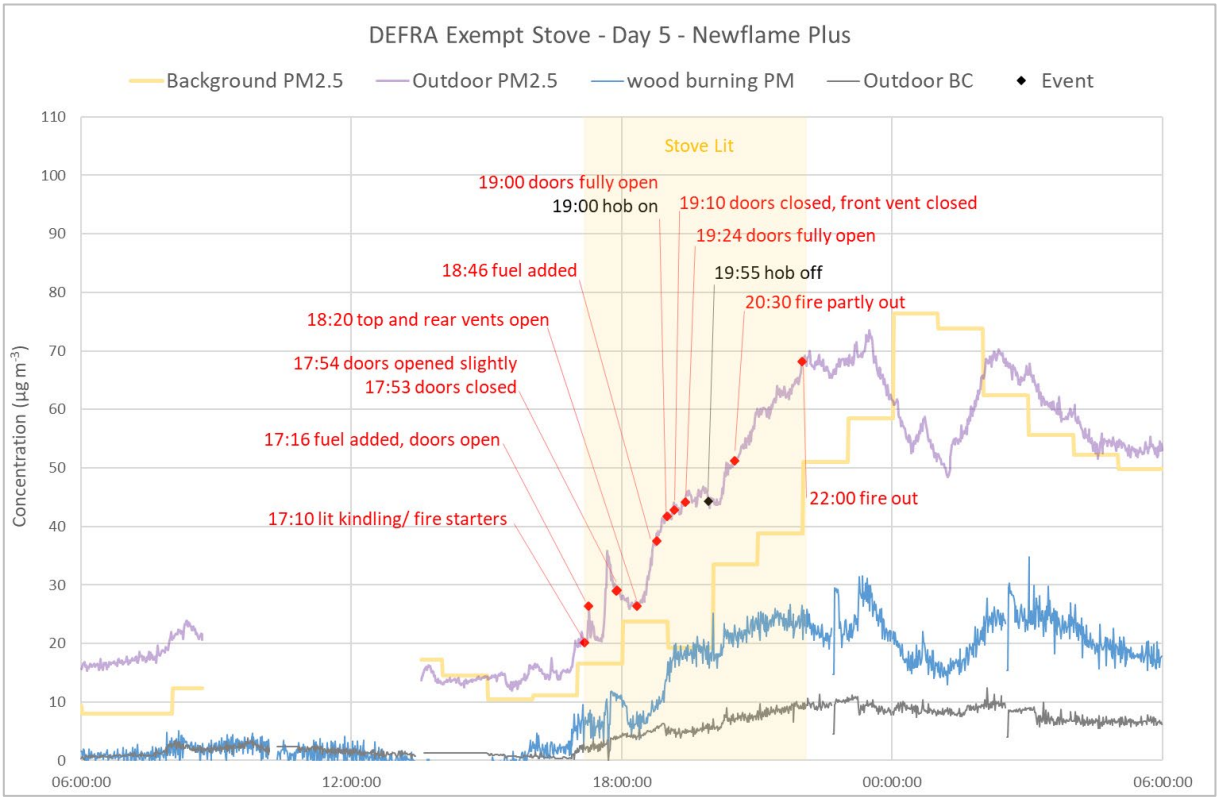


Figure 5-24 Home 2 outdoor measurements when Newflame Plus was burned, annotated with activities that may be expected to affect pollutant concentrations



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5.1.2.6 Home 2 Summary

Many events in Home 2 which involved interaction with the stove coincided very closely with cigarette smoking or cooking events. Despite cigarettes being smoked in a different room, the evidence was that increases at these times were mostly if not entirely due to the cigarette smoke rather than emissions from the stove. It was not possible to quantify the stove's contribution, if any, to these increases. Where any two events occurred close together and it was unclear of the exact contribution of either, measurement data was not included in further analysis.

Over Days 1-5 there were six separate standalone smoking events. For these events $PM_{2.5}$ in the living room increased between 6 and 28 µg m^{-3}. UV increased between 1 and 6 µg m^{-3} and BC increased between 0 and 2 µg m^{-3}. Cigarettes were smoked in the kitchen under the extraction fan, but these emissions were detected in the living room which demonstrated how indoor pollutants moved around the home. There was one standalone cooking event when a stir fry was cooked. With the extraction fan on, $PM_{2.5}$ increased by 4 µg m^{-3} with no corresponding increase in UV or BC observed.

A summary of all increases in indoor concentrations of $PM_{2.5}$, UV, and BC due to events associated with the DEFRA Exempt stove, is shown in Table 5-6.

Table 5-6 Summary of PM2.5, UV & BC measurement increases indoors at Home 2

Day	Fuel	Lighting Fire	Fuel Add 1	Fuel Add 2	Fuel Add 3	Fuel Add 4
		PM2.5, UV, BC Increase (µg m^{-3})				
1	**Kiln dried wood**	3,2,1	0,0,0	0,0,0		
2	**Coffee Logs**	5,1,1	3,4,4	11,2,2		
3	**Ecoal**		3,4,2	3,2,0	7,7,0	
4	**Unseasoned wood**	20,0,0	0,0,0	10,5,0		
5	**Newflame Plus**					

On the three days when it was possible to measure the individual fire lighting event, $PM_{2.5}$ increased when the fire was lit. Lighting the fire involved using firelighters, kindling and the addition of fuel. The highest $PM_{2.5}$ concentration increases during fire lighting were measured at 20 µg m^{-3} associated with burning unseasoned wood.

There were in total nine standalone events when the changes in $PM_{2.5}$, UV and BC could be measured. Of these, there were six instances when the addition of fuel to the fire resulted in an increase in $PM_{2.5}$ in the living room. Increases ranged from 3-11 µg m^{-3} with the highest concentrations for the addition of Coffee Logs and unseasoned wood. No increase in $PM_{2.5}$, UV or BC concentration was observed for either of the measurable kiln-dried wood fuel additions or one of the Unseasoned wood additions. The highest UV measurements signals were 7 µg m^{-3} on one occasion when Ecoal was added and 5 µg m^{-3} on one occasion when unseasoned wood was added. When Newflame Plus was burned it was not possible to find a standalone event corresponding to fuel addition to calculate increases in the three species.

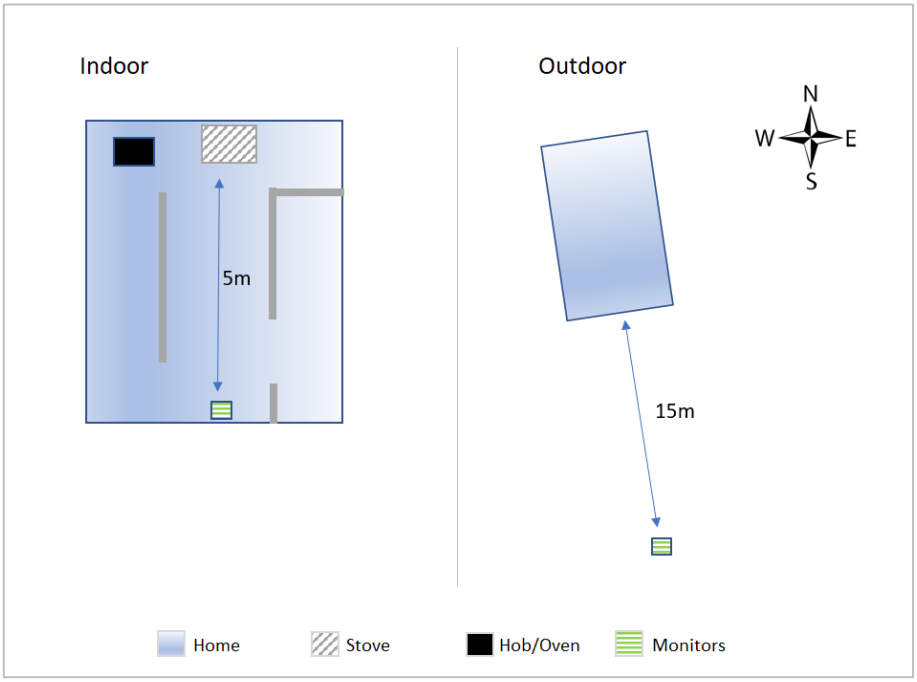
The ability to measure emissions from the fire outside the home was limited by the wind direction over Days 1-4 when a NW or SW breeze would have resulted in emissions being blown away from the monitor in the garden. Over these four days there were instances of gradual increases in concentrations measured by the outdoor monitors. These increases were associated with seven events of fuel being added to the stove.

Increases in $PM_{2.5}$ ranging from 2 to 8 µg m^{-3} with corresponding increases in WBPM from 2 to 6 µg m^{-3} and BC increases up to 2 µg m^{-3} were observed. On Day 5 the wind from NE was in a more favourable direction for the monitor to measure emissions outside. Increases associated with fire lighting and later with adding fuel were observed. $PM_{2.5}$ increases ranged from 6 to 15 µg m^{-3} and WBPM increases ranged from 1 to 4 µg m^{-3} with no change in BC.

5.1.3 Home 3 – clearSkies Level 5 Certified Stove

Home 3 was a terraced suburban property in London. It had a garden to the rear and neighbouring houses immediately to the east and west and another terraced row behind, to the north. The garden backed onto an A route which was approx. 40m to the south. The monitors were set-up in the garden, around 15m SSE of Home 3 and approx. 0.5m in height from the ground. The home was in a smoke control area (SCA) and wood burning carried out using the clearSkies Level 5 category stove. Indoors, the monitors were set-up in the living room, approx. 5m opposite the stove. The hob/oven located in the kitchen area had open access to the monitors. A plan of both indoor and outdoor monitoring is shown in Figure 5-25.

Figure 5-25 Plan of indoor & outdoor monitoring at Home 3



The clearSkies Level 5 stove was a wood burner and only kiln dried or seasoned wood was suitable for use as the fuel. Fuel was burned over four 24-hour periods from 06:00 in the morning to 06:00 the following morning, between 30th January 2023 and 4th February 2023. Fuel burning typically took place from the afternoon or evening, to later in the evening of the same day. On Days 1-2, the study provided kiln-dried wood, kindling and firelighters was used and on Days 3-4 the participant's usual brand of wood (Certainly Wood Fuel) and natural firelighters in addition to the study-provided wood kindling were used. Table 5-7 lists which fuel was burned on each day.

Table 5-7 Test dates and fuel burned at Home 3

Date	Day	Fuel Type	Brand
Mon 30 Jan 2023 06:00 - Tue 31 Jan 2023 06:00	**Day 1**	Seasoned/ Kiln Dried Wood	Homefire Kiln Dried Logs
Tue 31 Jan 2023 06:00 - Wed 01 Feb 2023 06:00	**Day 2**	Seasoned/ Kiln Dried Wood	Homefire Kiln Dried Logs
Wed 01 Feb 2023 06:00 - Thurs 02 Feb 2023 06:00	**Day 3**	Seasoned/ Kiln Dried Wood	Certainly Wood Fuel
Sat 04 Feb 2023 06:00 - Sun 05 Feb 2023 06:00	**Day 4**	Seasoned/ Kiln Dried Wood	Certainly Wood Fuel

Participant photos of the outdoor monitors in situ and of the stove burning wood, are shown in Figure 5-26. Meteorological data from London City Airport for Days 1-4 is presented in Table 5-8.

Figure 5-26 Photos from Home 3 of Outdoor monitors and wood burning

Table 5-8 Meteorological data for monitoring Days 1-4 at London City Airport

	Day 1																							
Time	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	1	2	3	4	5
Temp (Deg C)	8	7	7	7.5	8	8.5	9	9	9	8.5	8	7.5	7	7	6	5	5	4.5	5	5	6	6	6	6
Wind Direction (deg)	**296**	**290**	**280**	**275**	**275**	**286**	**295**	**295**	**295**	**280**	**285**	**275**	**270**	**246**	**225**	**215**	**225**	**235**	**240**	**245**	**240**	**250**	**250**	**240**
Wind Speed(m/s)	5.4	4.6	5.1	5.7	5.4	5.9	6.2	5.4	5.1	4.9	4.9	3.6	4.1	3.1	2.6	2.6	3.1	3.9	3.6	4.1	4.4	5.2	6.5	5.7
	Day 2																							
Time	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	1	2	3	4	5
Temp (Deg C)	6	7	7.5	8	8.5	9.5	11	11	11	11	10	10	9	8.5	8	8	6	6	6	5.5	6	6	6	6
Wind Direction (deg)	**250**	**240**	**250**	**245**	**250**	**250**	**250**	**280**	**286**	**295**	**290**	**280**	**295**	**286**	**270**	**260**	**250**	**255**	**250**	**250**	**250**	**250**	**250**	**250**
Wind Speed(m/s)	6.2	6.0	6.5	6.2	5.7	5.7	6.2	7.2	6.5	5.7	5.2	5.1	3.9	4.7	4.1	5.7	5.1	6.0	5.4	6.0	7.0	6.7	6.5	6.7
	Day 3																							
Time	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	1	2	3	4	5
Temp (Deg C)	6	6.5	7	7.5	8.5	9	11	11	11	10	10	10	9.5	9	9	9	9	9	9	9	8.5	8	7.5	7
Wind Direction (deg)	**250**	**250**	**245**	**250**	**250**	**250**	**260**	**270**	**260**	**260**	**260**	**270**	**255**	**255**	**250**	**260**	**250**	**250**	**250**	**250**	**250**	**250**	**246**	**240**
Wind Speed(m/s)	6.2	6.2	6.5	6.7	7.7	9.1	8.8	8.8	8.5	7.0	7.7	7.2	6.7	7.2	7.0	7.2	7.2	7.0	6.2	6.5	7.0	6.0	4.7	4.9
	Day 4																							
Time	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	1	2	3	4	5
Temp (Deg C)	9	9	9	9	9.5	10	10	10	9	9	9	9	9	9	9	9	9	9	9	9	8.5	8	6.5	5.5
Wind Direction (deg)	**250**	**260**	**280**	**270**	**276**	**259**	**260**	**254**	**275**	**266**	**260**	**240**	**240**	**246**	**250**	**260**	**250**	**246**	**275**	**285**	**300**	**328**	**340**	**350**
Wind Speed(m/s)	3.4	2.6	3.1	2.9	3.1	3.4	4.1	4.6	4.6	4.4	2.6	3.1	3.1	3.6	4.4	3.1	4.1	3.6	4.6	4.9	5.1	4.9	3.9	3.1

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5.1.3.1 Home 3, Day 1 – Seasoned/Kiln dried wood

Home 3 Day 1 indoor data is plotted in Figure 5-27. The stove was lit at 14:18 and fuel added. Fuel was added again at 15:20. There was no increase in $PM_{2.5}$ for any of the initial stove interactions. At 16:25 when the oven was switched on, $PM_{2.5}$ inside the living room began to increase approx. 10 minutes later from a background level of 4 µg m^{-3} to 35 µg m^{-3} over 30 minutes until the stove door was opened and fuel added at 17:05. At this point there was a decrease in $PM_{2.5}$ to 31 µg m^{-3}. It may be that air from the room was drawn into the stove and was replaced by cleaner air. Soon after, at 17:08 $PM_{2.5}$ continued to rise again, either due to emissions from the stove after fuel was added or due to continuing $PM_{2.5}$ from the oven. Ten minutes after the oven was switched on again at 18:30 $PM_{2.5}$ increased from 10 µg m^{-3} to 27 µg m^{-3} over 23 minutes. Fuel was added to the stove at 19:25 and at 20:45 with no obvious increase in $PM_{2.5}$ levels.

Outside data from Day 1 is shown in Figure 5-28. A NW gentle to moderate breeze became SW around 19:00. A NW breeze would have been favourable for monitors in the garden to pick up emissions from the home's stove. When the fire was lit at 14:18 spikes in $PM_{2.5}$, BC and WBPM were evident. There were many $PM_{2.5}$ peaks, the largest up to 31 µg m^{-3} from 4 µg m^{-3} after 10 minutes. At the same time BC increased by 14 µg m^{-3} and WBPM by 16 µg m^{-3}. Spikes in all three species continued immediately after fuel was added at 15:20. $PM_{2.5}$ increased by up to 6 µg m^{-3}, WBPM by up to 7 µg m^{-3} and BC by up to 1 µg m^{-3}. Again, 10 minutes after fuel was added at 17:05 there were spikes in $PM_{2.5}$ from 8 µg m^{-3} to 32 µg m^{-3} and in WBPM from 1 µg m^{-3} to 17 µg m^{-3} over 10 minutes. The BC increase for this event was much smaller at approx. 1 µg m^{-3}. This smaller BC concentration may reflect the different composition of emissions from starting a fire and incomplete combustion at lower temperatures, as opposed to adding fuel to an established fire resulting in more complete combustion at hotter temperatures. The spikes were not repeated for subsequent fuel additions later in the evening, by which time the wind direction had become SW and no longer from the direction of the home. It is notable however, that the WBPM content of $PM_{2.5}$ measured outside was high at approx. 50% with BC at approx. 15% of the $PM_{2.5}$ concentration over the course of the evening. This may indicate a contribution from local solid-fuel burning, and possible detection of traffic emissions from the road reflected in a higher BC measurement when the wind became SE around 19:00.

Figure 5-27 Home 3 indoor measurements when Homefire kiln-dried logs were burned (Day 1), annotated with activities that may be expected to affect pollutant concentrations

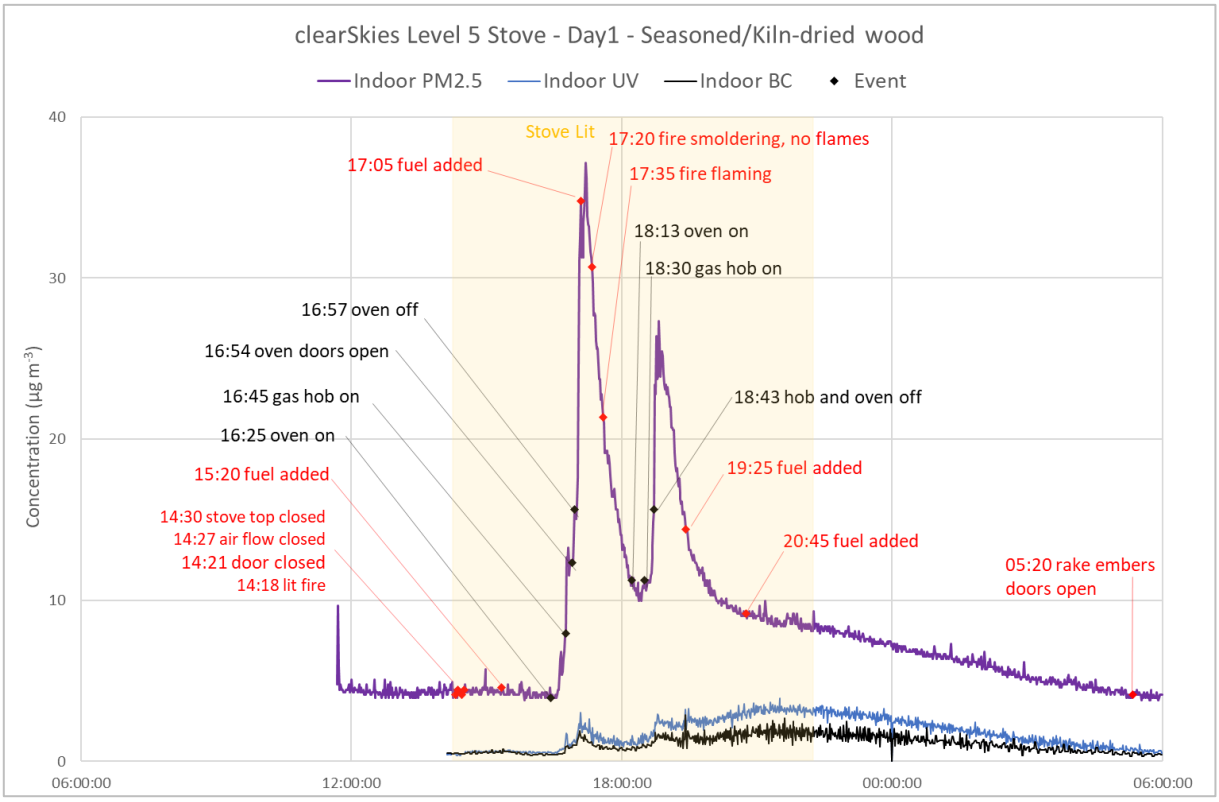
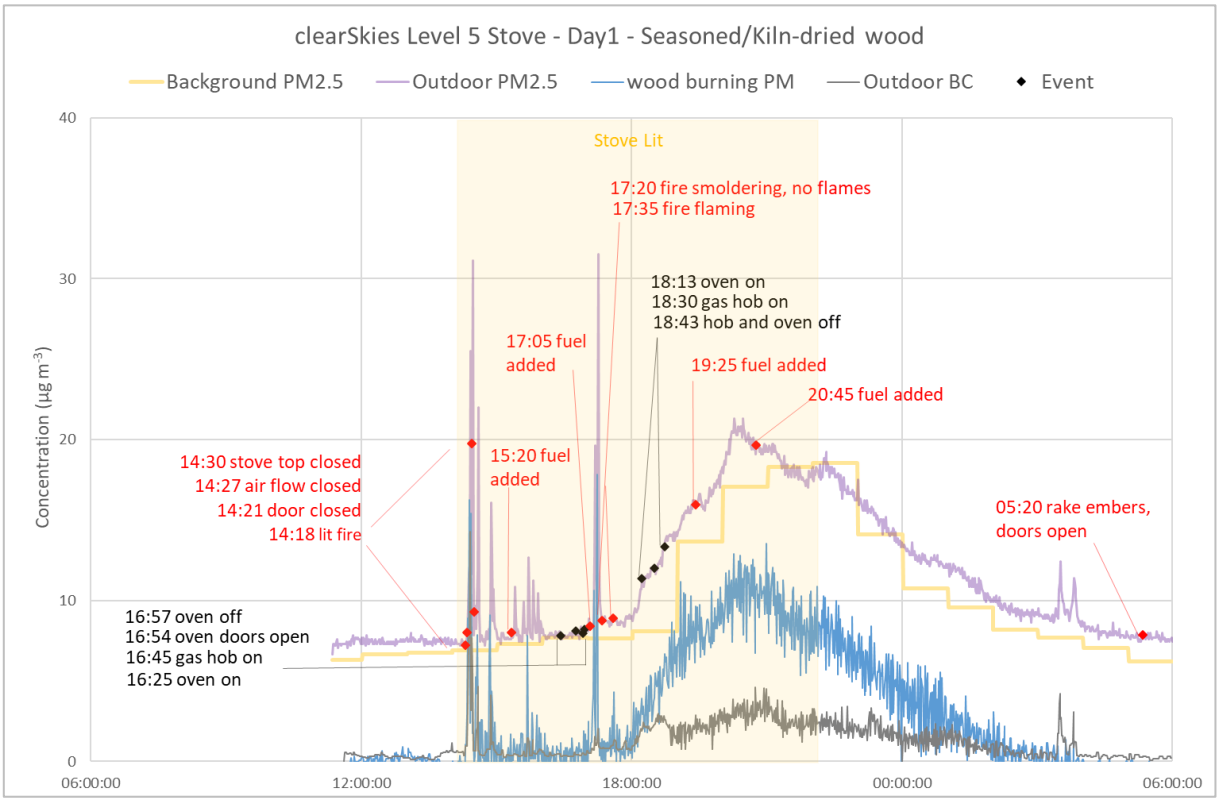


Figure 5-28 Home 3 outdoor measurements when Homefire kiln-dried logs were burned (Day 1), annotated with activities that may be expected to affect pollutant concentrations



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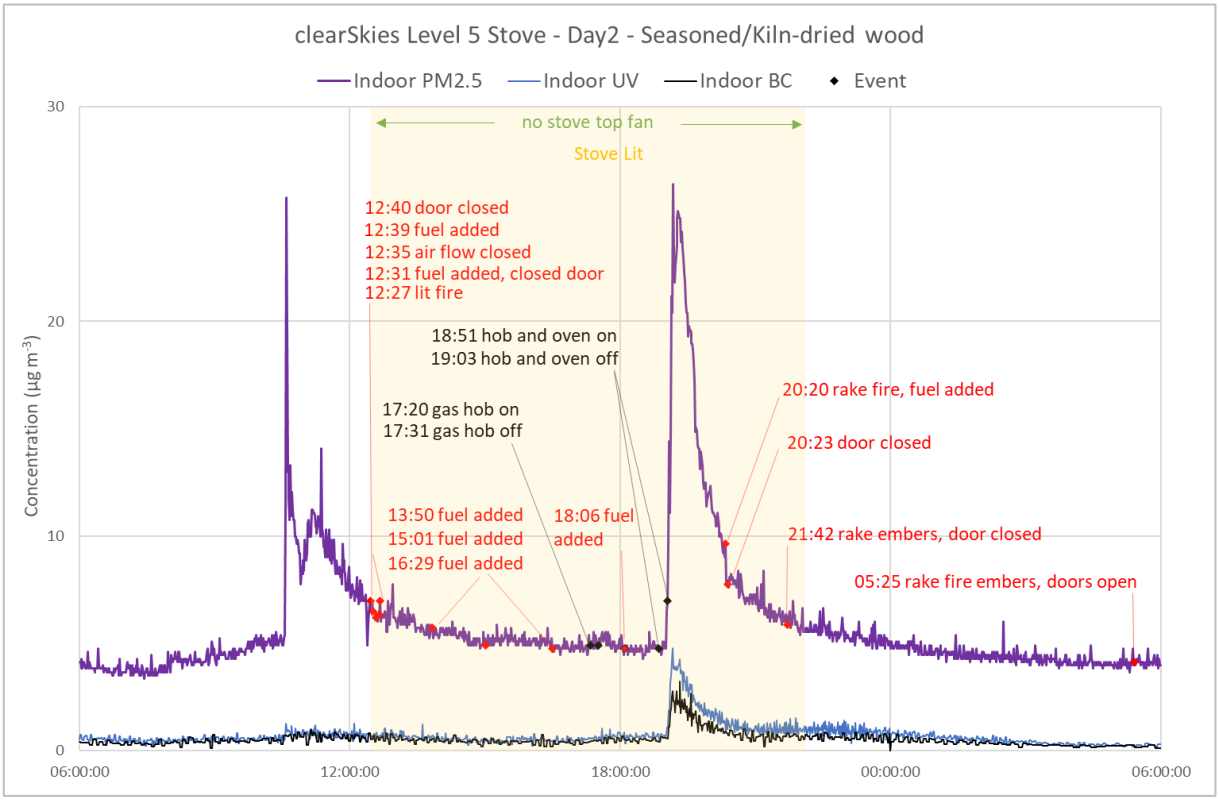
5.1.3.2 Home 3, Day 2 – Seasoned/Kiln dried wood

Figure 5-29 displays indoor data from Day 2. There was only one peak of any significance. Six minutes after the oven was switched on at 18:51, $PM_{2.5}$ increased from 5 µg m^{-3} to 26 µg m^{-3} over 20 minutes. The hob was used to fry an omelette at 18:51 which may also have contributed to increased $PM_{2.5}$. At the same time there was a 4 µg m^{-3} in UV and a 2 µg m^{-3} increase in BC. The stove top fan was not running on Day 2 so there would have been poorer circulation of air indoors. No increase in $PM_{2.5}$, UV or BC was measured after the fire lighting event or the subsequent five events when fuel was added to the stove. Again, as on Day 1 there was a decrease in $PM_{2.5}$ between 20:20 and 20:23 of 2 µg m^{-3} when the door of the stove was left open when fuel was being added.

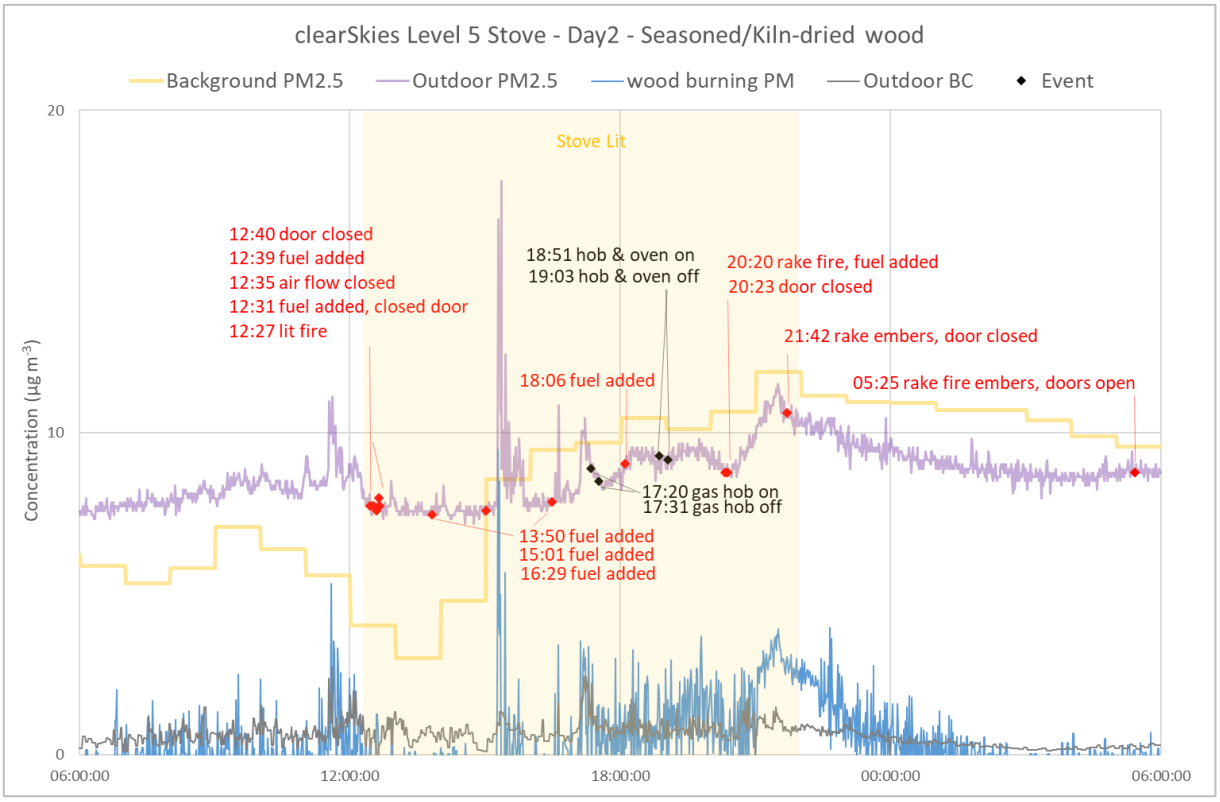
Outdoor data is shown in Figure 5-30. There was a gentle moderate breeze averaging 5-6 m s^{-1} mostly SW but NW between approx. 14:00 and 20:00. NW would have been a favourable direction to pick up emissions from the home. Within this window there were large peaks in $PM_{2.5}$ and WBPM, 15 minutes after fuel was added at 15:01. $PM_{2.5}$ increased from 9 µg m^{-3} to 18 µg m^{-3} over 5 minutes, with ongoing smaller peaks for approx. 40 minutes afterwards. At the same time WBPM increased by 9 µg m^{-3}. There were smaller peaks in $PM_{2.5}$ again at 16:29 minutes after fuel was added. An increase later at 17:04 did not correspond to an event in the home and had a higher BC composition than the previous peaks, so may not have been from the home but perhaps a neighbouring one. At 20:23 when fuel was added there was a gradual increase in $PM_{2.5}$ and WBPM. These peaks did not have the same profile as earlier ones and generally followed the London background $PM_{2.5}$, suggesting they were probably due to local solid-fuel burning emissions and not directly from Home 3. By this time the wind direction was SE in direction and so would have carried emissions from Home 3 away from the monitors in the garden.

Figure 5-29 Home 3 indoor measurements when Homefire kiln-dried logs were burned (Day 2), annotated with activities that may be expected to affect pollutant concentrations



This report is the independent expert opinion of the author(s).

Figure 5-30 Home 3 outdoor measurements when Homefire kiln-dried logs were burned (Day 2), annotated with activities that may be expected to affect pollutant concentrations



5.1.3.3 Home 3, Day 3 – Seasoned/Kiln dried wood

Measurement data from Day 3 indoors is presented in Figure 5-31. The participant used their own supply of kiln dried wood and natural firelighters, and the stove top fan was not used. At 07:30 the hob was used to make pancakes. 18 minutes later $PM_{2.5}$ peaked at 168 µg m^{-3}. There was a small increase in UV and BC for this event of 8 µg m^{-3} and 5 µg m^{-3} respectively. $PM_{2.5}$ continued to decrease after this event until the fire was lit at 15:05. When the fire was lit with natural firelighters and kindling, $PM_{2.5}$ increased from 6 µg m^{-3} to 17 µg m^{-3} over eight minutes, after the stove door was closed. Increases in both UV and BC were small at 1 µg m^{-3}. Fuel was added at 15:16 with no increase observed to any of the three species. A subsequent fuel addition at 16:23 also did not result in any observed emissions. At 17:53 the oven and hob were switched on and $PM_{2.5}$ began to increase. At 18:25 fuel was added but it is difficult to distinguish between its effects on $PM_{2.5}$ concentration and that of the oven. The hob was in use to heat water and soup and was unlikely to have affected the measurements.

Measurements outdoors are shown in Figure 5-32. The breeze was moderate at up to 9 m s^{-1} and from a SW direction. It was not favourable for picking up emissions from the home. $PM_{2.5}$ outdoors follows London background $PM_{2.5}$ and there was no evidence that any of the stove events or emissions was detected by the monitors in the garden.

Figure 5-31 Home 3 indoor measurements when Certainly Wood Fuel logs were burned (Day 3), annotated with activities that may be expected to affect pollutant concentrations

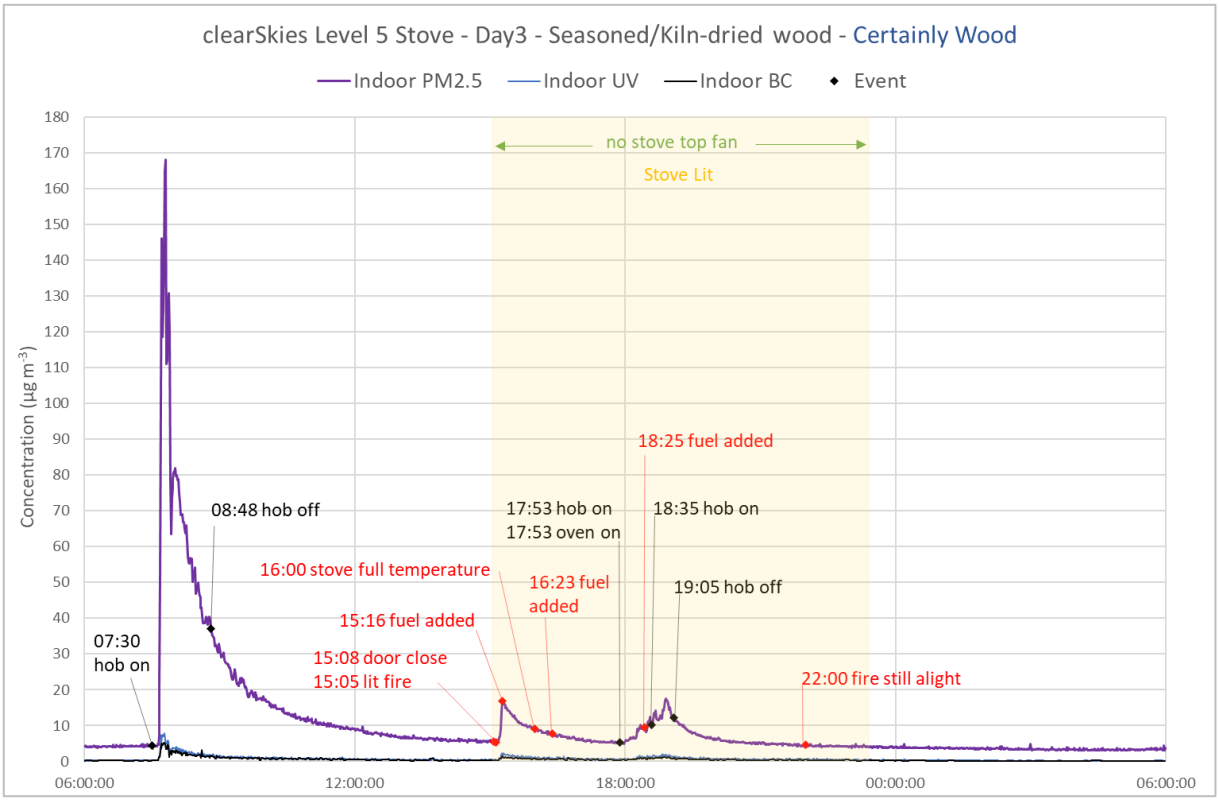
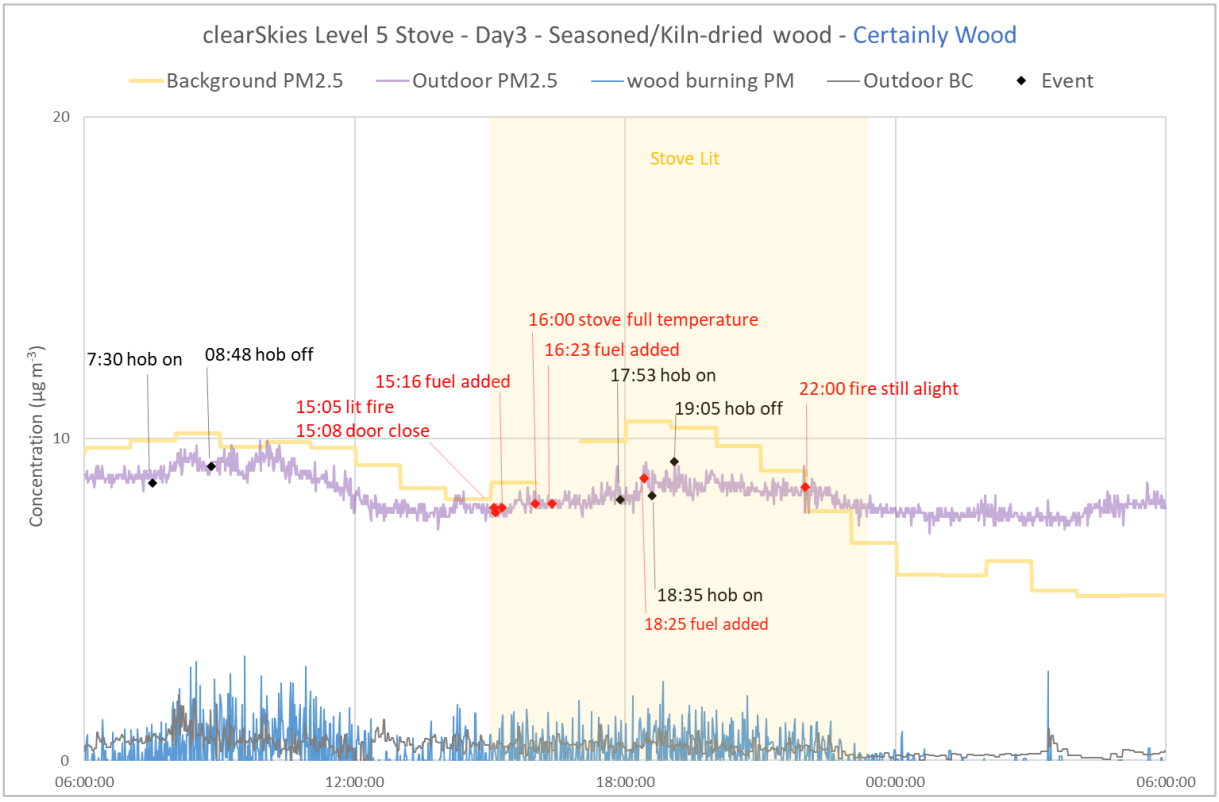


Figure 5-32 Home 3 outdoor measurements when Certainly Wood Fuel logs were burned (Day 3), annotated with activities that may be expected



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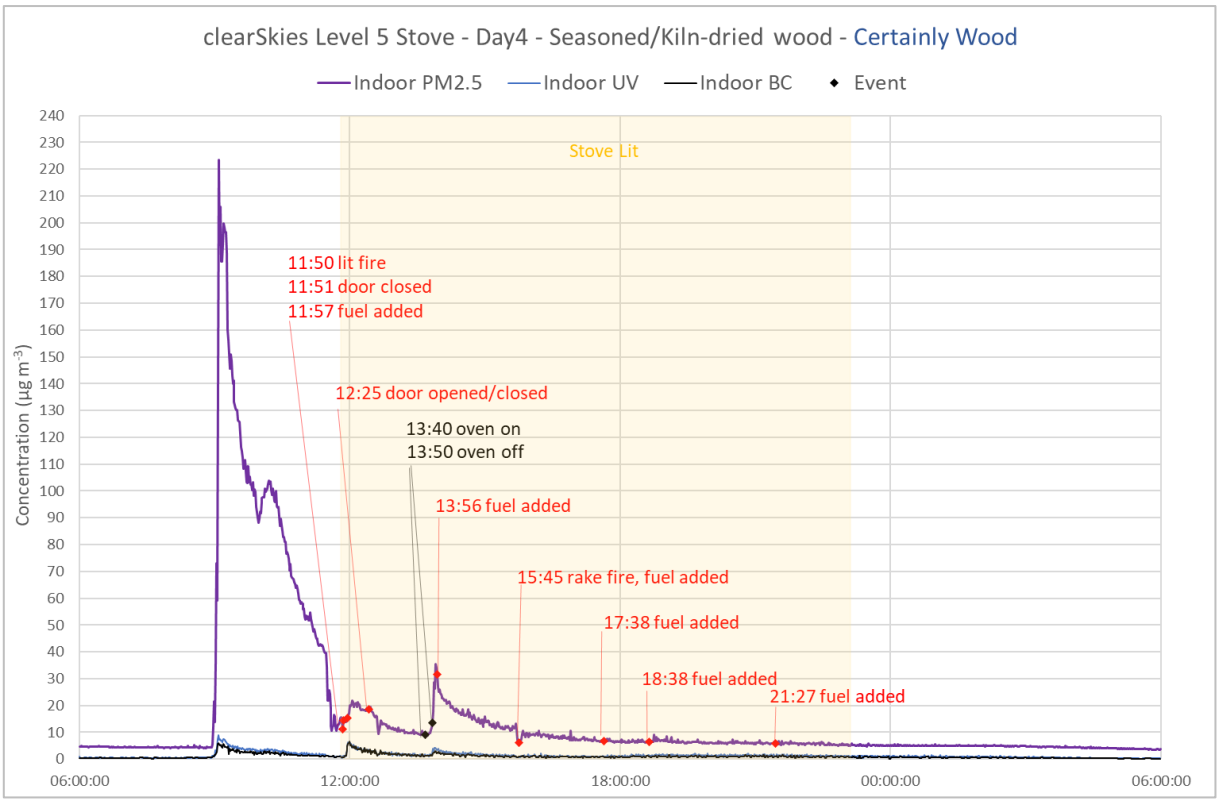
5.1.3.4 Home 3, Day 4 – Seasoned/Kiln dried wood

Day 4 measurements indoors at Home 3 are displayed in Figure 5-33. There was an increase in $PM_{2.5}$ when the fire was lit at 11:50 and after fuel was added at 11:57. $PM_{2.5}$ reached a peak of 21 µg m^{-3} at 12:00. UV and BC also increased by 5 µg m^{-3}. When the oven was used at 13:40, $PM_{2.5}$ began to increase, reaching a peak of 34 µg m^{-3} from 9 µg m^{-3} after 14 minutes. UV and BC increased by 2 µg m^{-3}. The addition of fuel to the stove at 13:56 did not increase indoor $PM_{2.5}$ concentrations. At 15:45 the addition of fuel corresponded to a temporary decrease in $PM_{2.5}$ from 13 µg m^{-3} to 6 µg m^{-3}. No further changes in indoor $PM_{2.5}$ were observed with subsequent fuel additions to the stove.

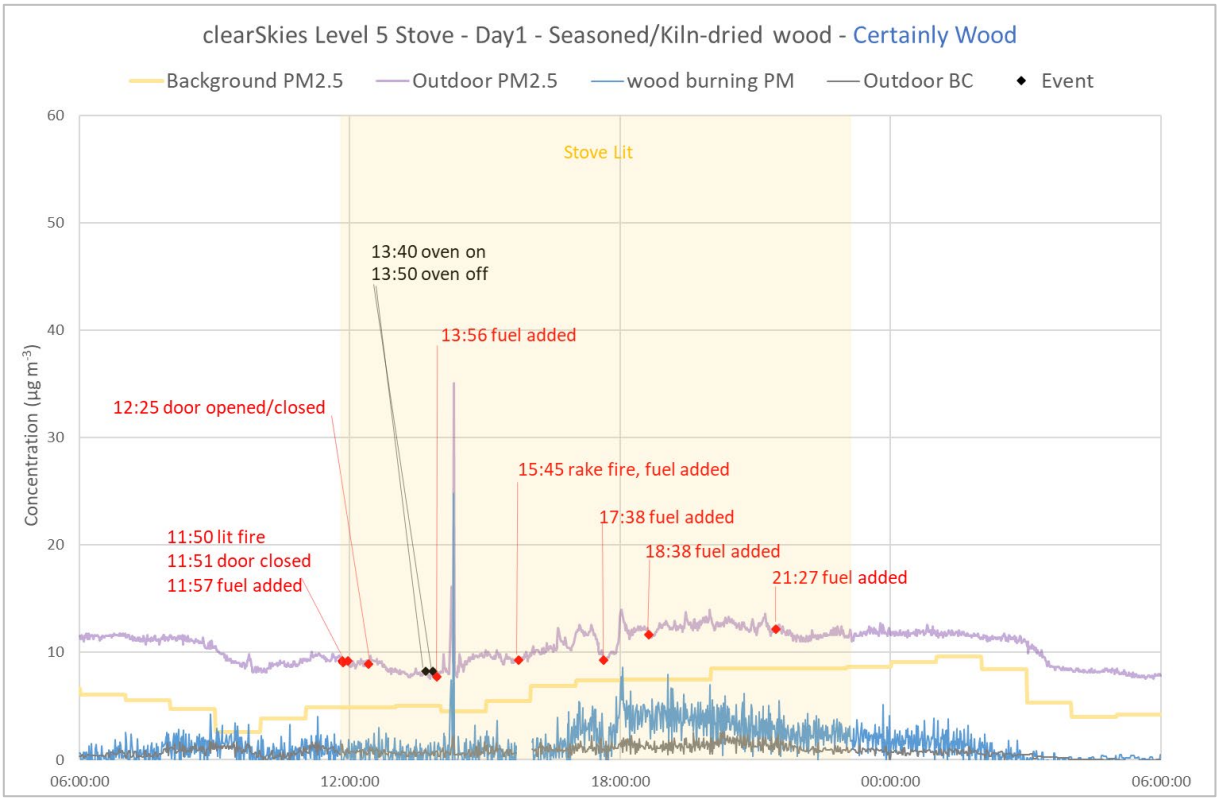
Outdoor measurements from Day 4 are shown in Figure 5-34. The wind direction was mostly SW except at around 14:00 when it was NW in direction for a short while. Around this time when the wind was favourable to the monitors picking up emissions from the home, large spikes in $PM_{2.5}$ and WBPM were observed. At 13:56 fuel was added to the stove. At 14:18 $PM_{2.5}$ peaks up to 35 µg m^{-3} from 7 µg m^{-3} were observed. WBPM peaks up to 25 µg m^{-3} from 1 µg m^{-3} and BC peaks up to 2 µg m^{-3} were measured. From 17:38 when fuel was added, a gradual increase in $PM_{2.5}$ was observed, reaching a peak of 14 µg m^{-3} from 9 µg m^{-3}. At the same time there was a gradual increase in WBPM of 5 µg m^{-3}. While these peaks were different to the large spikes in measurements observed when wind was in a more favourable direction, they nevertheless could be due to small changes in wind direction and activity around the house. A similar smaller increase possibly resulted from 18:38 when fuel was added.

Figure 5-33 Home 3 indoor measurements when Certainly Wood Fuel logs were burned (Day 4), annotated with activities that may be expected to affect pollutant concentrations



This report is the independent expert opinion of the author(s).

Figure 5-34 Home 3 outdoor measurements when Certainly Wood Fuel logs were burned (Day 4), annotated with activities that may be expected to affect pollutant concentrations



5.1.3.5 Home 3 Summary

The highest concentrations measured indoors at Home 3 over days 1-4 resulted from cooking events. Three events involving use of the oven and hob resulted in $PM_{2.5}$ increases between 17 and 42 µg m^{-3}, UV increases between 1 and 4 µg m^{-3} and BC increases between <1 and 2 µg m^{-3}. An event involving frying corresponded to a $PM_{2.5}$ increase of 168 µg m^{-3}, a UV increase of 8 µg m^{-3} and a BC increase of 5 µg m^{-3}. On another occasion use of the oven resulted in increases to $PM_{2.5}$, UV, and BC of 25, 2 and 2 µg m^{-3} respectively.

There were only a couple of events involving the clearSkies stove, over the four days, when any increases in $PM_{2.5}$, UV and BC were measured. A summary of all increases in indoor concentrations of $PM_{2.5}$, UV, and BC due to events associated with the clearSkies Level 5 certified stove, is shown in Figure 4-37.

Table 5-9 Summary of PM2.5, UV & BC measurement increases indoors at Home 3

Day	Fuel	Lighting Fire	Fuel Add 1	Fuel Add 2	Fuel Add 3	Fuel Add 4	Fuel Add 5
			PM2.5, UV, BC Increase (µg m^{-3})				
1	**Kiln dried wood**	0,0,0	0,0,0	0,0,0	0,0,0		
2	**Kiln dried wood**	0,0,0	0,0,0	0,0,0	0,0,0	0,0,0	0,0,0
3	**Kiln dried wood**	11,1,1*	0,0,0	0,0,0			
4	**Kiln dried wood**	11,5,5	0,0,0	0,0,0	0,0,0	0,0,0	0,0,0

* kindling only

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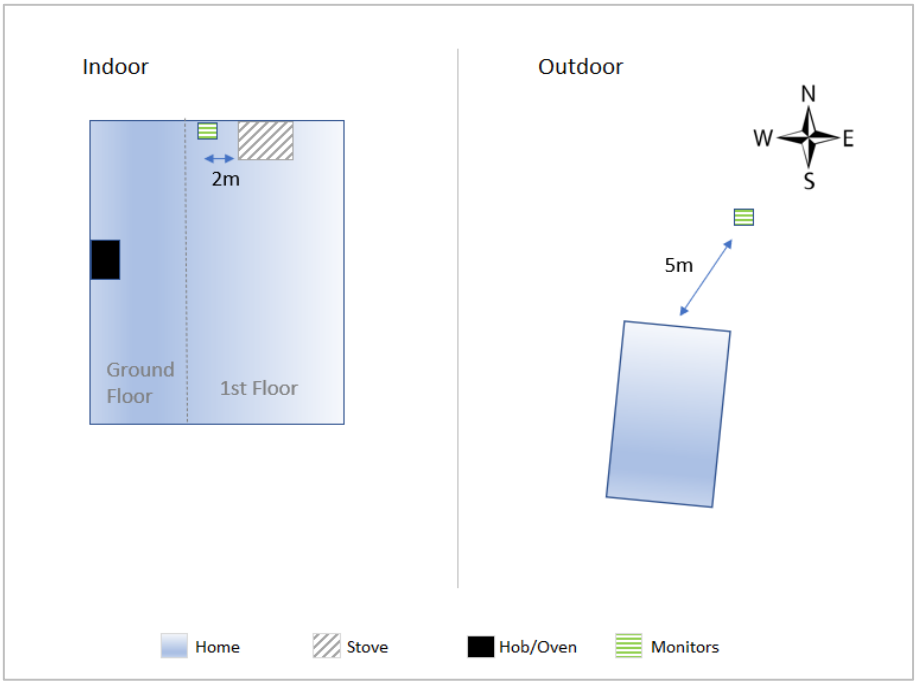
Over Days 1-2 the study supplied kiln dried logs were burned in the stove. There were eight separate events over the two days when fuel was added. None of the events led to any increase in the three species measured. There were actually two occasions when indoor air with an elevated $PM_{2.5}$ concentration from cooking events decreased briefly as the stove doors were opened and closed. Over Days 3-4 when the participant's own supply of kiln dried logs were burned in the stove, there were seven events where it was possible to measure the change in concentrations without interference from another event. For all seven events, there was no increase in concentration in any of the three species being measured. The only events involving interaction with the stove where increased indoor concentrations were measured were on Days 3-4 when the fire was lit with kindling and the natural firelighters and on another occasion when the fire was lit, and fuel was also added. On both occasions $PM_{2.5}$ indoors increased by 11 µg m^{-3}.

Outside the home on three of the four days there were times when the wind was in a favourable direction to directly measure emissions from the stove. On one of these days the emissions from lighting the stove were measured. There were spikes in concentrations of all three species with $PM_{2.5}$, UV and BC measurements of up to 27, 16 and 14 µg m^{-3} respectively. On three of the days spikes in data were observed when fuel was added to the stove. Concentrations of $PM_{2.5}$ ranged from 6 to 28 µg m^{-3}, UV ranged from 7 to 24 µg m^{-3}, and BC ranged from 1 to 2 µg m^{-3}. It was more difficult to attribute concentration increases to the stove emissions when the wind was in an unfavourable direction, however on one occasion there was a smaller increases in $PM_{2.5}$ of 5 µg m^{-3} and UV of 5 µg m^{-3} soon after fuel was added in poor dispersion conditions.

5.1.4 Home 4 – Non-DEFRA Exempt Stove

Home 4 was a rural property in Cornwall. It had a large garden on all sides and a neighbouring property close by, to the SE. The outdoor monitors were in the garden, approx. 5m NE of the home and approx. 1m in height from the ground. Indoors, the monitors were set-up in living room area on the first floor, approx. 2m from the non-DEFRA exempt stove. The cooker was located on the ground floor. The building was open plan, with the first floor open to the ground floor. A plan of both indoor and outdoor monitoring is shown in Figure 5-35.

Figure 5-35 Plan of indoor & outdoor monitoring at Home 4



All five fuels being investigated were burned in the non-DEFRA exempt stove. Fuel was burned over four 24-hour periods from 06:00 in the morning to 06:00 the following morning, between 16th March 2023 and 21st March 2023. On each Day 1-5, a separate fuel was burned in the stove. Fuel burning typically took place from the afternoon or evening, to later in the evening of the same day. Table 5-10 lists which fuel was burned on each day.

Table 5-10 Test dates and fuel burned at Home 4

Date	Day	Fuel Type	Brand
Thurs 16 Mar 2023 06:00 - Fri 17 Mar 2023 06:00	**Day 1**	Seasoned/ Kiln Dried Wood	Homefire Kiln Dried Logs
Fri 17 Mar 2023 06:00 - Sat 18 Mar 2023 06:00	**Day 2**	Exempt MSF	Bio-Bean Coffee Logs
Sat 18 Mar 2023 06:00 - Sun 19 Mar 2023 06:00	**Day 3**	Authorised MSF	Homefire Ecoal
Sun 19 Mar 2023 06:00 - Mon 20 Mar 2023 06:00	**Day 4**	Smokeless "Coal"	Maxibrite Newflame Plus
Mon 20 Mar 2023 06:00 - Tue 21 Mar 2023 06:00	**Day 5**	Unseasoned Wood	-

Participant photos of monitors in situ indoors and outdoors, and of the stove, including burning kiln-dried wood and preparation during test days, are shown in figure 5-36. Meteorological data from the Cardinham Bodmin met station in Cornwall for Days 1-5 is presented in Table 5-11.

Figure 5-36 Photos from Home 4 of Indoor monitors, outdoor monitors, wood burning, preparing Coffee Logs and setting up kindling.

Table 5-11 Meteorological data for monitoring Days 1-5 at Cardinham Bodmin Met station

	Day 1																							
Time	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	1	2	3	4	5
Temp (Deg C)	9	9	9	9	9	9	9	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	9	9
Wind Direction (deg)	**200**	**190**	**190**	**190**	**180**	**180**	**180**	**180**	**190**	**190**	**210**	**200**	**190**	**190**	**190**	**200**	**190**	**190**	**190**	**190**	**190**	**190**	**190**	**190**
Wind Speed(m/s)	8.8	9.3	10.3	9.8	9.3	7.2	7.7	7.7	8.2	6.7	6.7	6.2	4.6	4.1	4.6	5.1	5.1	5.1	6.7	5.7	6.7	6.2	6.2	6.2
	Day 2																							
Time	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	1	2	3	4	5
Temp (Deg C)	9	10	10	10	10	11	11	11	11	11	10	10	10	10	10	10	10	9	9	9	9	9	9	8
Wind Direction (deg)	**170**	**170**	**180**	**180**	**180**	**170**	**180**	**180**	**200**	**190**	**180**	**190**	**190**	**190**	**190**	**190**	**190**	**170**	**190**	**190**	**200**	**190**	**180**	**180**
Wind Speed(m/s)	6.7	7.7	8.2	7.7	8.8	9.8	9.3	10.3	10.3	10.3	9.3	8.2	6.2	6.7	6.2	4.6	5.7	5.1	4.6	3.1	3.6	2.6	1.5	1.5
	Day 3																							
Time	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	1	2	3	4	5
Temp (Deg C)	8	8	9	9	11	11	11	11	12	11	11	10	9	8	8	8	7	6	6	5	5	5	5	5
Wind Direction (deg)	**180**	**170**	**210**	**220**	**210**	**300**	**310**	**310**	**300**	**290**	**300**	**300**	**300**	**330**	**340**	**350**	**330**	**340**	**340**	**340**	**340**	**340**	**330**	**320**
Wind Speed(m/s)	2.1	1.5	1.0	0.5	1.5	3.1	3.1	5.1	5.1	4.1	4.6	5.1	5.7	7.7	4.1	5.1	3.6	5.1	5.7	5.7	5.1	5.1	4.1	4.1
	Day 4																							
Time	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	1	2	3	4	5
Temp (Deg C)	4	3	6	8	9	9	9	9	10	9	8	8	8	7	7	7	8	8	9	9	9	9	10	10
Wind Direction (deg)	**330**	**330**	**360**	**320**	**320**	**320**	**300**	**280**	**270**	**290**	**260**	**260**	**270**	**180**	**180**	**180**	**180**	**190**	**190**	**210**	**200**	**210**	**220**	**210**
Wind Speed(m/s)	3.1	2.6	1.0	4.6	4.1	3.6	3.6	3.6	3.1	4.1	3.6	3.6	3.1	2.1	3.1	3.1	4.6	5.1	4.1	4.1	4.1	3.6	4.1	3.6
	Day 5																							
Time	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	1	2	3	4	5
Temp (Deg C)	10	10	9	9	10	10	10	10	10	10	9	9	9	9	9	9	9	9	10	10	10	10	10	10
Wind Direction (deg)	**220**	**210**	**220**	**200**	**200**	**200**	**190**	**210**	**190**	**190**	**190**	**190**	**190**	**180**	**180**	**190**	**180**	**200**	**200**	**220**	**210**	**220**	**210**	**220**
Wind Speed(m/s)	4.1	3.6	4.6	3.6	4.1	2.1	4.6	5.7	5.7	5.1	7.7	7.7	8.8	9.3	7.7	7.7	6.2	7.7	7.2	7.7	6.2	5.7	6.7	6.7

5.1.4.1 Home 4, Day 1 – Seasoned/Kiln dried wood

Indoor data for Day 1 in Home 4 is shown in Figure 5-37. The moisture content of the seasoned wood burned was measured by the participant at 12.5%. There was a very small increase in $PM_{2.5}$ concentration of 1 µg m^{-3} when the oven was used from 18:15. At 19:50 the fire was lit with kindling, firelighters and kiln-dried logs. A large jump in $PM_{2.5}$, UV and BC concentrations was measured. $PM_{2.5}$ increased from 3 µg m^{-3} to 15 µg m^{-3} over 2 minutes. UV increased to 11 µg m^{-3} and BC increased to 4 µg m^{-3}. The participant noted that some smoke escaped while lighting the stove. At 20:15 fuel was added and there was a large jump in all three species measurements again. $PM_{2.5}$ increased from 3 µg m^{-3} to 13 µg m^{-3} over 3 minutes. UV increased from 1 to 13 µg m^{-3} and BC increased from 1 to 6 µg m^{-3} at the same time. At 20:15 one log was added and $PM_{2.5}$ increased by 1 µg m^{-3} over an hour before decreasing.

Outside measurements are shown in Figure 5-38. A moderate S to SW breeze with wind speeds up to 6-7 ms^{-1} would have been favourable for the monitors to pick up emissions from the stove. Once the fire was lit at 19:50 there were immediate large increases in all three species measured. $PM_{2.5}$ peaks up to 14 µg m^{-3} from 5 µg m^{-3}, WBPM peaks up to 39 µg m^{-3} from 1 µg m^{-3} and BC peaks up to 23 µg m^{-3} from 1 µg m^{-3} were observed. Large spikes in outdoor concentrations were evident throughout the evening. When fuel was added at 20:15, there were immediate spikes in $PM_{2.5}$, WBPM and BC measuring increases of 7, 6 and 2 µg m^{-3} respectively. At 21:15 one log was added to the stove, 20 mins later there were many large spikes, particularly in $PM_{2.5}$ and WBPM data. $PM_{2.5}$ concentrations increased from 4 up to 53 µg m^{-3} with many measurements > 20 µg m^{-3}, over the next hour. At the same time, WBPM increased from 1 up to 20 µg m^{-3} and BC increased by 2 µg m^{-3}. The spikes in both $PM_{2.5}$ and WBPM continued and decreased over the next two hours. Some caution is required when interpreting this later outdoor data as there was a 15 minute delay before the spikes in data were observed from when fuel was added. This may have been due to a

slight change in wind direction, a delay in the fuel catching fire or emissions from a neighbour's house which was in a similar path for emissions to be detected. There were no details of whether a fire was lit at the neighbour's house on Day 1.

Figure 5-37 Home 4 indoor measurements when Homefire kiln-dried logs were burned, annotated with activities that may be expected to affect pollutant concentrations

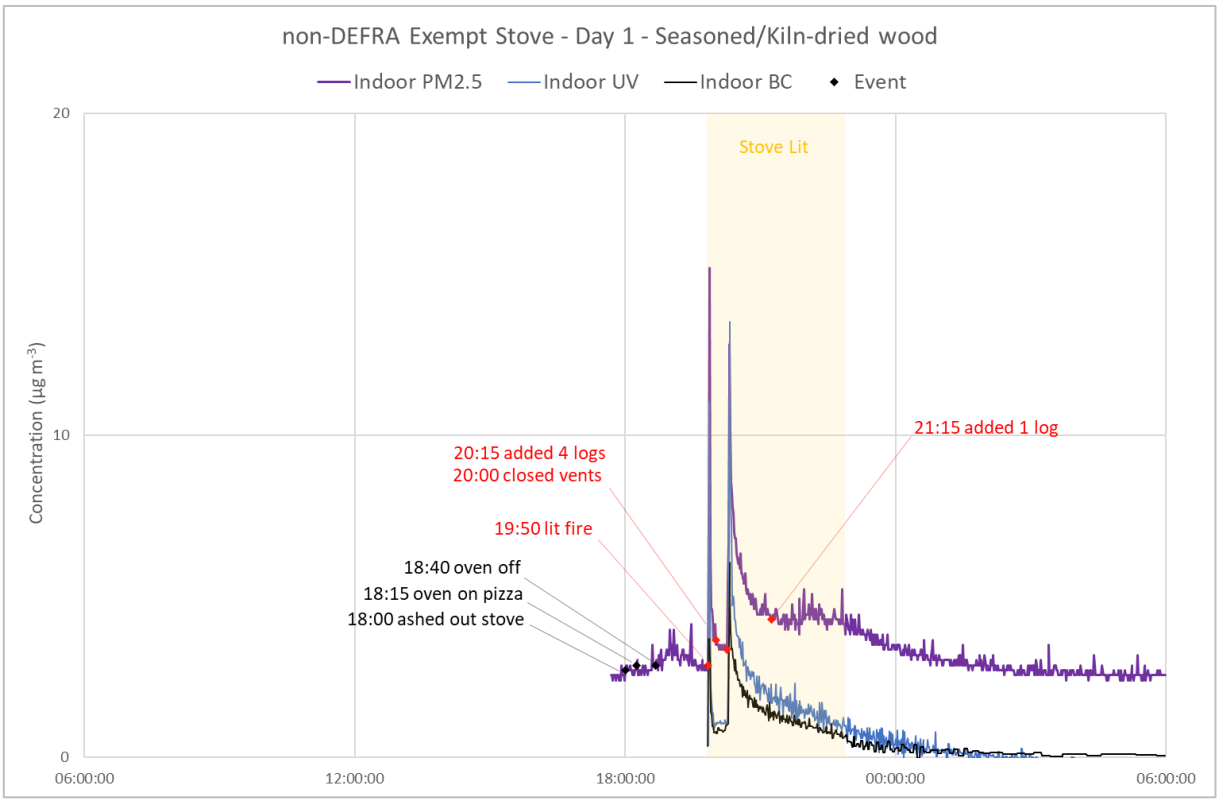


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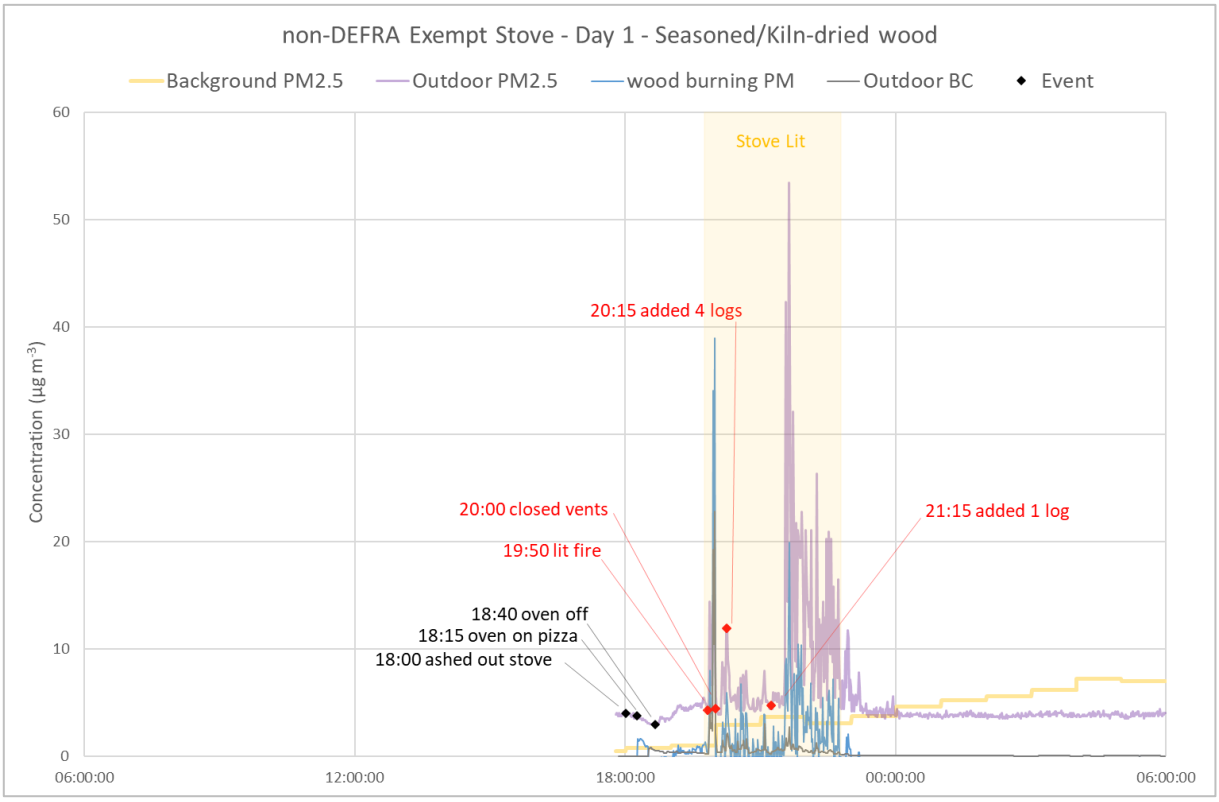
Figure 5-38 Home 4 outdoor measurements when Homefire kiln-dried logs were burned annotated with activities that may be expected to affect pollutant concentrations



5.1.4.2 Home 4, Day 2 – Coffee Logs

Figure 5-39 displays indoor measurements from Day 2 when Coffee Logs were the fuel used in the stove. The fire was lit at 19:08 and fuel added, kindling and kiln dried logs were used to light the stove. Four minutes later all three species started increasing. $PM_{2.5}$ then increased in a minute from 7 µg m^{-3} to 37 µg m^{-3}, UV from 2 to 26 µg m^{-3} and BC increased from 1 to 19 µg m^{-3}. By the time Coffee Logs were added at 19:15 levels had begun to decrease again. One minute later at 19:16 all three species began to increase again and within two minutes $PM_{2.5}$ had increased to 108 µg m^{-3} from 20 µg m^{-3}, UV to 54 µg m^{-3} from 10 µg m^{-3} and BC to 47 µg m^{-3} from 10 µg m^{-3}. By the time cooking started at 19:20 all three species had started to decrease again. At 19:20 when frying and oven use started the decrease in all three species was interrupted and there was a small increase for one minute, 2 µg m^{-3} in the case of $PM_{2.5}$, followed by a continuing decrease after another minute. Cooking finished at 19:40 when it is presumed the oven door was opened and at the same time fuel was added to the stove. There was a small increase in $PM_{2.5}$, BC and UV, but it is not possible to determine which event was responsible or if both contributed.

Outdoor data from Day 2 is plotted in Figure 5-40. Wind during the time the stove was lighting was generally S slightly SW. It was a gentle breeze. This was favourable to enable the monitor to pick up emissions from the stove. At 18:00 it was observed that the neighbour had their fire lit. Spikes in all three species were measured for approx. 45 minutes after 18:00 so these concentrations must have been due to emissions from the neighbour's fire or stove. At 19:08 the participant's stove was lit using firelighters, kindling and kiln dried logs with Coffee Logs added at 19:15. Immediately spikes were measured for all three species. It was presumed these increases were due to the stove in Home 4 because of the timing and the fact that in 15 minutes before these spikes in measurements there were no increases due to emissions from the neighbour's stove. $PM_{2.5}$ spikes from 4 up to 32 µg m^{-3}, UV from 1 up to 21 µg m^{-3} and BC from 1

up to 19 µg m^{-3} were measured. Later at 19:40, Coffee Logs were added to the stove, $PM_{2.5}$ increased from 5 by 8 µg m^{-3}, WBPM increased by 6 µg m^{-3} and BC by 1 µg m^{-3}. Coffee logs were added again at 20:10. Immediate increases of 3 µg m^{-3} for $PM_{2.5}$, 8 µg m^{-3} for WBPM and 2 for BC were measured. Concentrations of all three species returned to background levels 50 minutes after fuel was added.

Figure 5-39 Home 4 indoor measurements when Coffee Logs were burned, annotated with activities that may be expected to affect pollutant concentrations

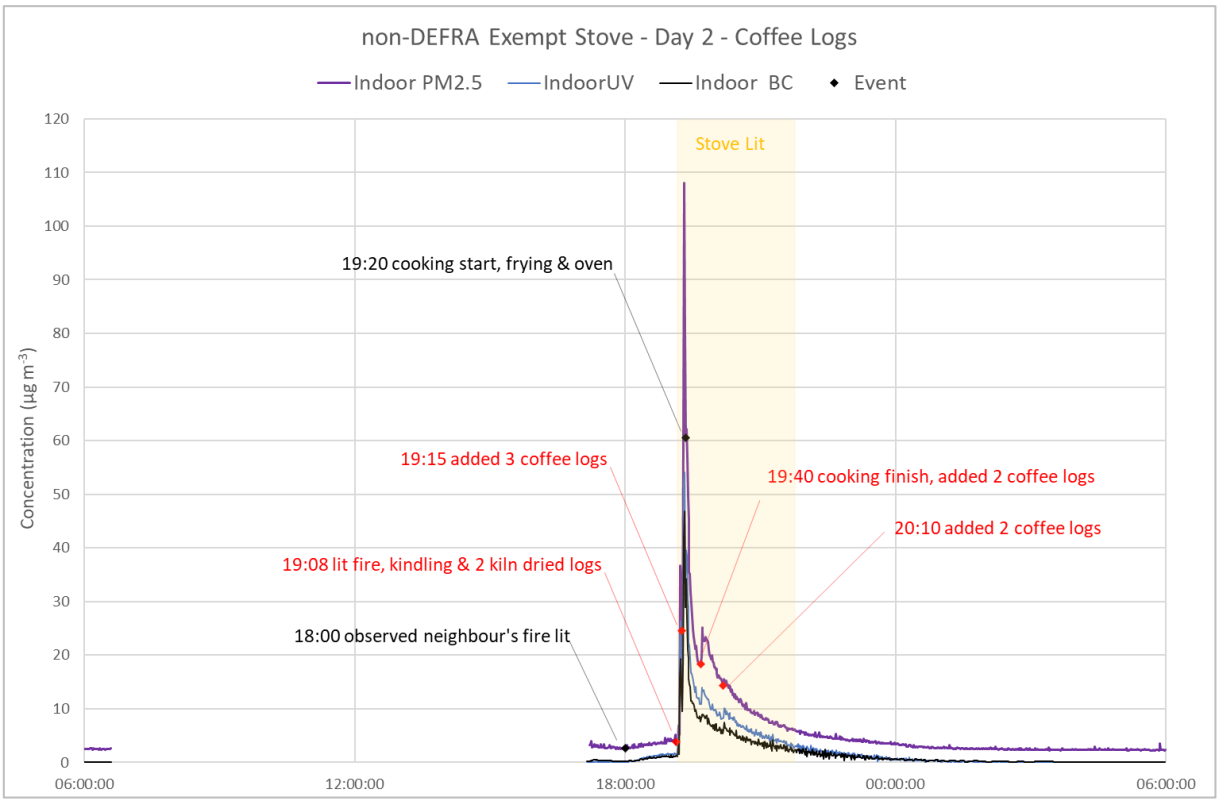


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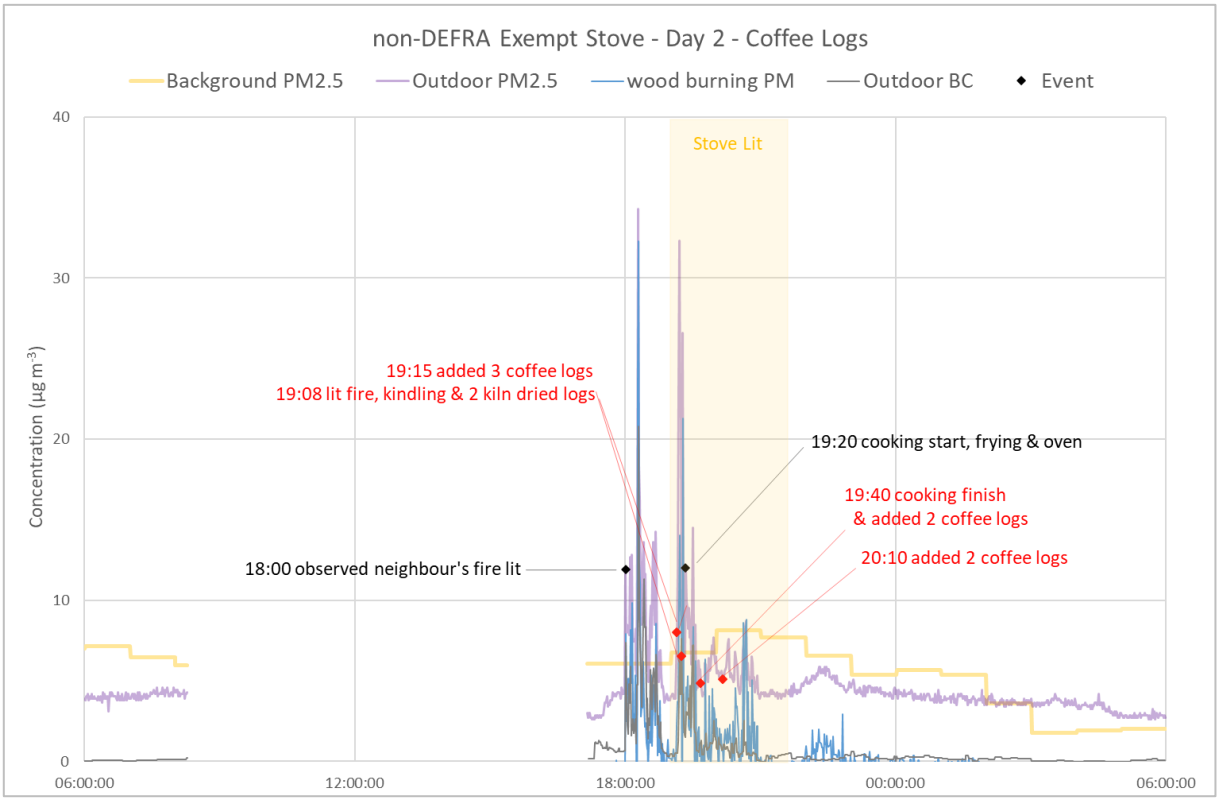
Figure 5-40 Home 4 outdoor measurements when Coffee Logs were burned, annotated with activities that may be expected to affect pollutant concentrations



5.1.4.3 Home 4, Day 3 – Ecoal

Figure 5-41 shows $PM_{2.5}$ data inside the home on Day 3 when Ecoal was the fuel. Kiln-dried logs were also added to the stove at times on Day 3. The aethalometer was not switched on so there were no UV or BC measurements. There was an increase in $PM_{2.5}$ when kiln dried logs were added to the stove at 18:30 from 6 to 10 µg m^{-3}. At 18:53 Ecoal was added and $PM_{2.5}$ increased from 6 to 181 µg m^{-3} over six minutes. The stove door was left open at this time and $PM_{2.5}$ concentrations remained > 100 µg m^{-3} for 14 minutes after the peak. No change in $PM_{2.5}$ was seen indoors when Ecoal was added at 19:30. At 20:10 some kiln dried wood was added by mistake, there was a small increase in $PM_{2.5}$ from 31 to 34 µg m^{-3}. At 20:45 there was a small increase in $PM_{2.5}$ indoors from 15 to 18 µg m^{-3} when Ecoal was added. $PM_{2.5}$ levelled off at 3 µg m^{-3} after midnight.

Outdoor data from Day 3 is plotted in Figure 5-42. Meteorological data indicated a NW breeze from 11:00, however, it is clear from data plots that there were spikes in concentrations, corresponding to fuel being added to the stove. It is possible that wind direction may have either been slightly different at Home 4, as the met station was > 30 km distance away or that there may have been some local effects which may have resulted in the breeze circulating emissions into the path of the monitors.

Spikes in all three species were measured at 18:40, 20 minutes after the fire was lit and 10 minutes after two kiln dried logs were added. At the same time as these elevated measurements, it was observed that the neighbour's fire was also lit. $PM_{2.5}$ spikes up to 18 from 5 µg m^{-3}, UV up to 18 µg m^{-3} and BC up to 3 µg m^{-3} were measured. At exactly the time that Ecoal was added to the stove at 18:53, $PM_{2.5}$ peaked at 12 from 5µg m^{-3}, UV at 8 µg m^{-3} and BC at 6 µg m^{-3}. Ten minutes later higher peaks were measured, $PM_{2.5}$ peaked at 63 µg m^{-3} from 5 µg m^{-3}, UV at 57 µg m^{-3} and BC at 2 µg m^{-3}. These delayed peaks may also have been due to the Ecoal added ten minutes earlier at 18:53, as the door of the stove was left open for a while, possibly

as the Ecoal was slow to light. Spikes in data then decreased until Ecoal was added at 19:30 and eight minutes later spikes in the data appeared again. $PM_{2.5}$ spiked from 4 µg m^{-3} up to 19 µg m^{-3}, UV increased to 14 µg m^{-3} and BC to 3 µg m^{-3}.

Some spikes in $PM_{2.5}$ and WBPM were observed after kiln dried logs were added to the stove at 20:10. Ecoal was added at 20:45, and within 10-15 minutes there were peaks in $PM_{2.5}$ from 4 up to 16 µg m^{-3} and increases in WBPM up to 13 µg m^{-3}. The highest BC measured was < 1 µg m^{-3}. The last peaks were observed approx. 75 minutes after this last fuel addition to the stove at 20:45. As the increased measurements were frequent and ongoing from the addition of the last fuel, it is likely they were due to stove emissions from Home 4.

Figure 5-41 Home 4 indoor measurements when Ecoal was burned, annotated with activities that may be expected to affect pollutant concentrations

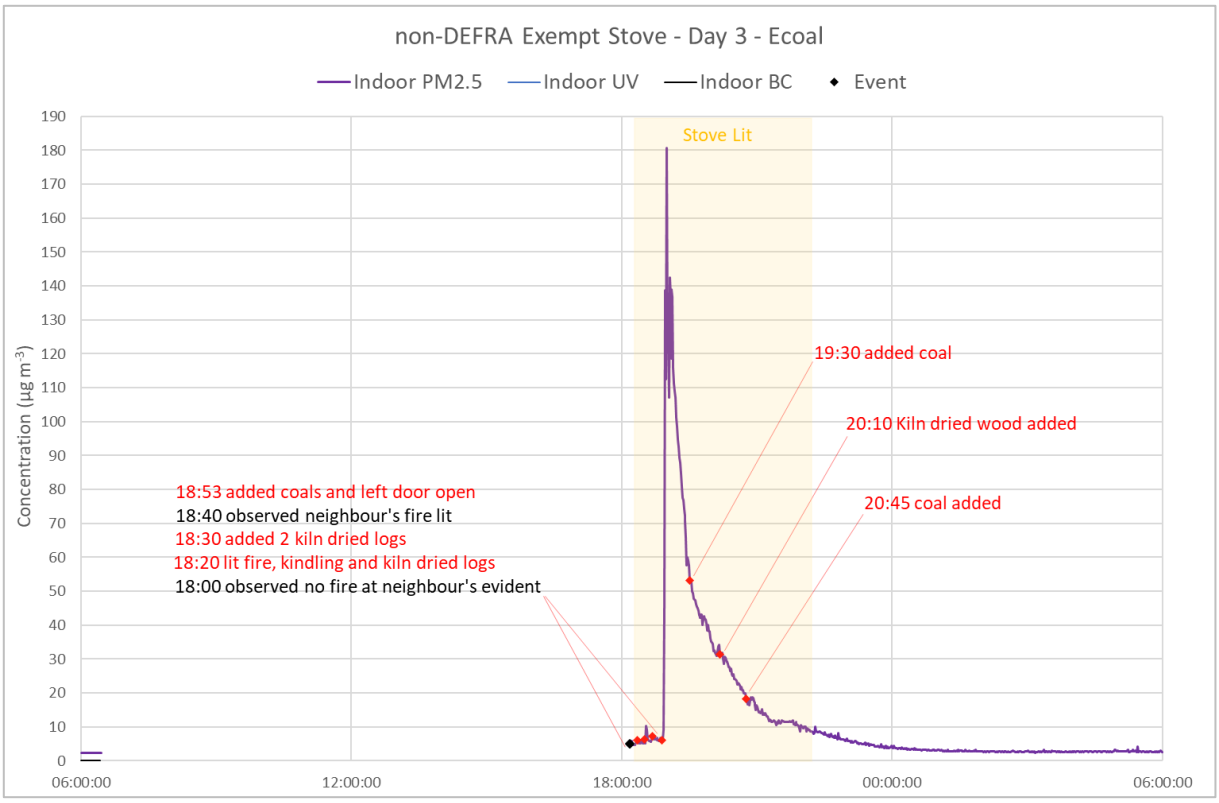


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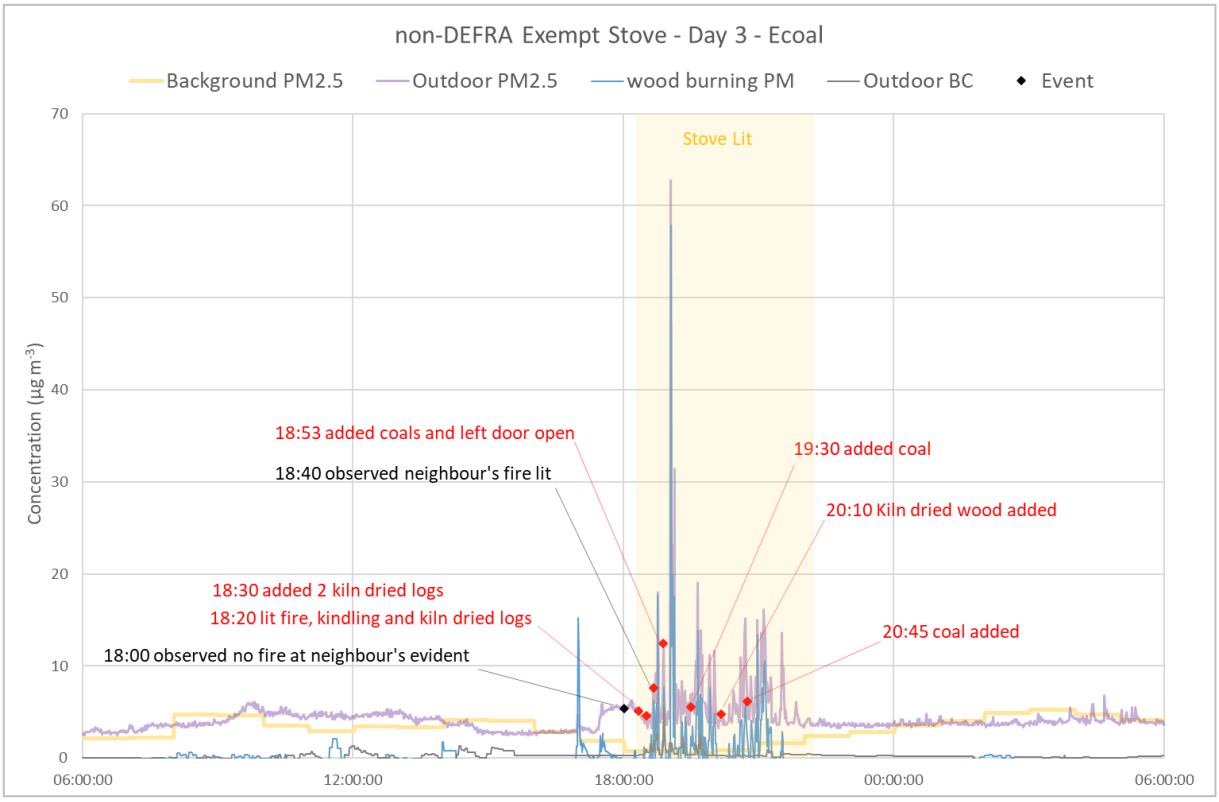
Figure 5-42 Home 4 outdoor measurements when Ecoal was burned, annotated with activities that may be expected to affect pollutant concentrations



5.1.4.4 Home 4, Day 4 – Newflame Plus

Indoor measurements from Day 4 are displayed in Figure 5-43. At 18:50 the fire was lit with firelighters, kindling, kiln dried logs and Newflame Plus coal. $PM_{2.5}$ immediately increased from 3 to 22 µg m^{-3}, UV increased to 10 µg m^{-3} and BC to 4 µg m^{-3}. At 19:15 Newflame Plus coal was added and $PM_{2.5}$ increased from 5 to 16 µg m^{-3}, UV increased from 1 to 9 µg m^{-3} and BC increased from 1 to 3 µg m^{-3}. At 20:30 Newflame Plus coal was added $PM_{2.5}$ increased from 6 to 8 µg m^{-3}, UV increased from 1 to 3 µg m^{-3} and there was no change in BC.

Outdoor data is plotted on Figure 5-44. There was a light breeze with a NW wind direction early in the day changing to S by the evening. Spikes in measurements corresponding to fuel additions to the stove were observed. After the fire was lit at 18:50, $PM_{2.5}$ increased from 5 to 38 µg m^{-3}, WBPM increased to 18 µg m^{-3} and BC to 4 µg m^{-3}. At 19:15 when Newflame Plus was added to the stove, $PM_{2.5}$ increased from 5 to 70 µg m^{-3}, WBPM increased from 1 to 88 µg m^{-3} and BC increased up to 4 µg m^{-3}. Later when Newflame Plus was added at 20:30, $PM_{2.5}$ increased from 5 to 15 µg m^{-3}, WBPM increased from 1 to 29 µg m^{-3} and BC increased by < 1 µg m^{-3}.

Figure 5-43 Home 4 indoor measurements when Newflame Plus was burned, annotated with activities that may be expected to affect pollutant concentrations

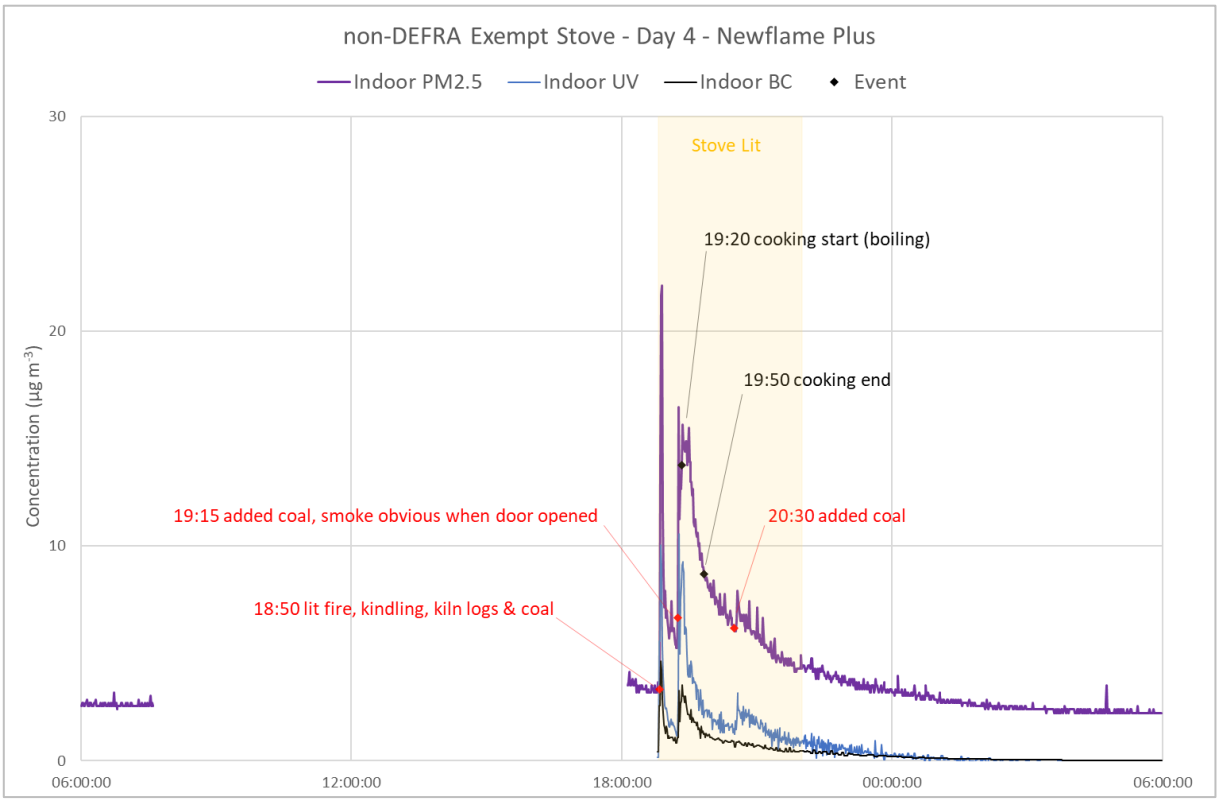
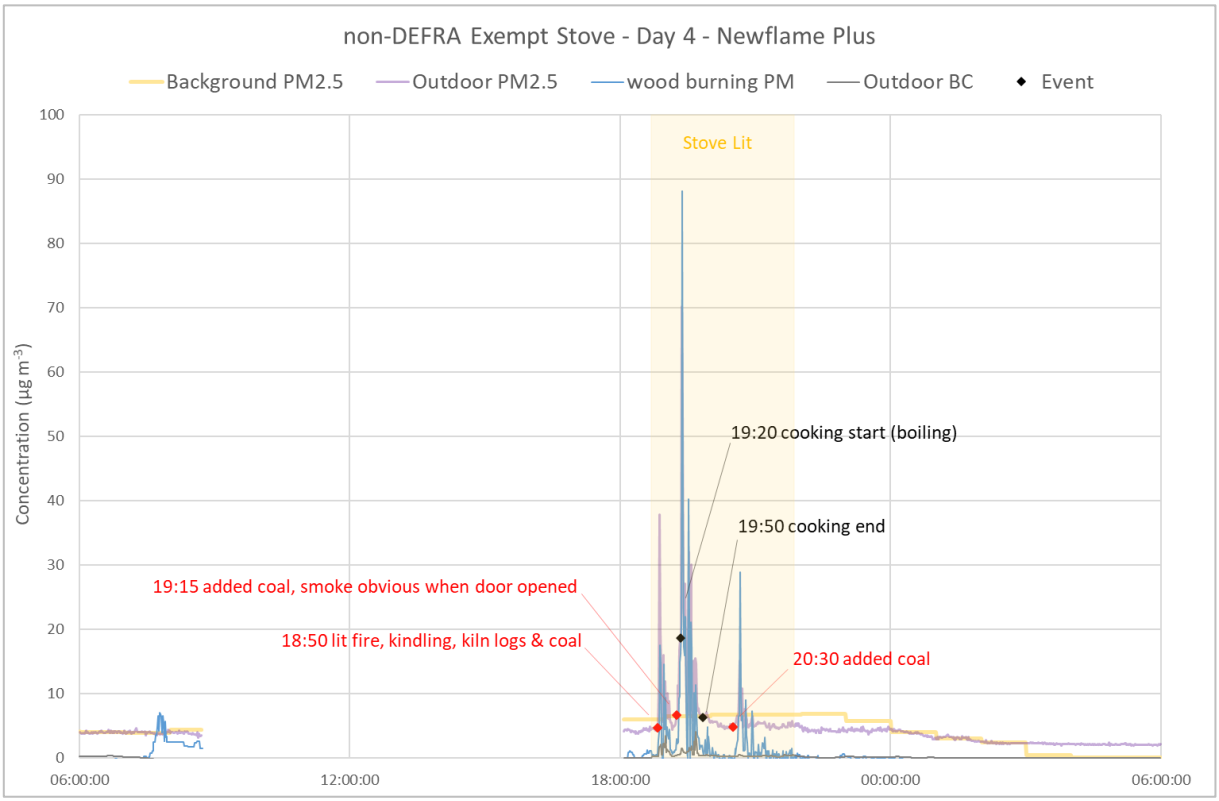


Figure 5-44 Home 4 outdoor measurements when Newflame Plus was burned, annotated with activities that may be expected to affect pollutant concentrations



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5.1.4.5 *Home 4, Day 5 – Unseasoned wood*

Indoor measurements from Day 5 are shown in Figure 5-45. The moisture content of the unseasoned wood burned was measured by the participant at 18.5%. From 18:45 to 19:15 the oven was in use. A very small increase in $PM_{2.5}$ of 1µg m^{-3} was measured. At 19:30 when the fire was lit, the participant commented that there was a waft of smoke, and an immediate increase in all three species was observed. $PM_{2.5}$ increased by 2 µg m^{-3} accompanied by small increases in UV and BC of < 1 µg m^{-3}. By the time logs were added at 19:50, levels had reduced again. At 19:50 $PM_{2.5}$ increased from 4 to 7 µg m^{-3}, UV increased by 2 µg m^{-3} and BC increased by 1 µg m^{-3}. At 21:16 unseasoned wood logs were added to the stove. $PM_{2.5}$ increased by 1 µg m^{-3} with a very small UV increase of < 1 and there was no change in BC.

Outdoor measurements from Day 5 are shown in Figure 5-46. Outside on Day 5 there was a moderate breeze up to 9 ms^{-1} from a SW and S direction. This would have been favourable for measuring stove emissions from the home. It was noted that the neighbour's fire was not lit. Within minutes of fuel being added to the stove at 18:50, spikes were observed in all three species measurements. $PM_{2.5}$ peaks measured up to 11 µg m^{-3} from 3 µg m^{-3}, WBPM up to 10 µg m^{-3} and BC up to 3 µg m^{-3}. When logs were added at 19:50, spikes in concentrations continued. The highest for each species were $PM_{2.5}$ at 28 µg m^{-3}, WBPM at 16 µg m^{-3} and BC at 6 µg m^{-3}. The spikes in data stopped and all three measured species returned to their background levels at 20:20, 30 minutes after the logs were added. Concentrations remained at background levels until 21:16 when logs were added to the stove again. Immediately, spikes in concentrations were observed outside and continued for the next 70 minutes. $PM_{2.5}$ spikes were measured at up to 23 µg m^{-3}. WBPM at up to 9 µg m^{-3} and BC at up to 3 µg m^{-3}.

Figure 5-45 Home 4 indoor measurements when unseasoned wood was burned, annotated with activities that may be expected to affect pollutant concentrations

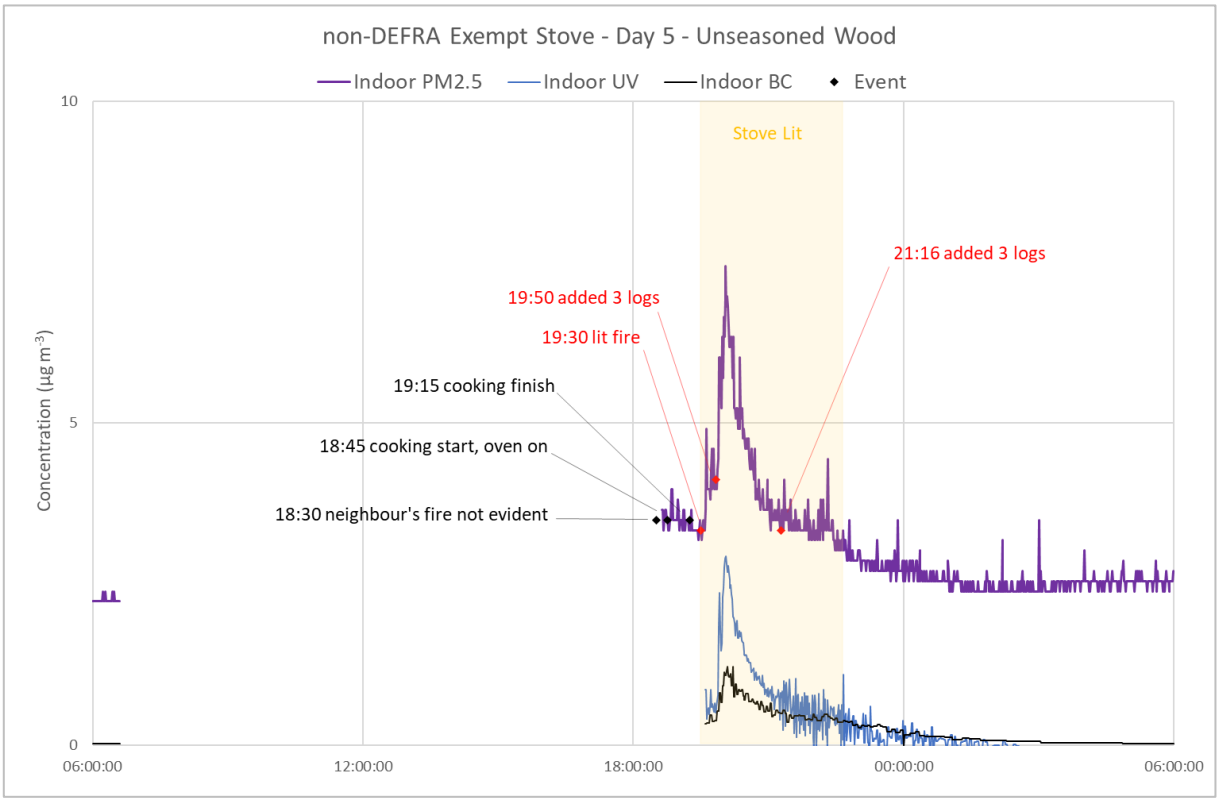

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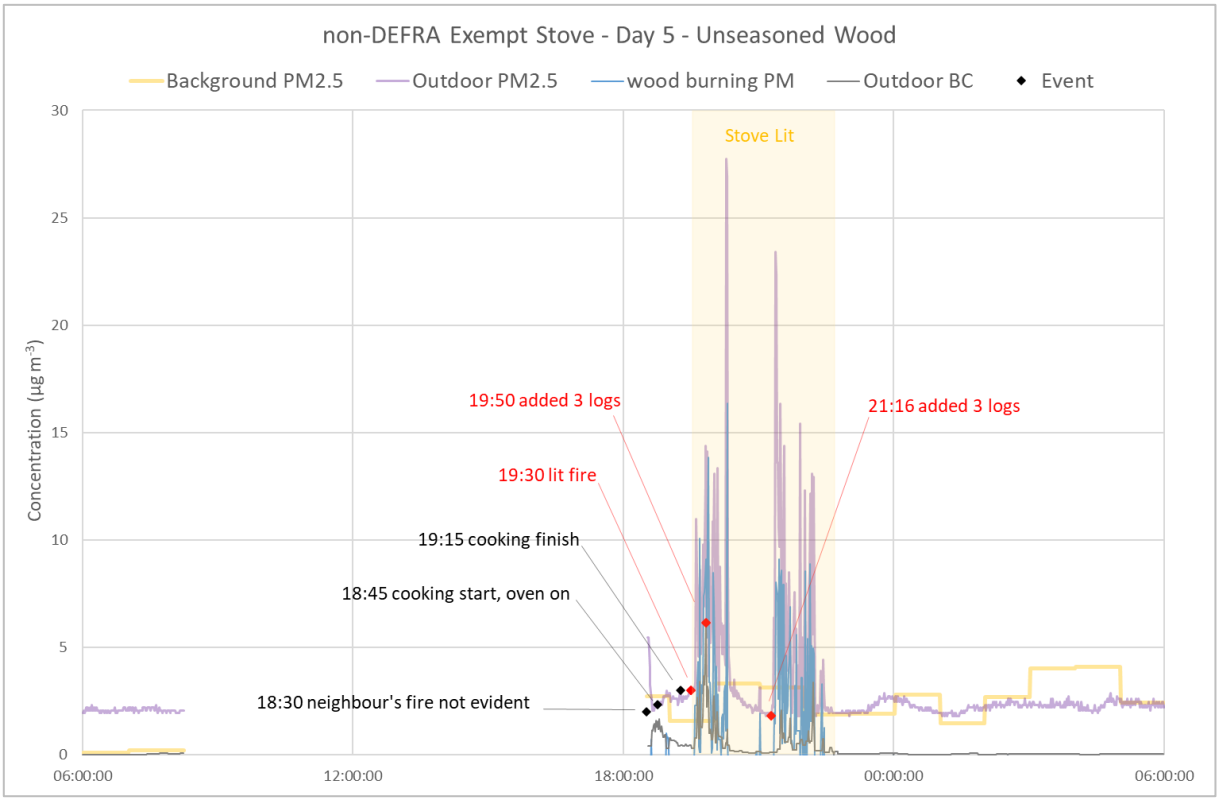
Figure 5-46 Home 4 outdoor measurements when unseasoned wood was burned, annotated with activities that may be expected to affect pollutant concentrations



5.1.4.6 Home 4 Overview

A summary of all increases in indoor concentrations of $PM_{2.5}$, UV and BC due to events associated with the non-DEFRA Exempt stove, is shown in Table 5-12.

Table 5-12 Summary of PM2.5, UV & BC measurement increases indoors at Home 4

Fuel	Lighting Fire	Fuel Add 1	Fuel Add 2	Fuel Add 3	Fuel Add 4
	PM2.5, UV, BC Increase (µg m^{-3})				
Kiln dried wood	12,11,4	10,12,6	1,0,0		
Coffee Logs	30,24,18*	88,44,37			
Ecoal	4,-,-*	181,-,-	0,-,-	3,-,-	
Newflame Plus	18,10,4**	11,8,2	2,2,0		
Unseasoned wood	1, < 1,< 1	3,2,1	1,< 1,0		

*including kiln dried wood, no fuel

**including kiln dried wood

Generally cooking emissions were not significant in Home 3 with fewer spikes in measurements than at other homes. Most of the cooking involved use of the oven only, with frying on only one occasion, and no grilling. Emissions were detected on all five days indoors when the stove was lit. The highest increases due to emissions were on Day 2 when coffee logs were being used, with increases in $PM_{2.5}$ measured up to 30 µg m^{-3}, UV up to 30 µg m^{-3} and BC up to 18 µg m^{-3}. The lowest increases were measured on Day 5 when unseasoned wood was tested.

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After fuel was added to the stove the highest $PM_{2.5}$, WBPM and BC levels measured indoors were when Ecoal was burned followed by Coffee Logs. On one occasion the addition of Ecoal to the stove resulted in an increase in PM2.5 of 181 µg m^{-3} indoors. The addition of Coffee logs resulted in high concentrations of all three species being measured, with $PM_{2.5}$ increases of up to 88 µg m^{-3} and BC of up to 37 µg m^{-3}. The lowest increases were observed when unseasoned wood was burned. For four of the fuels, increases due to the addition of a second refill of fuel were much less than when the first addition was made. This may indicate that there were less emissions indoors when fuel is added to an established fire in the stove.

Increases in concentration of $PM_{2.5}$, WBPM and BC outdoors were successfully measured on all five days due to a favourable wind direction blowing emissions towards the monitors. This was a marked contrast to outdoor measurements at the other homes. Over these five days, spikes in concentrations of all three species were closely related to the lighting of the stove and the addition of fuel events. This allowed some comparison of concentration increases associated with the different fuels. An overview of the increases is shown in Table 5-13.

Table 5-13 Summary of PM2.5, UV & BC measurement increases outdoors at Home 4

Fuel	Lighting Fire	Fuel Add 1	Fuel Add 2	Fuel Add 3	Fuel Add 4
			PM2.5, UV, BC Increase (µg m^{-3})		
Kiln dried wood	9,38,22	7,6,2	49,19,2		
Coffee Logs	28,20,18**	3,6,1	3,8,2		
Ecoal	13,18,3*	7,8,6	58,57,2	15,14,3	12,13,< 1
Newflame Plus	33,18,4**	65,87,4	10,28,< 1		
Unseasoned wood	11,10,3	28,16,6	21,9,3		

*including kiln dried wood, no fuel

**including kiln dried wood

Measurements were characterised by rapid increases and decreases in concentration. Some caution must be exercised with interpretation, as the wind direction and strength would not have been exactly the same on all five days. Generally, BC increases were highest when the fire was being lit with increases up to 22 µg m^{-3} measured outdoors. By contrast, for the 12 fuel addition events over the five days, the highest BC increase measured was 6 µg m^{-3}. At lower temperatures when the fire is being started there is likely to be more incomplete combustion which increases the BC content.

The highest $PM_{2.5}$ and WBPM measurements when fuel was added to the stove were observed when Ecoal or Newflame Plus were used. Increases in $PM_{2.5}$ of 65 µg m^{-3} and 58 µg m^{-3} were observed on separate occasions and associated increases in WBPM of 87 µg m^{-3} and 57 µg m^{-3}. The higher concentration of WBPM possibly owing to the fact that some of the micro-aethalometer measured particulates were outside the PM2.5 size fraction. The micro-aethalometer did not have a size selection sampler fitted. For each of these the BC increase was much lower at 4 µg m^{-3} and 2 µg m^{-3}. The lowest emissions were measured when Coffee Logs were added to the stove.

Home 4 did not have an extractor fan and during cooking all windows were closed. For this reason, it can be considered very unlikely that any cooking events indoors contributed to an increase in measurements outdoors.

5.1.5 Part 1: Key findings

Indoor measurements from solid-fuel burning in homes

- Most fire or stove lighting events resulted in increased $PM_{2.5}$ indoors, mainly in the range of 1-20 µg m^{-3}. Adding fuel to the fire or stove increased $PM_{2.5}$ in some cases.
- The variance observed in indoor increases of all three measured species, and across all fuels, was too large to confidently quantify the contribution of an individual fuel or individual appliance to indoor pollution although some findings were of note:
  - Increases in indoor pollutant concentrations from interactions with the open fire were not large and generally lower than those from the DEFRA exempt stove and the non-DEFRA exempt stove.
  - Use of the clearSkies Level 5 stove demonstrated some benefits for indoor air quality. Indoor $PM_{2.5}$ did not increase when adding fuel to the stove once lit. Indoor $PM_{2.5}$ increased only on some occasions when lighting the stove. At times there was actually a decrease in indoor concentrations of $PM_{2.5}$ when adding fuel.
  - No substantial or consistent benefit for indoor air quality was observed from the use of authorised, exempt or "smokeless" fuels compared with seasoned wood.
- Increases in pollutant concentrations may be more affected by participant technique or specific airflow characteristics of an individual appliance, rather than to the type of appliance or fuel.
- However, the biggest increases in $PM_{2.5}$ concentrations indoors did not relate to indoor wood or solid-fuel burning but instead were a result of cooking, especially frying, grilling and use of the oven, and particularly when the extraction fan was not used.
- Cigarette smoke, when present, contributed much more $PM_{2.5}$ than interaction with the stove. Excluding homes where cigarettes are smoked for similar future studies may give clearer results.
- Combined emissions events which take place with little or no time difference, made measurement and interpretation of the associated individual events very difficult or impossible. For example, people appear to light or refuel their fire at the same time as other chores such as cooking. More controlled experimental conditions with sufficient time separation between individual events may be more informative for future investigations.
- Increased monitoring throughout the home could improve understanding of how the open fire or stove affects overall air quality indoors, showing how emissions spread from room to room.

Outdoor measurements from solid-fuel burning in homes

- Weather conditions, particularly wind direction, played a vital part in the ability to measure pollutant increases due to fire or stove emissions outdoors. Location of the monitors was limited by the availability of a secure location. Some of the variation between homes may also have been due to flue design. Further testing could be carried out with a larger number of monitors around the home and increased provision for security of the instruments.
- Wind direction was favourable for comparison of outdoor emissions at the homes with clearSkies Level 5 and non-DEFRA exempt stoves, when kiln dried or seasoned wood was added. The $PM_{2.5}$ increase measured outdoors, due to the non-DEFRA exempt stove, was double the increase due to the clearSkies Level 5 stove. $PM_{2.5}$ increased by approx. 50 µg m^{-3} and approx. 25 µg m^{-3} respectively. Related WBPM increases were significant while associated increases in BC were much lower.

- All types of fuel tested in the non-Defra exempt stove caused significant $PM_{2.5}$ increases outdoors. This evidence does not suggest a benefit for outdoor air quality to using authorised, exempt or "smokeless" fuels compared to seasoned or unseasoned wood.
- BC increases outside were highest due to emissions from starting a fire as opposed to emissions from adding fuel to an existing fire.

5.2 Part 2: Portable measurements of BC, UV absorption and $PM_{2.5}$ along two transects.

Walks were undertaken with portable monitors along two transects: one in north London and one in south London, detailed in section 4.2.1. For both transects, 10 walks along identical routes were completed. Portable monitors measured $PM_{2.5}$ and, UV and BC. All data was location and time stamped at 30 second intervals.

5.2.1 North London monitoring route walks.

Details of the dates and times of the ten monitoring walks in north London along with weather conditions are presented in Table 5-14.

Table 5-14 Details of north London monitoring route walks

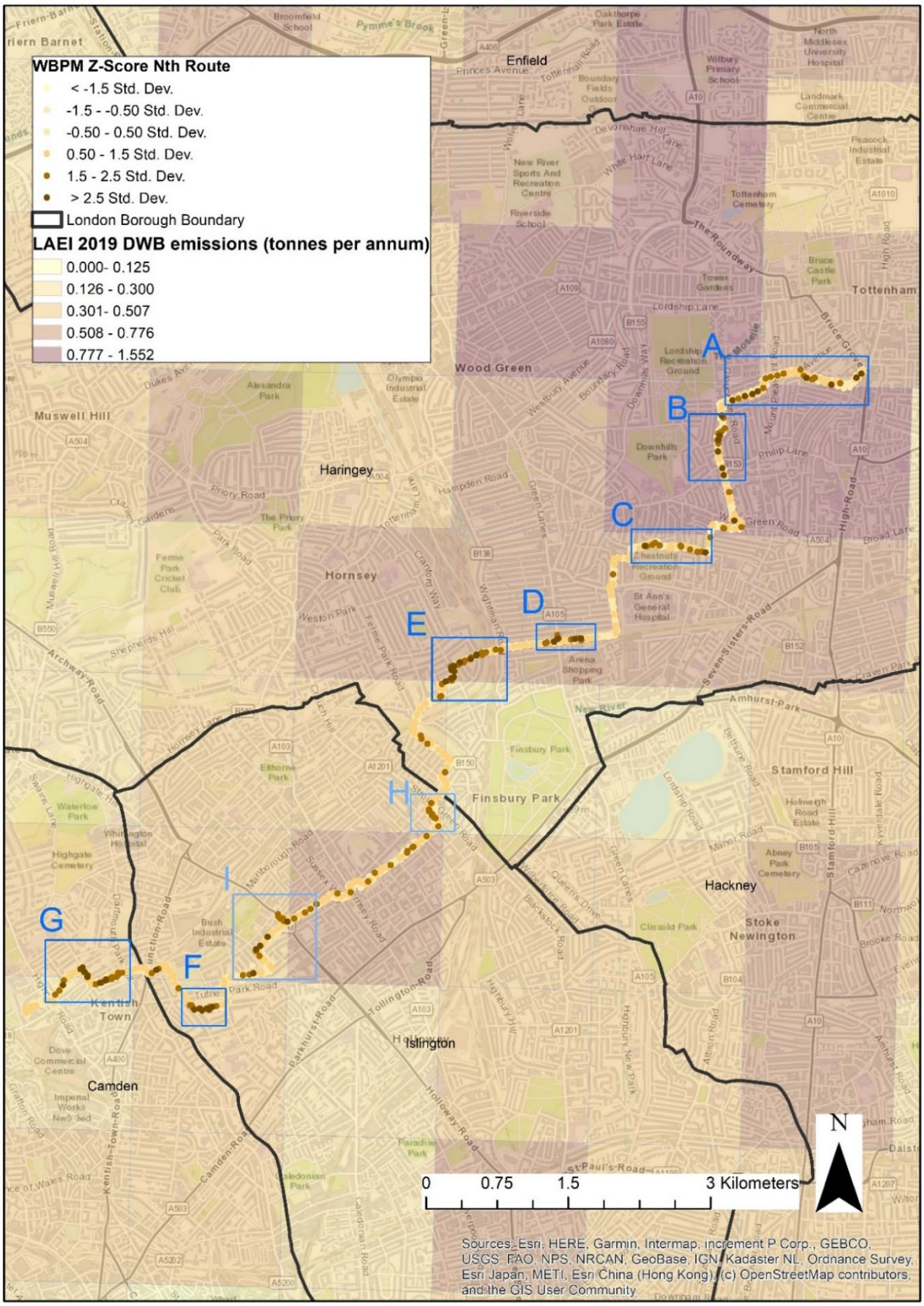
Walk ID		Date	Start	End	Duration	Temp deg C	Wind Direction	Wind Speed m s^{-1}
N-01	Tue	17/01/2023	16:35:30	18:39:30	02:04:00	1	W	2.8
N-02	Thurs	19/01/2023	18:27:00	20:46:00	02:19:00	3	W	3.9
N-03	Sat	21/01/2023	17:10:29	19:17:29	02:07:00	2	E	0.5
N-04	Sun	22/01/2023	18:32:03	20:44:03	02:12:00	0	S	0.8
N-05	Tue	24/01/2023	18:20:00	20:36:30	02:16:30	4	SE	1.8
N-06	Sat	28/01/2023	16:20:04	18:31:04	02:11:00	6	W	2.7
N-07	Mon	30/01/2023	18:35:00	20:42:30	02:07:30	6	SW	3.1
N-09	Mon	06/02/2023	18:41:59	20:42:29	02:00:30	5	E	2.4
N-10	Sat	11/02/2023	18:56:00	21:01:00	02:05:00	9	S	1.1
N-11	Sun	12/02/2023	18:42:30	20:58:00	02:15:30	8	SE	2.5

2489 individual 30 second average measurements, for each of the three species, WBPM, BC and $PM_{2.5}$, were recorded or calculated covering over 21 hours walking along the route. For each species, individual location stamped Z-scores, classified quantitatively by standard deviation difference from the mean, were mapped. Mapping was undertaken to identify clusters of high concentrations, or hotspots, along the route.

WBPM Z-score mapping on the north route is shown in Figure 5-47. Areas that contained clusters of the highest Z-score WBPM data i.e., high relative measurement data, denoted by darker coloured spots, are highlighted and labelled A-G. Other areas with slightly lower values but nonetheless notably high Z-score WBPM data, are labelled H-I. Over all ten walks, the highest concentrations of WBPM were measured in these areas, A-I.

Modelled domestic wood and solid-fuel burning emissions are also displayed on the map. This emissions layer was created for the London Atmospheric Emissions Inventory 2019 (LAEI 2019), using residential wood and solid-fuel burning emissions, as estimated by ERG. It was then spatially represented using dwelling stock data categorised by property build period and type (ERG, 2019).

Figure 5-47 WBPM Z score north route map including LAEI 2019 domestic wood and solid-fuel burning emissions



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There is a good match between measured WBPM and modelled LAEI 2019 domestic wood and solid-fuel burning emissions, especially evident in areas A-E. Table 5-15 highlights the streets identified by hotspot mapping.

Table 5-15 North route areas identified by WBPM hotspot mapping

Bruce Grove Station			St Ann's Road (B152)	Haringey		Hornsey Road (A103)	Islington	
Moorefield Road	Haringey		Warwick Gardens	Haringey		Tollington Way	Islington	
Sperling Road	Haringey		Stanhope Gardens	Haringey		Sussex way	Islington	
The Avenue	Haringey	A	Green Lanes (A105)	Haringey	D	Alexander Road	Islington	
Marden Road	Haringey		Burgoyne Road	Haringey		Holloway Road (A1)	Islington	
Higham Road	Haringey		Railway Approach	Haringey		Tavistock Terrace	Islington	I
Clonmell Road	Haringey	B	Quernmore Road	Haringey		Yerbury Road	Islington	
Summerhill Road	Haringey		Oakfield Road	Haringey		Mercers Road	Islington	
West Green Road (A504)	Haringey		Addington Road	Haringey	E	Dalmeny Road	Islington	
Elmar Road	Haringey		Albany Road	Haringey		St Georges Avenue	Islington	F
Avenue Road	Haringey		Stapleton Hall Road	Haringey		Huddleston Road	Islington	
Newsam Avenue	Haringey		Florence Road	Haringey		Station Road	Islington	
Gorleston Road	Haringey		Osbourne Road	Haringey		Junction Road	Islington	
Falmer Road	Haringey	C	Victoria Road	Haringey		Wyndham Crescent	Islington/Camden	
Clarence Road	Haringey		Upper Tollington Park Road	Haringey		Spencer Rise	Camden	
La Rose Lane	Haringey		Stroud Green Road (A1201)	Islington		York Rise	Camden	G
Cranleigh Road	Haringey		Tollington Park	Islington	H	Dartmouth Park Road	Camden	
Etherley Road	Haringey		Charteris Road	Islington		Grove End	Camden	
Conway Road	Haringey		Moray Road	Islington		Chetwynd Road	Camden	
Ritches Road	Haringey		Birnam Road	Islington		Higate Road	Camden	
			Tollington Park	Islington		Glenhurst Avenue	Camden	

Maps of the areas E and G, are shown in 5-48 and Figure 5-49. These areas include clusters of the highest relative measured WBPM. These larger scale maps show individual relative measurement values on streets and roads in the areas.

Figure 5-48 North route individual Z-scores WBPM – Area E

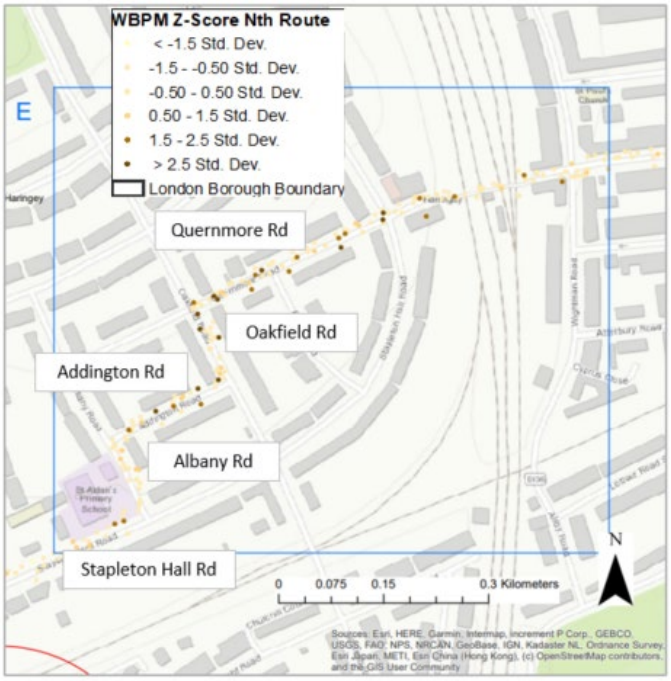
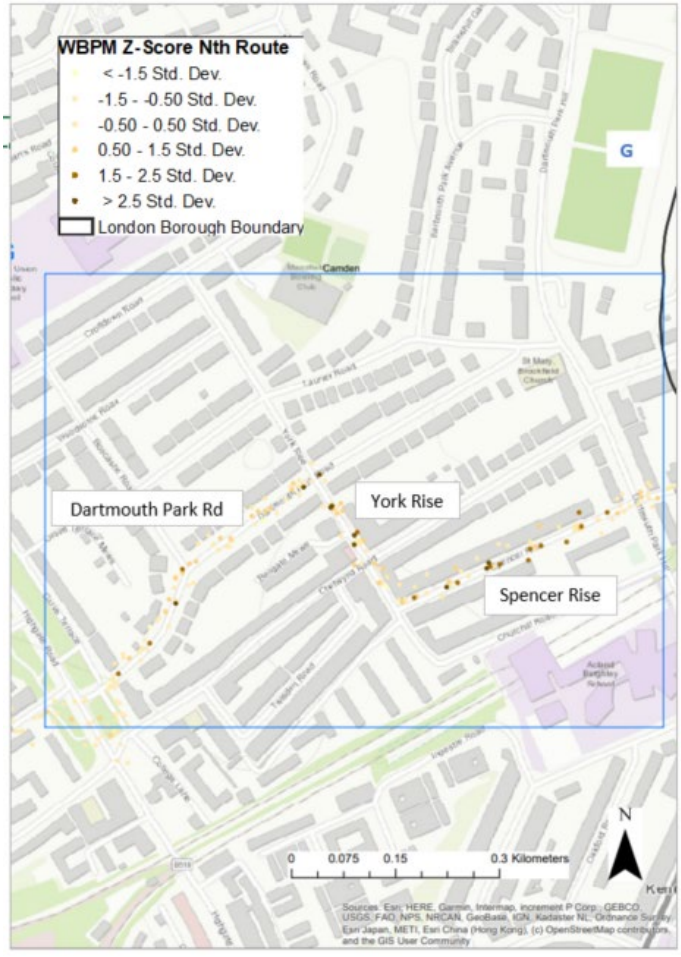


Figure 5-49 North route individual Z-scores WBPM – Area G



This report is the independent expert opinion of the author(s).

BC Z-score mapping on the north route is shown in Figure 5-50. Areas that contained clusters of high Z-score WBPM data, highlighted and labelled A-I, are also included on the BC Z-score map. All of these areas also contain clusters of high BC measurements, reinforcing the association between BC and WBPM in solid-fuel burning emissions. However, BC is also emitted by vehicle exhausts. There are areas on the BC map that do not appear or are not as prominent on the WBPM map. These areas 1-3 have clusters of high relative BC measurements, but not higher relative WBPM measurements.

Area 1 includes a small section of West Green Road (A504) as the north route crosses the road, and then includes the whole length of Elmar Road, a residential street. The higher BC measurements may be because of vehicle emissions, due to its proximity to the A504 or possibly cooking emissions from a restaurant backing onto Elmar Road. Further investigation would be required to positively identify the source. Area 2 includes Florence Road around the junction with Stapleton Hall Road, with a garage forecourt close by. Area 3 includes measurements on Station Road, then crossing Junction Road into Wyndham Crescent. Junction Road is a busy trafficked route and BC in this area may be due to vehicle emissions. Table 5-16 highlights all the streets identified by BC hotspot mapping along the north route. Although one of the limitations of using the aethalometer to calculate wood and solid-fuel burning PM is possible interference from traffic emissions in roadside locations, it is reassuring that separate areas were identified from the BC measurements that are indicative of higher traffic emissions that were not evident in the wood and solid-fuel burning PM concentrations. This supports the validity of using wood and solid-fuel burning PM calculations along quieter sideroads.

Figure 5-50 BC- Z score north route map

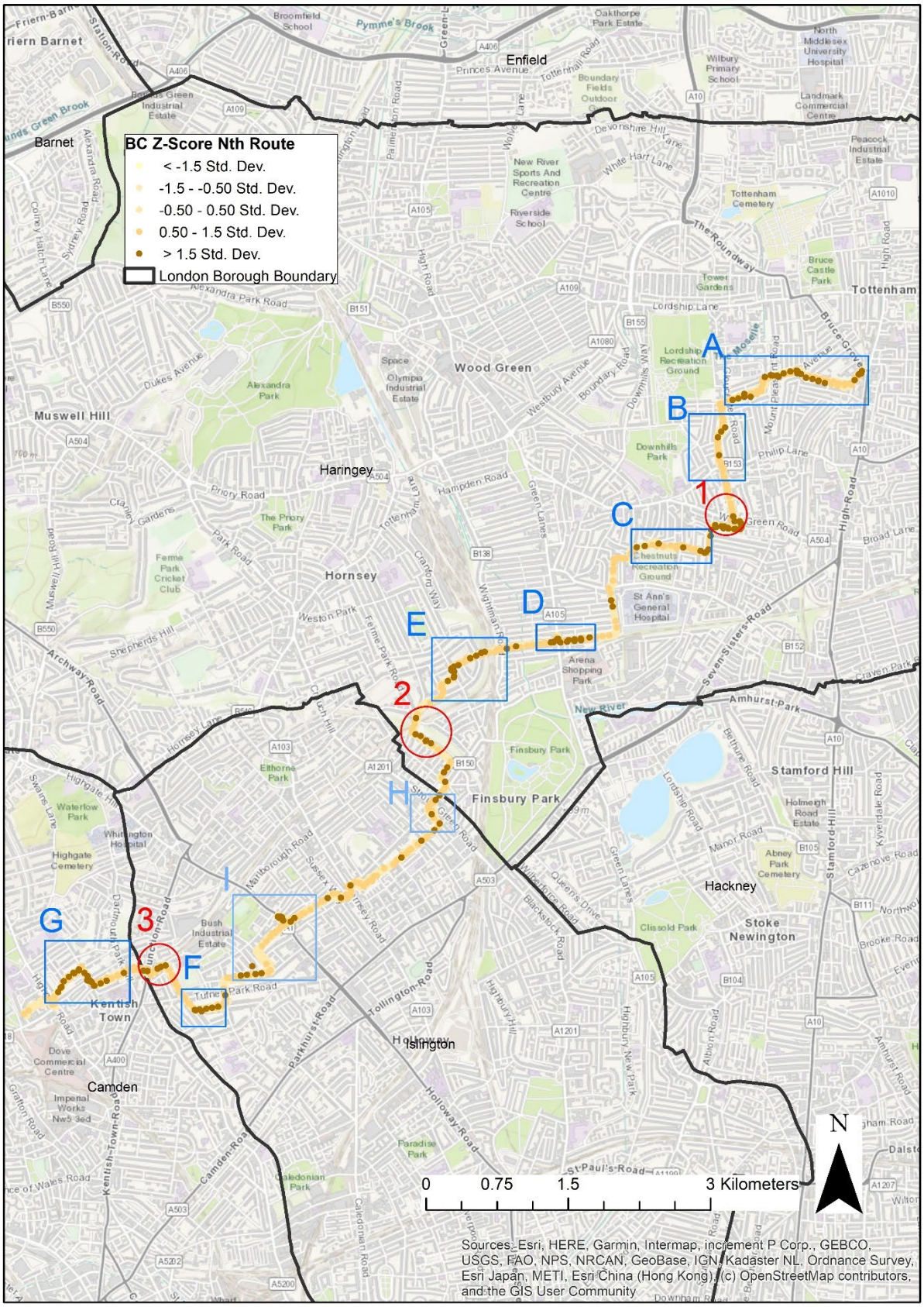


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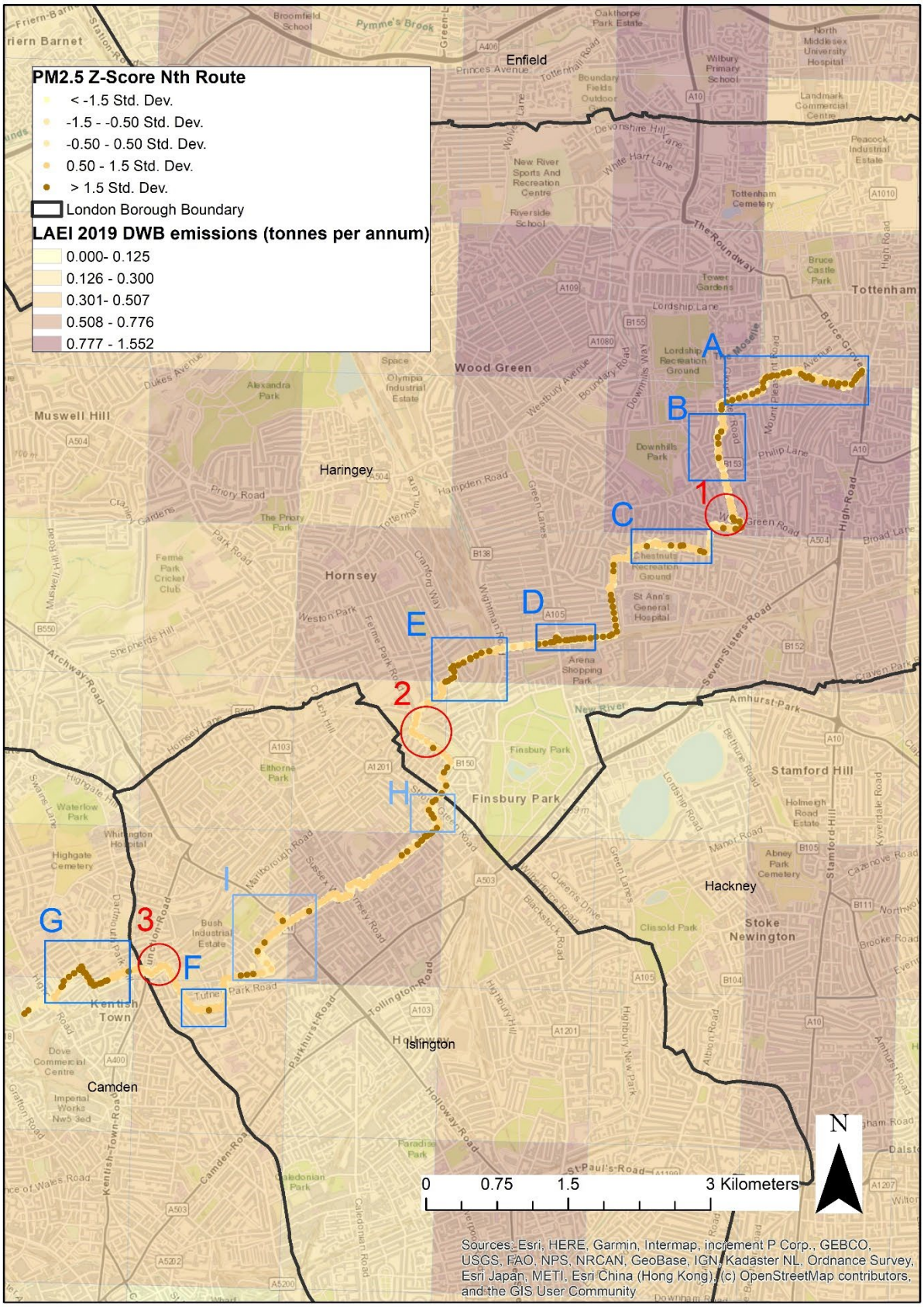
Table 5-16 North route areas identified by BC hotspot mapping

Bruce Grove Station			St Ann's Road (B152)	Haringey		Hornsey Road (A103)	Islington	
Moorefield Road	Haringey		Warwick Gardens	Haringey		Tollington Way	Islington	
Sperling Road	Haringey		Stanhope Gardens	Haringey		Sussex way	Islington	
The Avenue	Haringey	A	Green Lanes (A105)	Haringey	D	Alexander Road	Islington	
Marden Road	Haringey		Burgoyne Road	Haringey		Holloway Road (A1)	Islington	
Higham Road	Haringey		Railway Approach	Haringey		Tavistock Terrace	Islington	I
Clonmell Road	Haringey	B	Quernmore Road	Haringey		Yerbury Road	Islington	
Summerhill Road	Haringey		Oakfield Road	Haringey		Mercers Road	Islington	
West Green Road (A504)	Haringey	1	Addington Road	Haringey	E	Dalmeny Road	Islington	
Elmar Road	Haringey		Albany Road	Haringey		St Georges Avenue	Islington	F
Avenue Road	Haringey		Stapleton Hall Road	Haringey		Huddleston Road	Islington	
Newsam Avenue	Haringey		Florence Road	Haringey	2	Station Road	Islington	
Gorleston Road	Haringey		Osbourne Road	Haringey		Junction Road	Islington	3
Falmer Road	Haringey	C	Victoria Road	Haringey		Wyndham Crescent	Islington/Camden	
Clarence Road	Haringey		Upper Tollington Park Road	Haringey		Spencer Rise	Camden	
La Rose Lane	Haringey		Stroud Green Road (A1201)	Islington		York Rise	Camden	G
Cranleigh Road	Haringey		Tollington Park	Islington	H	Dartmouth Park Road	Camden	
Etherley Road	Haringey		Charteris Road	Islington		Grove End	Camden	
Conway Road	Haringey		Moray Road	Islington		Chetwynd Road	Camden	
Ritches Road	Haringey		Birnam Road	Islington		Higate Road	Camden	
			Tollington Park	Islington		Glenhurst Avenue	Camden	

$PM_{2.5}$ Z-score mapping on the north route is shown in Figure 5-51. Areas that contained clusters of high Z-score WBPM data, highlighted and labelled A-I, and areas that contained clusters of high Z-score BC data, labelled 1-3 are also included on the $PM_{2.5}$ Z-score map. Higher relative measurements of $PM_{2.5}$ are a feature of all areas A-I, but not as prominent in BC areas 2 and 3. This is likely because BC is a lesser contributor than WBPM, to overall $PM_{2.5}$ composition. The 2019 wood and solid-fuel burning emissions LAEI layer is included on the $PM_{2.5}$ Z-score map. Areas A-E show good agreement between measured $PM_{2.5}$ and modelled wood and solid-fuel burning PM.

Figure 5-51 PM2.5- Z score north route map including LAEI 2019 domestic wood and solid-fuel burning emissions



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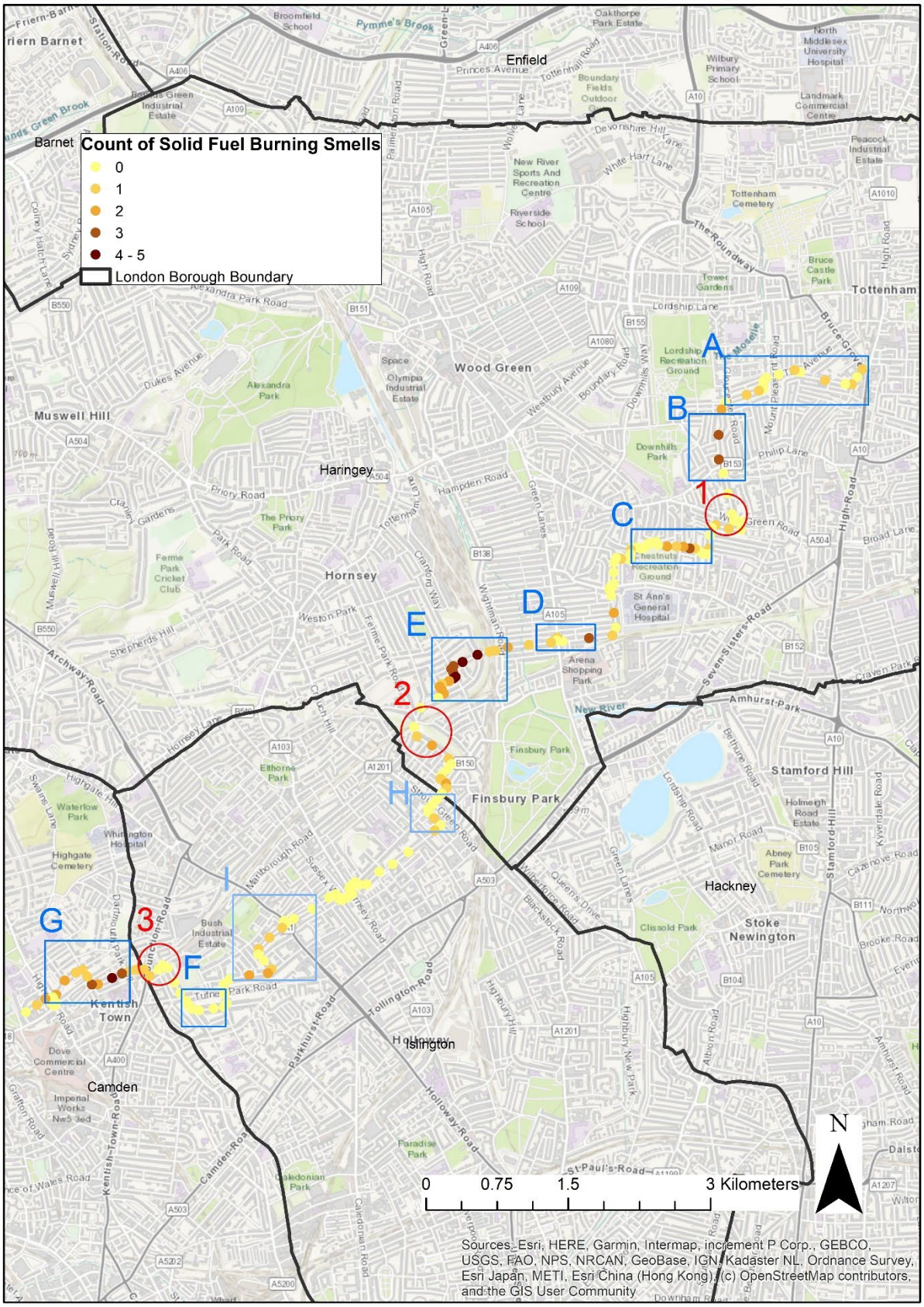
Solid-fuel burning smells encountered when doing the walks were recorded. A note was made of where on the street or road – beginning, middle or end - a solid-fuel burning smell was encountered on each walk. The number of solid-fuel burning smells encountered across the 10 route walks was then mapped to create a solid-fuel burning smell frequency map. Figure 5-52. The highest frequencies were in areas with clusters of higher relative WBPM measurements, particularly areas B, C, D, E and G. This correlation between solid-fuel burning smells and higher WBPM measurements may suggest that higher quantities of particulates are being inhaled whenever solid-fuel burning is smelt.

Figure 5-52 Solid-fuel smell frequency north route map



This report is the independent expert opinion of the author(s).

5.2.2 South London monitoring route walks

Details of the dates and times of the ten monitoring walks in south London along with weather conditions are presented in are presented in Table 5-17.

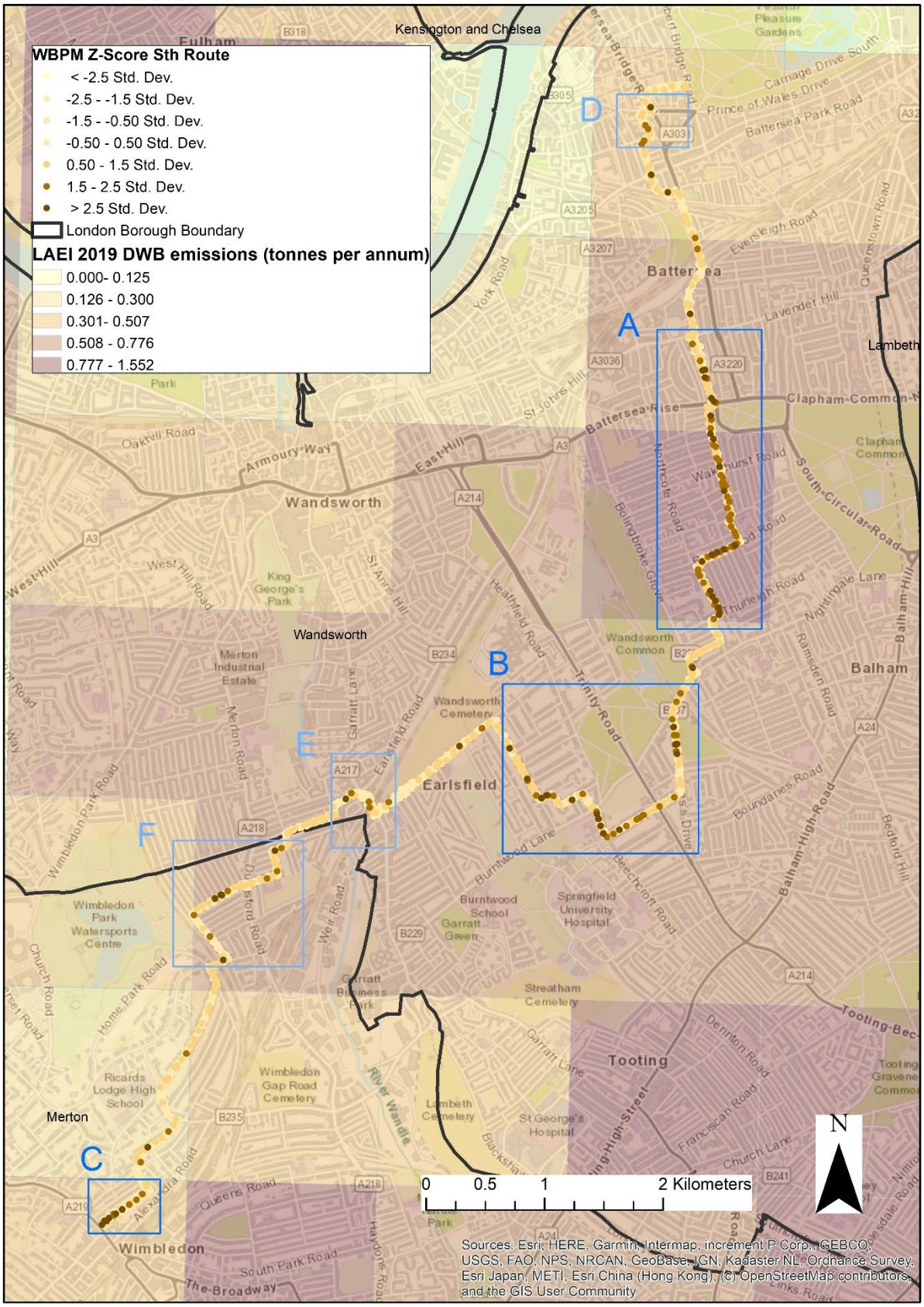
Table 5-17 Details of south London monitoring route walks

Walk ID		Date	Start	End	Duration	Temp deg C	Wind Direction	Wind Speed m s^{-1}
S-05	Sun	15/01/2023	17:24:03	19:42:33	02:18:30	5	SW	3.9
S-06	Mon	16/01/2023	19:56:30	22:10:30	02:14:00	1	W	2.8
S-07	Fri	20/01/2023	15:59:29	18:21:59	02:22:30	5	NW	3.5
S-08	Sat	21/01/2023	20:40:59	22:48:59	02:08:00	0	-	0.1
S-09	Sun	22/01/2023	14:59:03	17:20:33	02:21:30	3	S	1.1
S-10	Sat	28/01/2023	19:54:34	22:00:34	02:06:00	5	W	1.3
S-11	Sun	29/01/2023	16:46:30	18:58:00	02:11:30	8	SW	4.7
S-12	Sat	04/02/2023	18:15:29	20:26:59	02:11:30	9	W	3.5
S-13	Sun	05/02/2023	15:13:00	17:22:30	02:09:30	7	N	1.7
S-14	Thurs	09/02/2023	19:57:59	22:00:29	02:02:30	5	W	1.3

2653 individual 30 second average measurements, for each of the three species, WBPM, BC and $PM_{2.5}$ were recorded over more than 22 hours of monitoring along the route. For each species, individual location stamped Z-scores, classified quantitatively by standard deviation difference from the mean, were mapped. Mapping was undertaken to help identify clusters of high concentrations, or hotspots, along the route.

WBPM Z-score mapping on the south route is shown in Figure 5-53. Areas that contained clusters of the highest Z-score WBPM data, i.e., high relative measurement data, denoted by darker coloured spots, are highlighted and labelled A-C. Other areas with slightly lower values but nonetheless notably high Z-score WBPM data, are labelled D-F. Over all ten walks, the highest concentrations of WBPM were measured in these areas A-F. The LAEI 2019 domestic wood and solid-fuel burning layer is included on the WBPM Z-score map. There are areas of good agreement between measured WBPM and modelled wood and solid-fuel burning PM, especially evident in areas A and B. Table 5-18 highlights the roads and streets in each of the areas A-F.

Figure 5-53 WBPM - Z score south route map including LAEI 2019 domestic wood and solid-fuel burning emissions



This report is the independent expert opinion of the author(s).

Table 5-18 South route areas identified by WBPM hotspot mapping

Wimbledon			Penwith Road	Wandsworth		Broomwood Road	Wandsworth	
Compton Road	Merton	C	Garratt Lane	Wandsworth	E	Wroughton Road	Wandsworth	
Worcester Road	Merton		Magdalen Road	Wandsworth		Chatto Road	Wandsworth	A
Woodside	Merton		Ellerton Road	Wandsworth		Leathwaite Road	Wandsworth	
Glendale Drive	Merton		Burntwood Grange Road	Wandsworth		Sth Circular Road (A205)	Wandsworth	
Bernard Gardens	Merton		Burntwood Close	Wandsworth		Attenburg Gardens	Wandsworth	
Leopold Road	Merton		Collamore Avenue	Wandsworth		Dorothy Road	Wandsworth	
Vineyard Hill Road	Merton		Lyminge Gardens	Wandsworth		Amies Street	Wandsworth	
Home Park Road	Merton		Burntwood Lane (B229)	Wandsworth	B	Latchmere Road (A3220)	Wandsworth	
Arthur Road	Merton		Beechcroft Road	Wandsworth		Abercrombie Street	Wandsworth	
Melrose Avenue	Merton		Brodrick Road	Wandsworth		Frere Street	Wandsworth	
Ashen Grove	Merton		St James's Drive	Wandsworth		Battersea Park Road (A3205)	Wandsworth	
Havana Road	Merton	F	Bellvue Road (B237)	Wandsworth		Stanmer Street	Wandsworth	
Lucien Road	Merton		Bollingbroke Grove (B229)	Wandsworth		Shuttleworth Road	Wandsworth	
Mount Road	Wandsworth		Granard Road	Wandsworth		Bridge Lane	Wandsworth	D
Acuba Road	Wandsworth		Hendrick Avenue	Wandsworth		Surrey Lane	Wandsworth	
Ravensbury Road	Wandsworth		Thurleigh Road	Wandsworth	A	Battersea Bridge Road (A3220)	Wandsworth	
Ravensbury Terrace	Wandsworth		Montholme Road	Wandsworth		Petworth Street	Wandsworth	
						Battersea Park	Wandsworth	

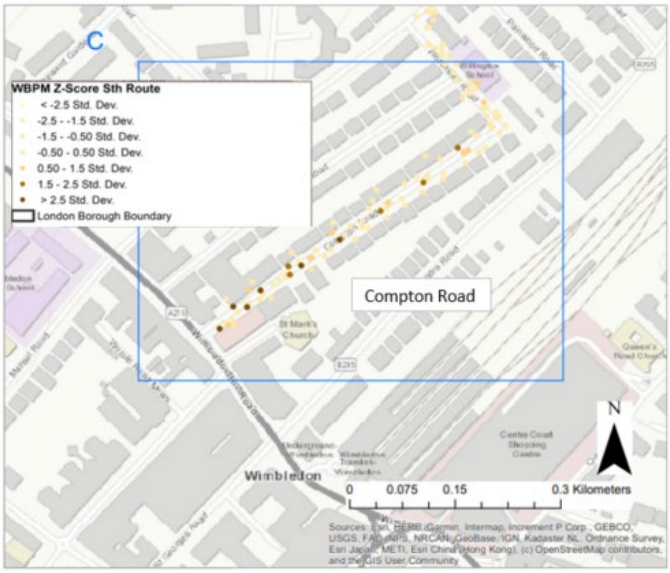
Maps of the areas A, B and C, with clusters of the highest relative WBPM measurements, are shown in Figure 5-54, Figure 5-55 and Figure 5-56. Only areas A, B and C are shown in detail as these areas have the highest relative measured WBPM. These larger scale maps show individual relative measurement values on streets and roads in these areas.

Figure 5-54 South route individual Z-scores WBPM – Area A

This report is the independent expert opinion of the author(s).

Figure 5-55 South route individual Z-scores WBPM - Area B

Figure 5-56 South route individual Z-scores WBPM – Area C



This report is the independent expert opinion of the author(s).

Figure 5-57 BC- Z score south route map

This report is the independent expert opinion of the author(s).

BC Z-score mapping on the south route is shown in Figure 5-57. Areas that contained clusters of high Z-score WBPM data, highlighted and labelled A-F, are also included on the BC Z-score map. All of these areas also contain clusters of high BC measurements, reinforcing the association between BC and WBPM in solid-fuel burning emissions. There are areas on the BC map however that do not appear or are not as prominent on the WBPM map. So, these areas 1-3 have clusters of high relative BC measurements, but not higher relative WBPM measurements. This combination of WBPM and BC mapping improves the sensitivity of the method to differentiate genuine WBPM from other types of emissions.

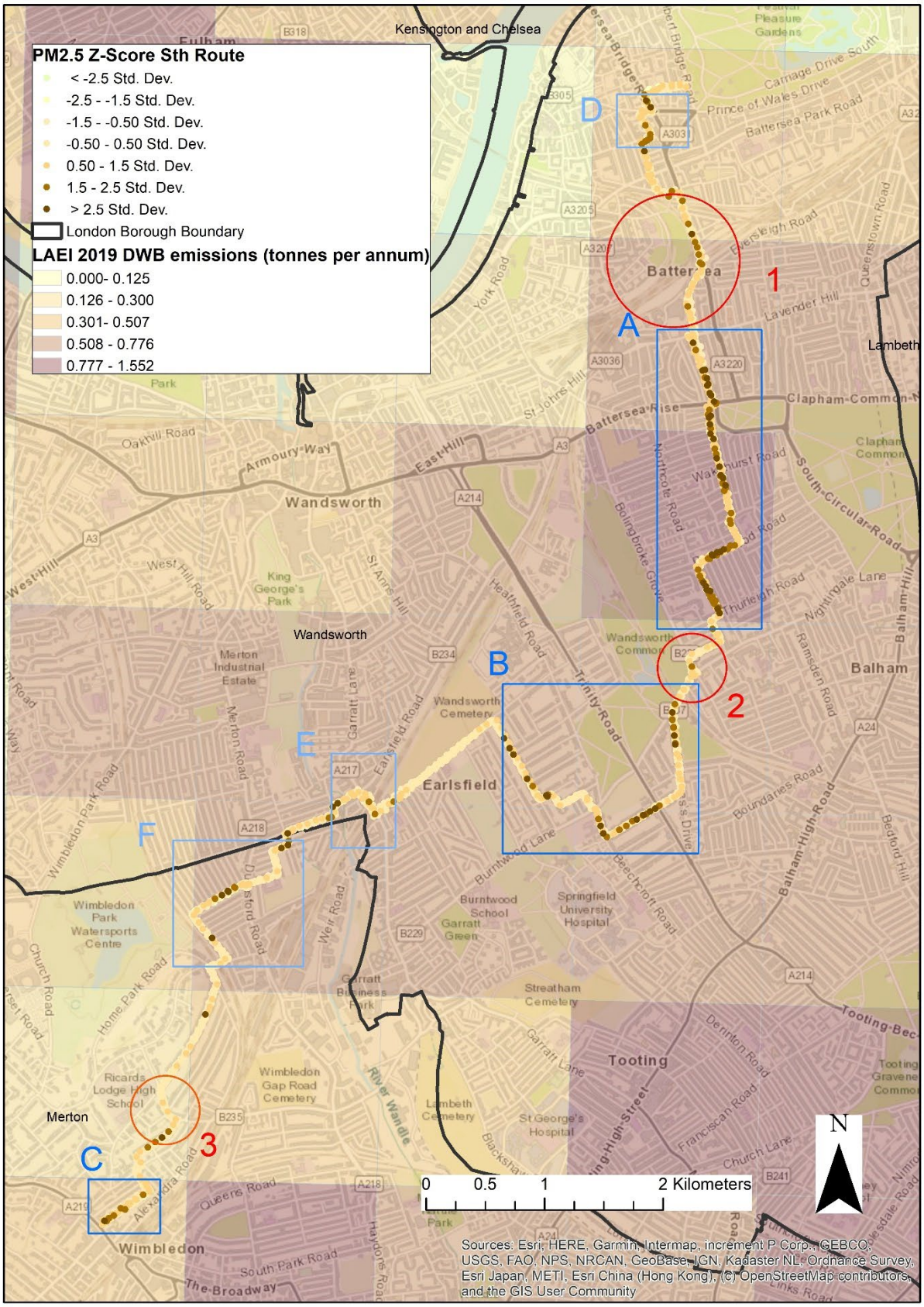
Area 1 includes the entire stretch walked along Latchmere Road (A3220), including the Latchmere Road tunnel section under railway lines. Diesel emissions from this heavily trafficked route are the likely source. Area 1 also includes Dorothy Road, which is opposite a large supermarket car park, a possible source of diesel emissions. Area 2 highlights Bellevue Road (B229), a busy trafficked route which is the likely source of BC measured. Bellevue Road is also included in Area B however the section highlighted by Area 2 extends further along the road. Area 3 includes measurements on Leopold Road where a traffic link is possible. Table 5-19 highlights all the streets identified by BC hotspot mapping along the south route.

Table 5-19 South route areas identified by BC hotspot mapping

Wimbledon			Penwith Road	Wandsworth		Broomwood Road	Wandsworth	
Compton Road	Merton	C	Garratt Lane	Wandsworth	E	Wroughton Road	Wandsworth	
Worcester Road	Merton		Magdalen Road	Wandsworth		Chatto Road	Wandsworth	A
Woodside	Merton		Ellerton Road	Wandsworth		Leathwaite Road	Wandsworth	
Glendale Drive	Merton		Burntwood Grange Road	Wandsworth		Sth Circular Road (A205)	Wandsworth	
Bernard Gardens	Merton		Burntwood Close	Wandsworth		Attenburg Gardens	Wandsworth	
Leopold Road	Merton	3	Collamore Avenue	Wandsworth		Dorothy Road	Wandsworth	
Vineyard Hill Road	Merton		Lyminge Gardens	Wandsworth		Amies Street	Wandsworth	1
Home Park Road	Merton		Burntwood Lane (B229)	Wandsworth	B	Latchmere Road (A3220)	Wandsworth	
Arthur Road	Merton		Beechcroft Road	Wandsworth		Abercrombie Street	Wandsworth	
Melrose Avenue	Merton		Brodrick Road	Wandsworth		Frere Street	Wandsworth	
Ashen Grove	Merton		St James's Drive	Wandsworth		Battersea Park Road (A3205)	Wandsworth	
Havana Road	Merton	F	Bellevue Road (B237)	Wandsworth	2	Stanmer Street	Wandsworth	
Lucien Road	Merton		Bollingbroke Grove (B229)	Wandsworth		Shuttleworth Road	Wandsworth	
Mount Road	Wandsworth		Granard Road	Wandsworth		Bridge Lane	Wandsworth	D
Acuba Road	Wandsworth		Hendrick Avenue	Wandsworth		Surrey Lane	Wandsworth	
Ravensbury Road	Wandsworth		Thurleigh Road	Wandsworth	A	Battersea Bridge Road (A3220)	Wandsworth	
Ravensbury Terrace	Wandsworth		Montholme Road	Wandsworth		Petworth Street	Wandsworth	
						Battersea Park	Wandsworth	

$PM_{2.5}$ Z-score mapping on the south route is shown in Figure 5-58. Areas that contained clusters of high Z-score WBPM data, highlighted and labelled A-F, and additional areas that contained clusters of high Z-score BC data, labelled 1-3 are also included on the $PM_{2.5}$ Z-score map. Higher relative measurements of $PM_{2.5}$ are a feature of all areas A-F, but not as prominent in BC areas 1-3. This is likely because BC is a lesser contributor than WBPM, to overall $PM_{2.5}$ composition. The 2019 LAEI domestic wood and solid-fuel burning emissions layer is included on the $PM_{2.5}$ Z-score map. There are areas of good correlation between measured $PM_{2.5}$ and modelled wood and solid-fuel burning PM, especially in area A.

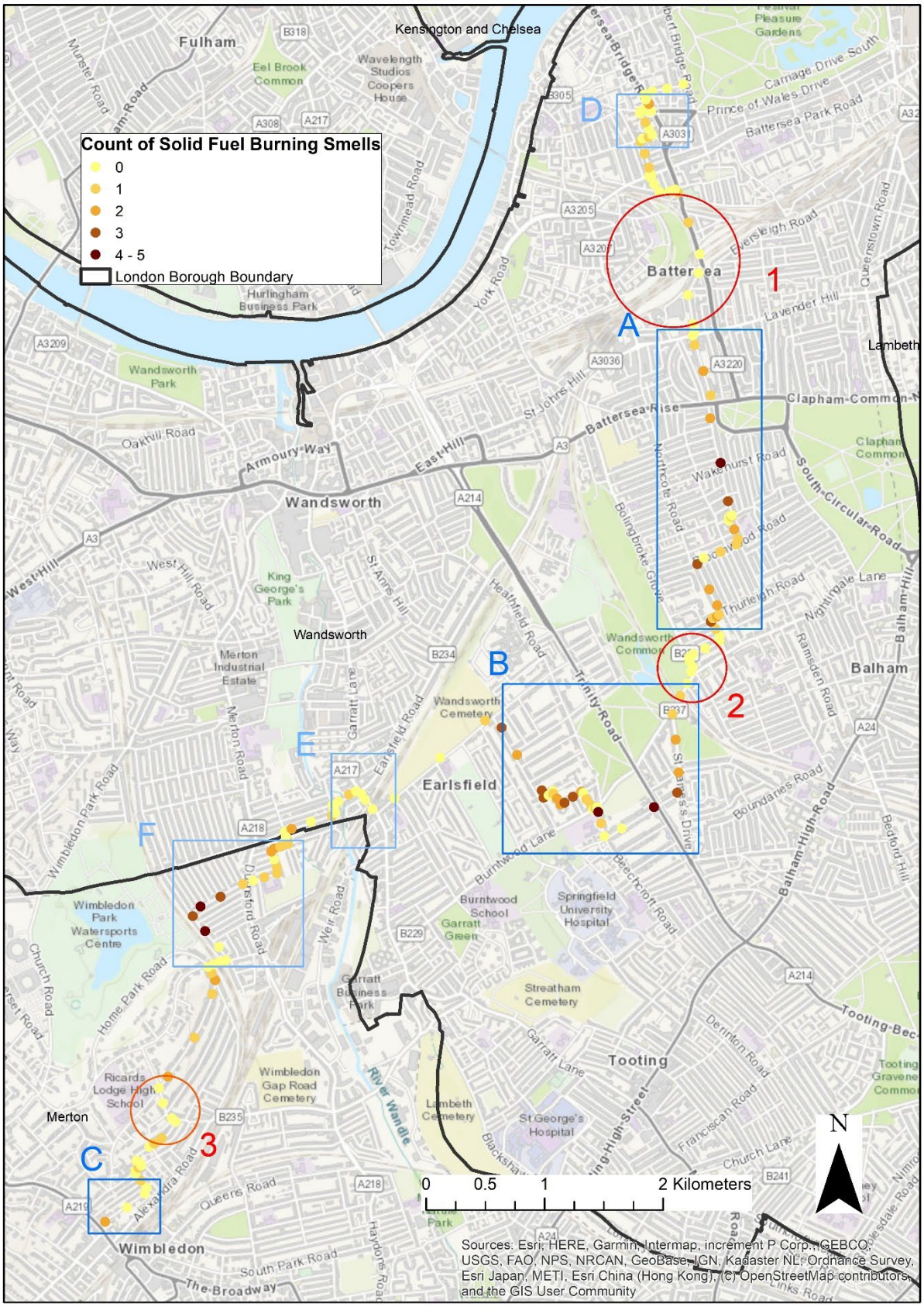
Figure 5-58 PM2.5- Z score south route map including LAEI 2019 domestic wood and solid-fuel burning emissions



This report is the independent expert opinion of the author(s).

Solid-fuel burning smells encountered when doing the walks were recorded. A note was made of where on the street or road - beginning, middle or end - the smell was encountered. The number of solid-fuel burning smells encountered across the 10 route walks was then mapped to create a solid-fuel burning smell frequency map. Figure 5-59. The highest frequencies were in area A and B showing a good correlation with WBPM measurements. There was also a high frequency of smells encountered in area F, another area with higher WBPM measurements.

Figure 5-59 Solid-fuel smell frequency south route map



This report is the independent expert opinion of the author(s).

5.2.3 Part 2: Key findings

- Mapping WBPM, BC and $PM_{2.5}$, Z-score relative measurement data, along walking routes highlighted relative concentrations along the routes enabling identification of areas with clusters of higher measurements, or 'hotspots' of pollution related to each species.
- The close association observed between mapped BC and WBPM hotspots, validated the mapping method used, as both are known to be present in solid-fuel and wood burning emissions.
- Some areas with increased BC were not associated with increased WBPM. This gives confidence in the method to differentiate between wood and solid-fuel burning and other sources of BC such as traffic.
- $PM_{2.5}$ hotspots matched well with WBPM hotspots providing evidence that these were caused by wood and solid-fuel burning
- There was good correlation between LAEI modelled $PM_{2.5}$ from wood and solid-fuel burning and measurements of WBPM and $PM_{2.5}$. This type of mapping methodology could contribute to inform future modelling in some areas with less good agreement.
- The LAEI 2019 domestic wood and solid-fuel burning map was created using residential wood and solid-fuel burning emissions, estimated by ERG, which were spatially represented using dwelling stock data categorised by property build period and type. This may be a good representation of the potential for wood or solid-fuel to be burned in an area whereas mapping based on measurements could provide additional information about whether solid-fuels are being burned or not.
- Mapped solid-fuel burning smells encountered during monitoring walks, correlated well with WBPM measurements, supporting the use of this method used to identify solid-fuel and wood burning hotspots.
- Good correlation between mapping solid-fuel burning smells and $PM_{2.5}$ measurements and WBPM, shows that encountering a solid-fuel burning smell means particulates are being inhaled.

5.3 Part 3: Fixed aethalometer measurements

5.3.1 Percentage contribution of wood and solid-fuel burning PM to annual mean

The percentage contribution of wood and solid-fuel burning to ambient PM concentrations was calculated for each site. Annual mean concentrations of PM associated with wood and solid-fuel burning, along with annual mean $PM_{2.5}$ and PM_{10} concentrations are shown in Table 5-20 for each site, as described in section 4.3, for the years 2020, 2021 and 2022. The percentage contribution of wood and solid-fuel burning PM to the total annual mean $PM_{2.5}$ and PM_{10} concentrations was also calculated and are shown in Table 5-20, Figure 5-60 and Figure 5-61.

Table 5-20: Annual mean concentrations of WBPM and percentage contribution to annual mean $PM_{2.5}$ and PM_{10} concentrations in 2020 to 2022. Results with annual data capture rate < 75% is marked in red italics and should be considered with caution.

	Total PM from wood and solid-fuel burning (µg m^{-3})	$PM_{2.5}$		PM_{10}	
		Total Concentration (µg m^{-3})	% from wood and solid-fuel burning	Total Concentration (µg m^{-3})	% from wood and solid-fuel burning
2020					
Chilbolton	0.58	8	7	12	5
Honor Oak Park	0.85	9	9	14	6
North Kensington	0.70	8	9	13	5
2021					
Chilbolton	*0.64*	*7*	*9*	*11*	*6*
Honor Oak Park	0.70	9	8	13	5
North Kensington	0.62	9	7	14	4
2022					
Chilbolton	0.61	8	8	12	5
Honor Oak Park	0.76	8	9	13	6
North Kensington	0.76	9	8	15	5

Figure 5-60: Percentage contribution of PM from wood and solid-fuel burning to annual $PM_{2.5}$ concentrations

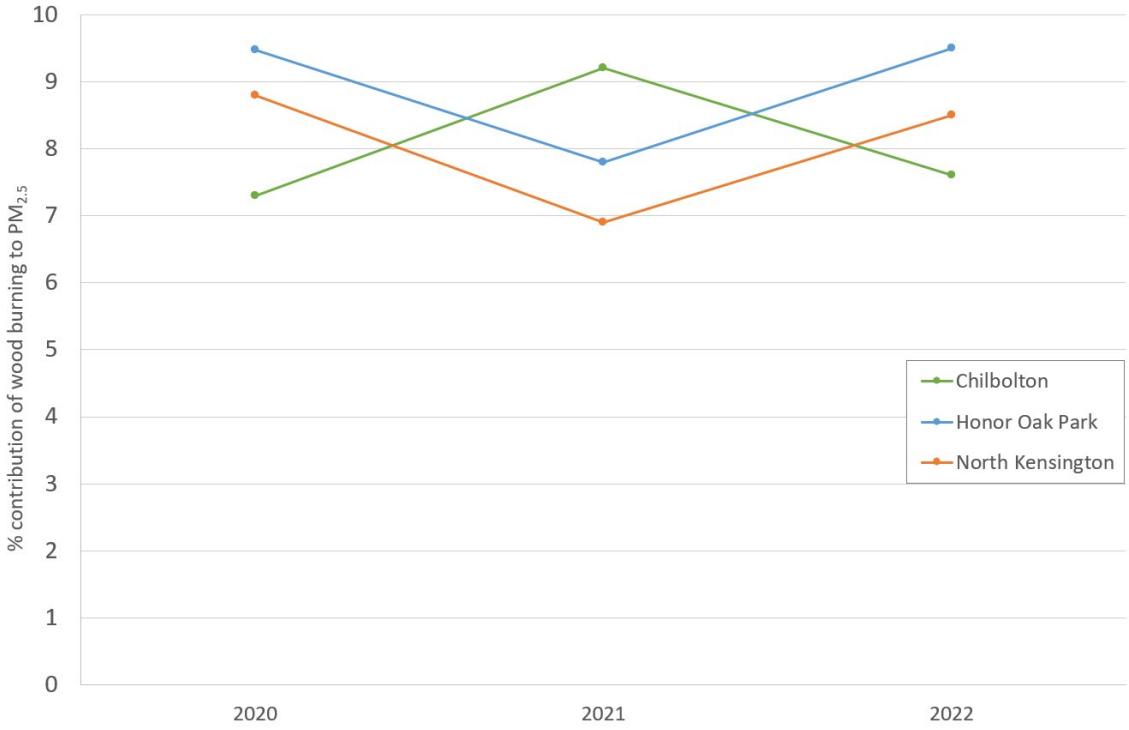
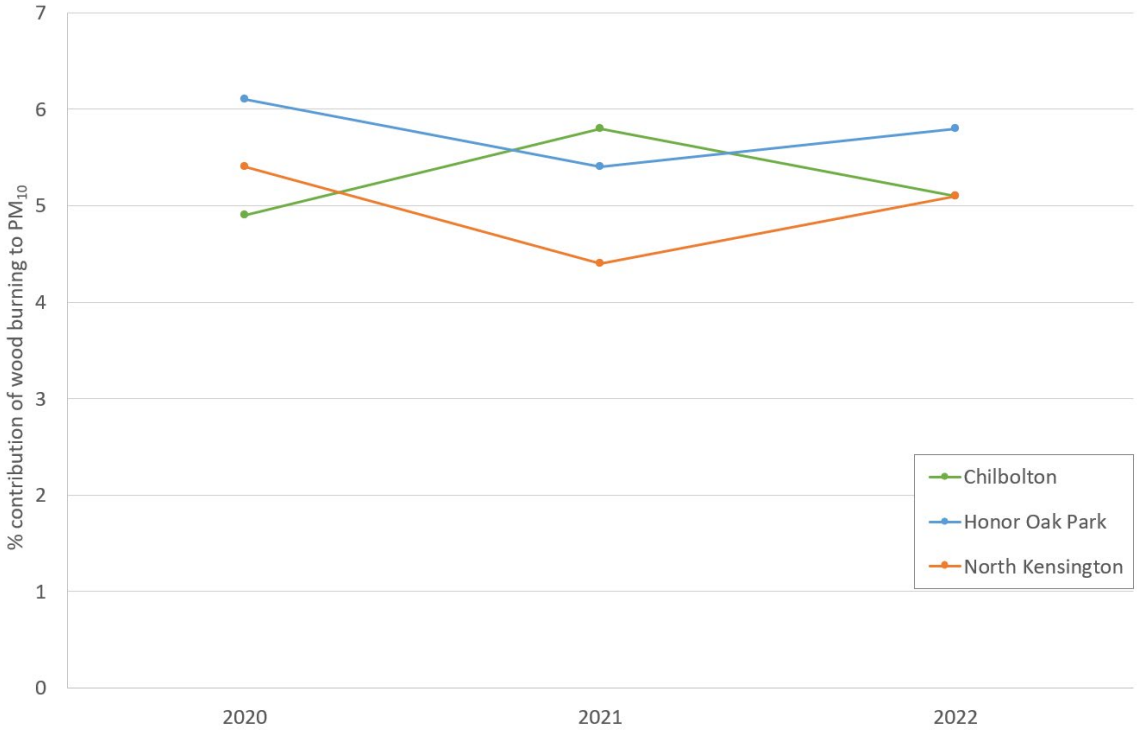


Figure 5-61: Percentage contribution of PM from wood and solid-fuel burning to annual PM_{10} concentrations



The results show that emissions from wood and solid-fuel burning contributed 7-9% of $PM_{2.5}$ concentrations at rural and background locations in each year. Ambient pollution concentrations are influenced by a variety of factors, including local emissions, long range transport and meteorology. The

percentage of $PM_{2.5}$ from wood and solid-fuel burning was greater in 2020 and 2022 at Honor Oak Park and North Kensington and less in 2021. The opposite is true at Chilbolton.

A similar pattern was seen for the contribution of wood and solid-fuel burning to annual PM_{10} concentrations. Wood and solid-fuel burning was the source of 4-6% of PM_{10} measured in urban background locations in London. At the rural site in Chilbolton, annual PM_{10} concentrations were greater in 2020 and 2022 than in 2021 and wood and solid-fuel burning concentrations showed little variation for each year so made greater percentage contribution to PM_{10} concentrations in 2021.

5.3.2 Urban contribution to PM from wood and solid-fuel burning

The urban contribution to PM from wood and solid-fuel burning was calculated using the methodology developed by ERG for the LAEI 2016 (Transport for London, 2016), which was based on the Lenschow approach[28] (Lenschow, 2001). This approach considers that pollution concentrations in urban locations include contributions from local urban sources as well as a regional background that includes $PM_{2.5}$ from outside the UK (Font et al. 2022). Generally, this contribution is derived using average concentrations from a rural location, unaffected by urban sources. However, determining the contribution of the regional background to PM from wood and solid-fuel burning is not straightforward since there are local sources of this pollutant in rural locations. The LAEI methodology addressed this by using the minimum concentration measured at a rural site during the afternoon to represent the regional background concentration.

For the years 2020 to 2022, the rural site in Chilbolton, which is part of Defra's black carbon network, was used to determine the regional background concentrations. The site is upwind of London at the prevailing wind direction so is should not be significantly impacted by pollution from London. The diurnal concentration profiles of wood and solid-fuel burning PM for the Chilbolton site and sites in London are shown in Figure 5-62 . This illustrates the raised concentrations of PM from wood and solid-fuel burning in the evenings at all sites, indicating local sources. The afternoon minimum concentrations of wood and solid-fuel burning PM at Chilbolton, designated as the regional background, are indicated by the dotted line in Figure 5-62 and shown in Table 5-21. The concentration was very similar for each year.

[28] Lenschow, P., Abraham, H.J. Kutzner, K. Lutz, M. Preuß, J.D., Reichenbächer, W. Some ideas about the sources of PM10. Atmos. Environ., 35 (2001), pp. S23-S33

Figure 5-62: Diurnal concentrations of PM from wood and solid-fuel burning. The plots were produced using the openair package in R [29, 30]

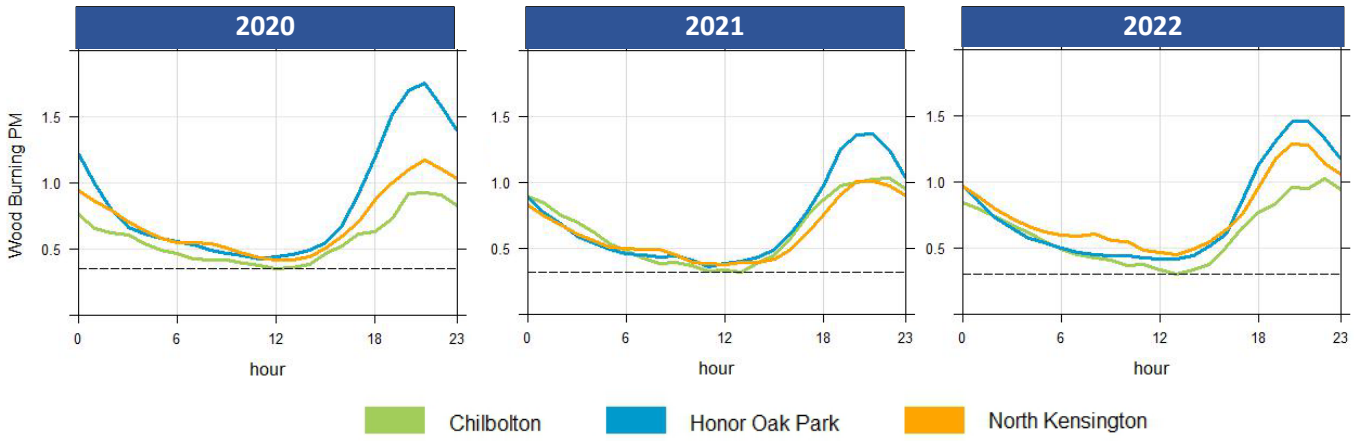


Table 5-21: Regional background concentrations of PM from wood and solid-fuel burning (µg m^{-3})

	2020	2021	2022
Regional background wood and solid-fuel burning PM	0.35	0.32	0.30

The estimated urban contribution for London for each year was calculated using the mean of the annual wood and solid-fuel burning PM concentrations at North Kensington and Honor Oak Park urban background sites and subtracting the regional background concentrations. The results are shown in Table 5-22.

Table 5-22: London urban contribution of PM from wood and solid-fuel burning (µg m^{-3})

	2020	2021	2022
London urban wood and solid-fuel burning PM	0.43	0.34	0.46

5.3.3 Temporal variations at Honor Oak Park

The Honor Oak Park site was chosen for a more detailed examination of variations in wood and solid-fuel burning PM concentrations over time between 1st January 2020 and 7th March 2023 since this site measured the greatest concentrations of PM from wood and solid-fuel burning of the sites in London and as a relatively new site has not previously been analysed in detail for this metric. Figure 5-63 shows the variation in average concentrations by hour of day, month of year and day of week. The plots were produced using the openair package in R (Carslaw and Ropkins, 2012, Carslaw, 2019). This shows a clear seasonal pattern with greater average concentrations of wood and solid-fuel burning PM in winter pointing to home heating: the greatest concentrations were measured in the months of November, December and

[29] Carslaw, D.C. and K. Ropkins, (2012). openair — an R package for air quality data analysis. Environmental Modelling & Software. Volume27-28,pp. 52–61.

[30] Carslaw, D.C. (2019). The openair manual — open-source tools for analysing air pollution data. Manual for version 2.6-6, University of York.

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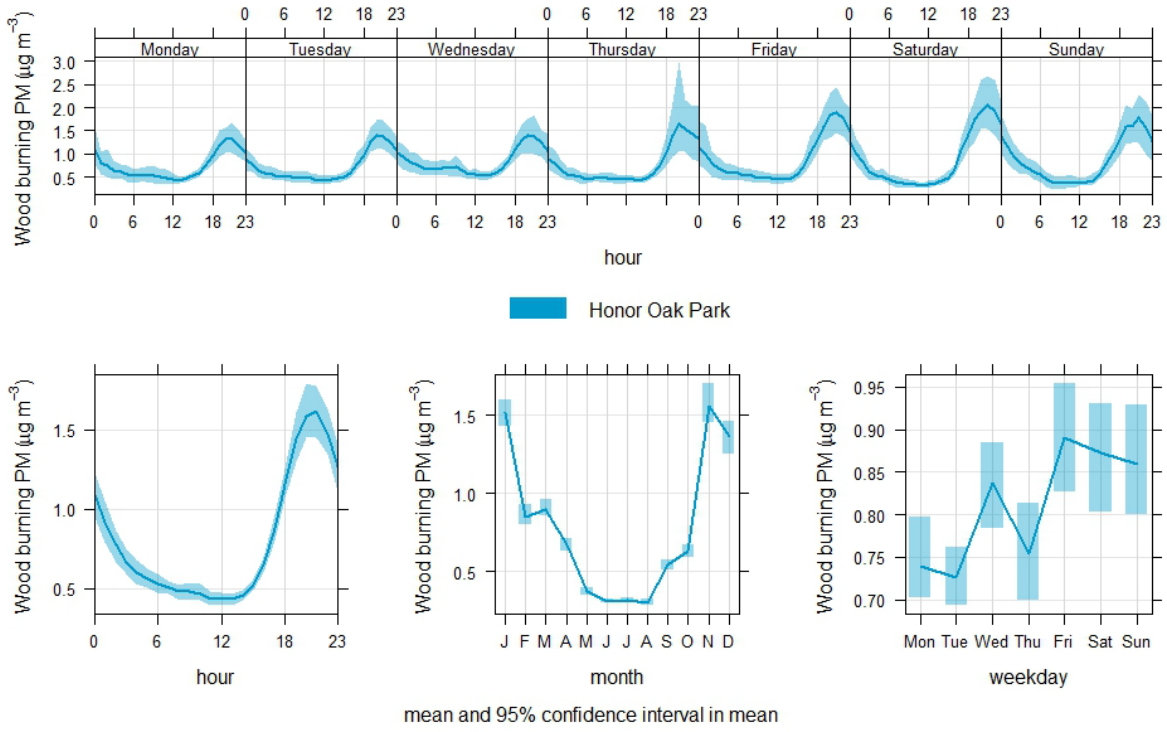
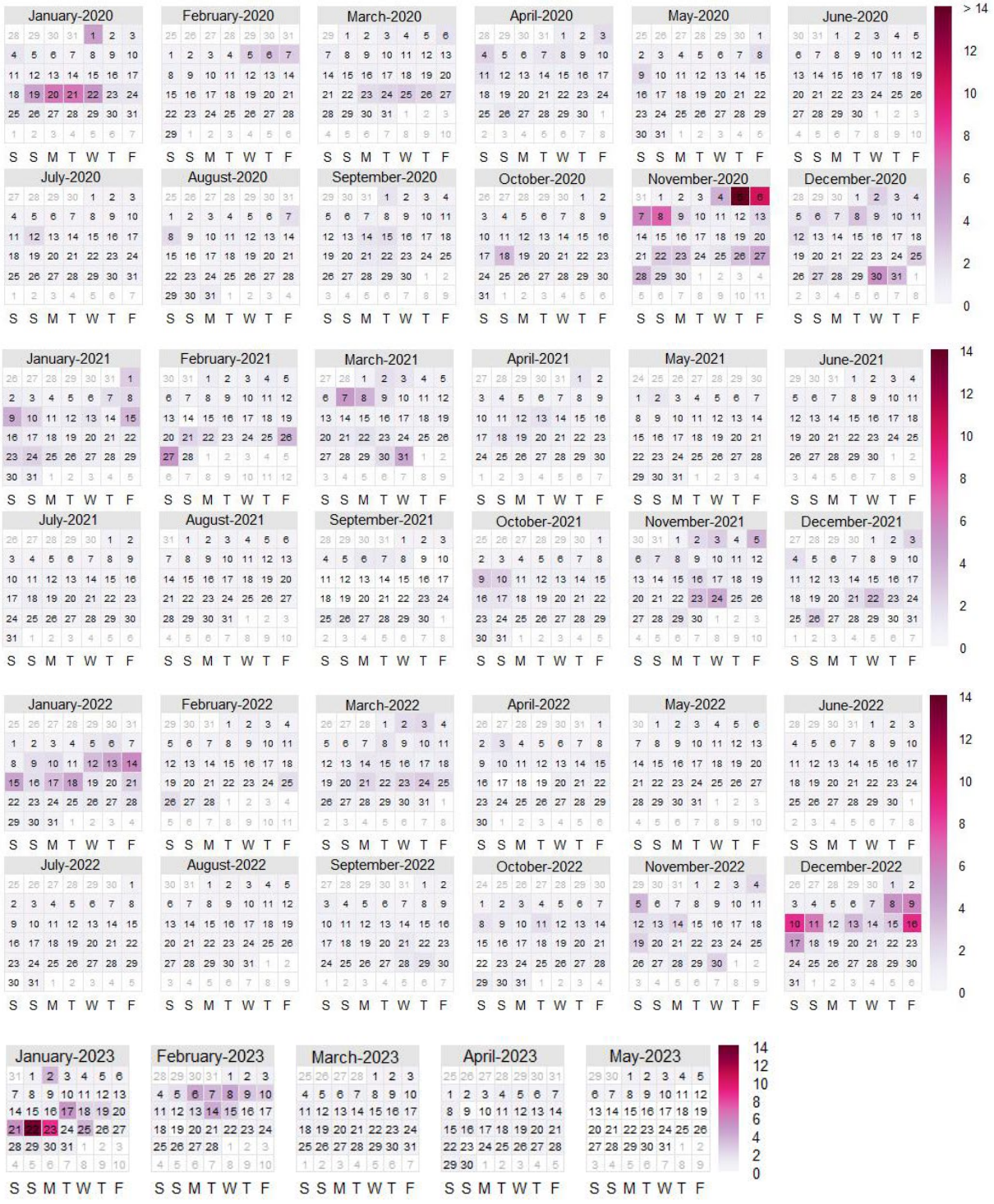
January, with much lower concentrations in the summer months when outdoor burning would be expected. The variation in hourly concentrations was described in for the analysis in section 5.3.2, with the greatest concentrations measured in the evenings and the lowest in the afternoons. There is also evidence of increased wood and solid-fuel burning on weekends, with greater average concentrations measured on Fridays, Saturdays and Sundays. These variations fit with expected use of fires and wood and solid-fuel burning appliances when people are more likely to be at home.

Figure 5-63: Temporal variations in wood and solid-fuel burning PM at Honor Oak Park



The calendar plots in Figure 5-64 show the average daily concentrations of PM from wood and solid-fuel burning for the period 1st January 2020 to 7th March 2023. These show a similar pattern to the monthly variations in Figure 5-63 but it is possible to identify individual days where there was evidence of more wood and solid-fuel burning taking place that are not evident from the monthly averages. In 2020, a period with increased wood and solid-fuel burning PM concentrations occurred in January and there is a clear signal from Guy Fawkes night in November 2020. Daily average wood and solid-fuel burning PM concentrations at Honor Oak Park were relatively lower in 2021, with only a small number of days in February, March and November showing elevated daily concentrations. In 2022, there was a period of increased wood and solid-fuel burning PM in the middle two weeks of January and a period with greater concentrations in December. January and February 2023 also had periods with increased concentrations of PM associated with wood and solid-fuel burning. This pattern is due to a combination of emissions and weather conditions which is why the increases in concentrations are not seen at exactly the same time each year. Even events known for wood burning, such as Guy Fawkes night, show variable amounts of measured wood and solid-fuel burning PM in different years due to weather conditions.

Figure 5-64: Calendar plots of wood and solid-fuel burning PM concentrations (µg m^{-3}) at Honor Oak Park. The plots were produced using the openair package in R (Carslaw and Ropkins, 2012, Carslaw, 2019).



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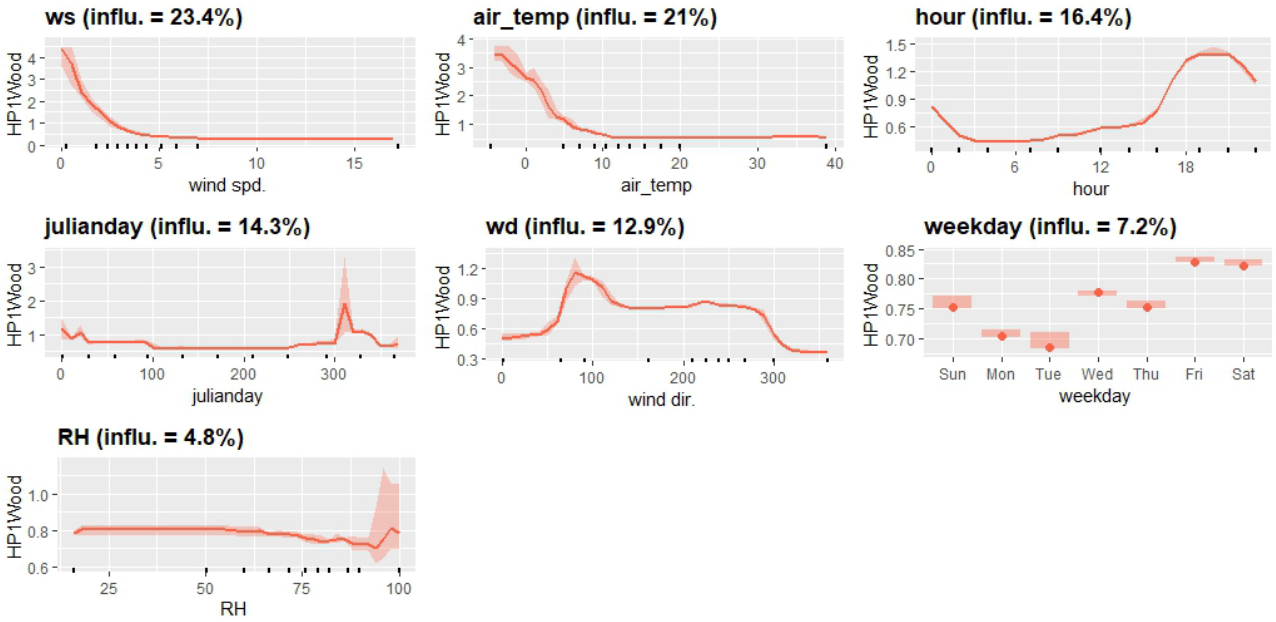
5.3.4 Influence of meteorology

Partial dependency plots can be used to show the relative influence of temporal and meteorological factors on pollution concentrations. These were produced to show the influence of such factors on concentrations of WBPM at Honor Oak Park, using the methodology described in Carslaw and Taylor, 2009[31]. These are shown in Figure 5-65. The greatest influence on wood and solid-fuel burning PM concentrations was wind speed with greater concentrations at lower wind speeds. Air temperature was also highly correlated with measured wood and solid-fuel burning PM concentrations at Honor Oak Park, with the greatest concentration in colder conditions. Such conditions allow pollution to accumulate, with poor dispersal, however the partial dependency shows that temperature also affects emissions directly, presumably through heat demand. These two meteorological factors had a greater influence than the temporal factors, hour of day, and day of year (Julian day) which were the next most significant.

Figure 5-65: Influence of temporal and meteorological factors on PM concentrations from wood and solid-fuel burning at Honor Oak Park



The bivariate polar plots in Figure 5-66 were used to examine the influence of wind speed and direction on WBPM in more detail, with the plot for total $PM_{2.5}$ for comparison. The plots were produced using the openair package in R (Carslaw and Ropkins, 2012, Carslaw, 2019). The bivariate polar plot function partitions wind speed, wind direction and concentration data into bins and calculates the mean concentration for each bin. A Generalized Additive Model (GAM) produces a representation of the variation in concentration by wind speed and direction. Plots were divided according to season. The plots show increased concentrations of total $PM_{2.5}$ and WBPM at low wind speeds in winter, but this is particularly evident for WBPM. The total $PM_{2.5}$ plots show the influence of other sources, such as traffic, with greater concentrations from a variety of wind directions and some at higher wind speeds. Total $PM_{2.5}$ concentrations are also more evenly distributed throughout the year, compared to WBPM where the

[31] Carslaw, D.C. and P.J. Taylor (2009). Analysis of air pollution data at a mixed source location using boosted regression trees. Atmospheric Environment. Vol. 43, pp. 3563–3570.

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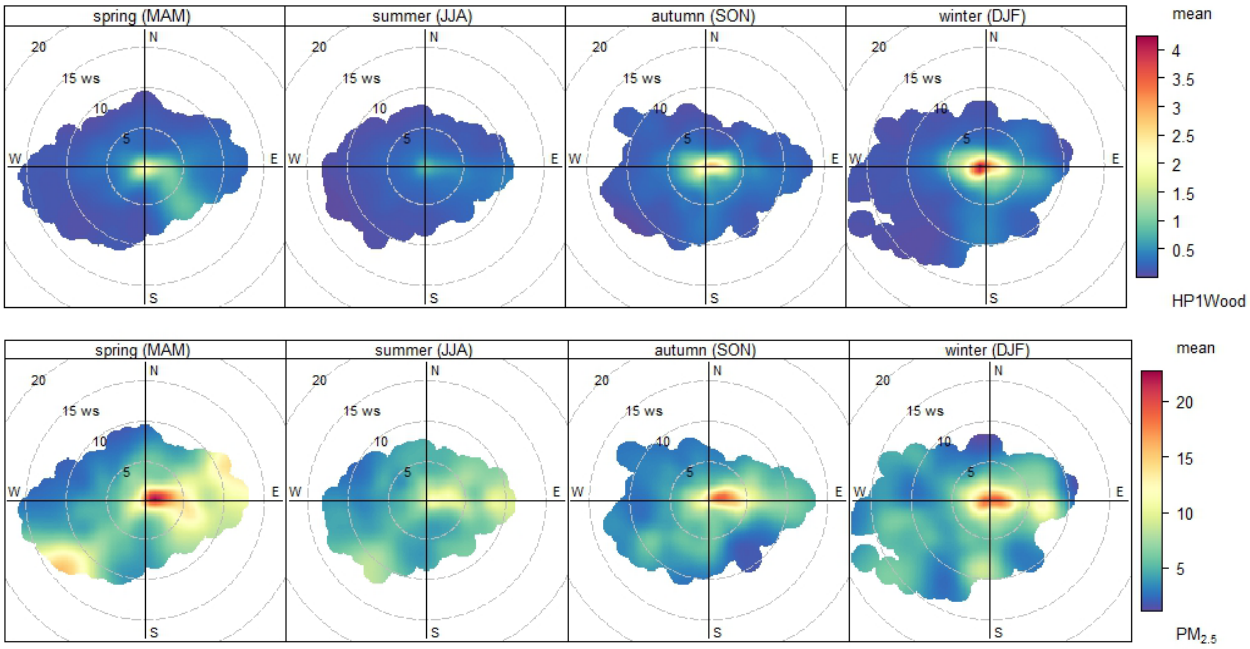
greatest concentrations occur mainly in autumn and winter. The low WBPM concentrations in summer compared to winter suggest that the main source is from wood and solid-fuel burning for home heating with less contribution from the type of burning more common in the summer months such as barbecues or burning of garden waste. The polar plot for PM from wood and solid-fuel burning shows an increase in concentrations with increased wind speeds from the south-east, particularly in the spring. This could indicate longer-range transport of wood and solid-fuel burning emissions, as was found in Font et al., 2022.

Figure 5-66: Polar plots showing influence of wind speed and direction on wood and solid-fuel burning PM concentrations and PM2.5 at Honor Oak Park. The plots were produced using the openair package in R (Carslaw and Ropkins, 2012, Carslaw, 2019).



5.3.5 Part 3: Key findings

- PM from wood and solid-fuel burning comprised 7-10% of the annual $PM_{2.5}$ concentration and 4-6% of the annual mean PM_{10} concentration at background locations in London from 2020 to 2022. A similar percentage contribution from wood and solid-fuel burning was measured at the Chilbolton rural site. The concentration of wood and solid-fuel burning PM ranged from 0.58 to 0.85 µg m^{-3}. These concentrations are based on measurements from Defra's black carbon network.
- The annual mean contribution of wood and solid-fuel burning PM from London sources was estimated to be 0.34 to 0.46 µg m^{-3} from 2020 to 2022.
- There was a clear seasonal pattern with higher wood and solid-fuel burning PM concentrations in November, December and January during this period. The greatest hourly mean concentrations were measured in the evenings from 18:00 to 23:00 and the greatest daily mean concentrations were measured on Fridays, Saturdays and Sundays, suggesting a recreational or decorative explanation for some wood and solid-fuel burning
- Analysis of temporal and meteorological factors showed that the biggest influence on wood and solid-fuel burning PM at Honor Oak Park was from wind speed, followed by air temperature, with the greatest concentrations at low wind speeds and low temperatures.

- The evidence indicates that domestic wood and solid-fuel burning in winter makes a significant contribution to PM concentrations in London. There was little evidence of outdoor summer burning activities.

5.4 $PM_{2.5}$ Breathe London measurements

Breathe London $PM_{2.5}$ measurements were examined, alongside evidence of wood and solid-fuel burning from fixed aethalometer measurements. Measurements from the London Boroughs of Croydon, Richmond-upon-Thames and Sutton were chosen for their relatively large number of Breathe London sites and because these participating boroughs were not covered by the other aspects of the project. They are also relatively close to the Honor Oak Park supersite from which measurements from the AE33 aethalometer were used for comparison.

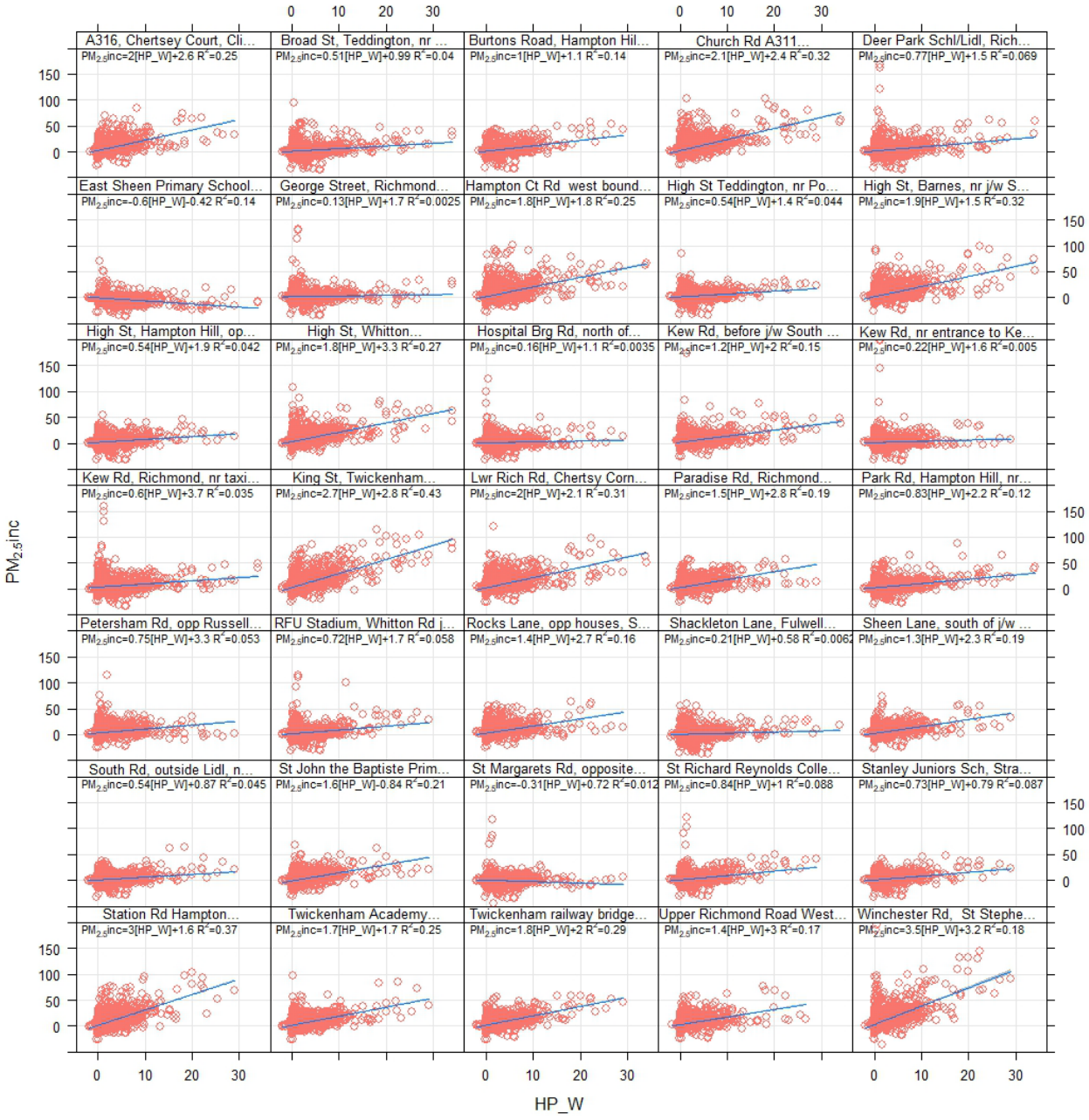
Paired mean $PM_{2.5}$ concentrations from all Breathe London urban background sites were subtracted from $PM_{2.5}$ concentrations for each of the Breathe London sites being investigated to produce a local $PM_{2.5}$ increment concentration. When considering wood and solid-fuel burning emissions, the choice of background measurements to subtract from the local $PM_{2.5}$ concentration to highlight local sources is not straightforward. When considering a traffic or industrial source, measurements from locations less affected by that source are simpler to identify but wood and solid-fuel burning emissions occur in a variety of location types. Measurements from urban background locations across London were chosen to reduce the influence of localised emissions. Although these measurements are expected to include increased $PM_{2.5}$ concentrations due to wood and solid-fuel burning, subtracting these mean concentrations can potentially highlight areas with wood and solid-fuel burning emissions above the London average. However, the sources of local $PM_{2.5}$ increment concentrations alone cannot be readily differentiated. Therefore, similarities in the temporal patterns between the local $PM_{2.5}$ increment concentrations and WBPM were used to determine at which sites $PM_{2.5}$ concentrations may be more influenced by wood and solid-fuel burning emissions.

5.4.1 London Borough of Richmond-upon-Thames

Local $PM_{2.5}$ increment concentrations were plotted against WBPM concentrations calculated from AE33 aethalometer measurements from Honor Oak Park to determine where the $PM_{2.5}$ concentrations were best correlated with increased PM from wood and solid-fuel burning. This may indicate a bigger contribution to $PM_{2.5}$ concentrations from wood and solid-fuel burning sources. Wood and solid-fuel burning PM concentrations from the North Kensington site were also considered for this analysis. A similar correlation was noted but the Honor Oak Park measurements were chosen due to the greater concentrations measured at this site, as described in section 5.3.

Scatter plots showing the relationship between local $PM_{2.5}$ increment concentrations at Richmond Breathe London sites and wood and solid-fuel burning PM from Honor Oak Park are shown in Figure 5-67.

Figure 5-67: Correlation between local $PM_{2.5}$ increment at Breathe London sites in London Borough of Richmond-upon-Thames with Honor Oak Park wood and solid-fuel burning PM



An exact correlation between the two metrics would not be expected due to the existence of other sources, particularly at roadsides so locations with a positive correlation and an R^2 value greater than 0.3 were chosen for further examination. For Richmond, these sites were: Church Road A311, High Street – Barnes, King Street – Twickenham, Lower Richmond Road – Chertsey Corner, Station Road – Hampton. One site that had a poor correlation with the wood and solid-fuel burning PM concentrations: George Street, Richmond, was chosen as an example for comparison. The locations of these sites, other Richmond Breathe London sites and the fixed aethalometer sites are shown in Figure 5-68, with the LAEI modelled wood and solid-fuel burning emissions for comparison.

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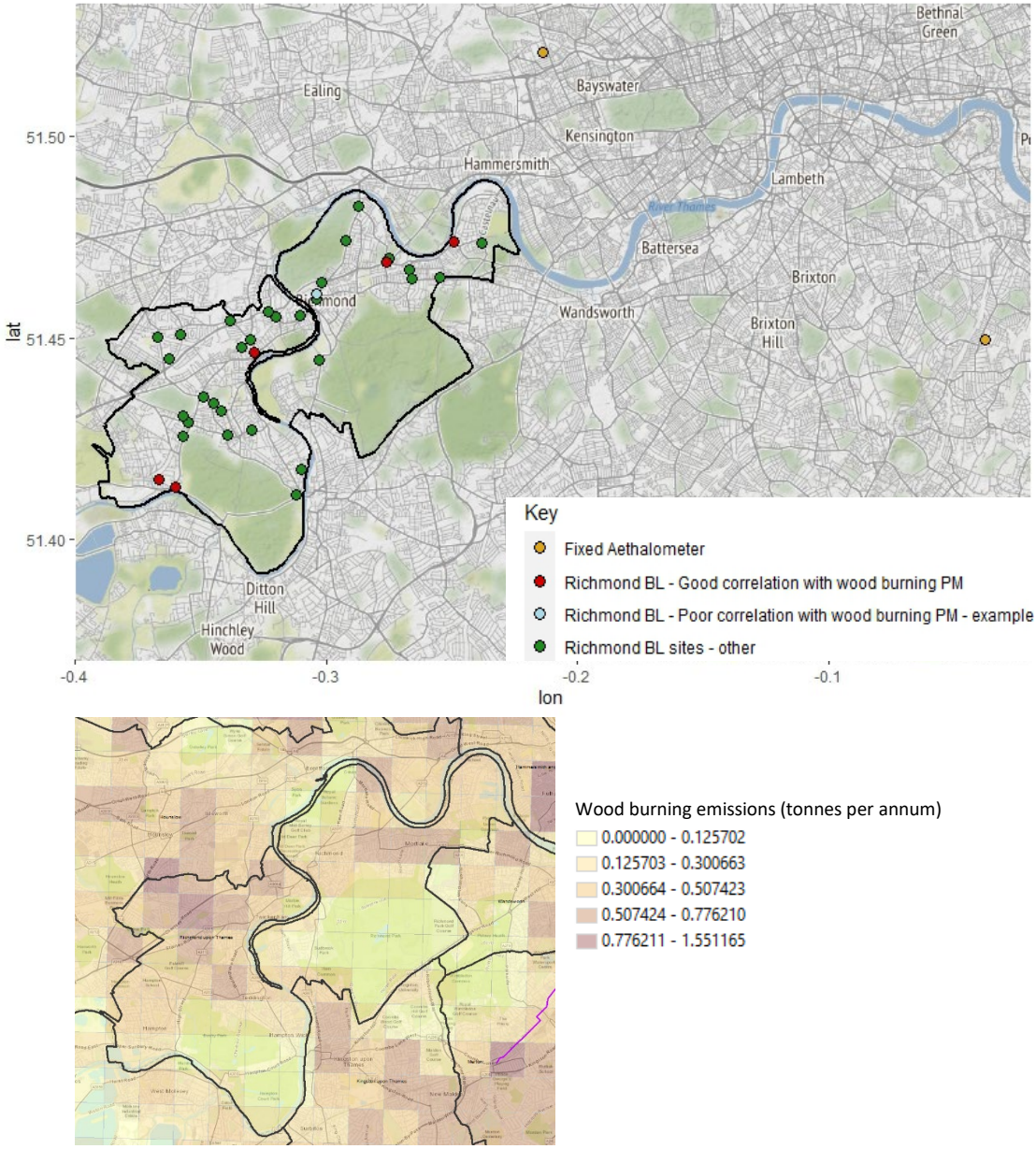
Figure 5-68: Locations of the Richmond-Upon-Thames Breathe London sites (green) and the fixed aethalometer at Honor Oak Park (yellow). The five sites where $PM_{2.5}$ increment concentrations correlated well with the Honor Oak Park wood and solid-fuel burning PM are shown in red and the example comparison site which had a poor correlation with wood and solid-fuel burning PM is shown in light blue.



There was a reasonably good match between the locations which had a better correlation of $PM_{2.5}$ increment concentrations with wood and solid-fuel burning PM and the modelled wood and solid-fuel burning PM emissions. Several sites with a good correlation with wood and solid-fuel burning PM are located close to the River Thames which could indicate a contribution from solid-fuel burning on boats. Two sites in Hampton showed a good correlation with wood and solid-fuel burning PM, suggesting possible wood and solid-fuel burning in that area. The dominance of parkland in some LAEI grid squares in the south of the borough may mask localised areas of wood and solid-fuel burning emissions within the inventory.

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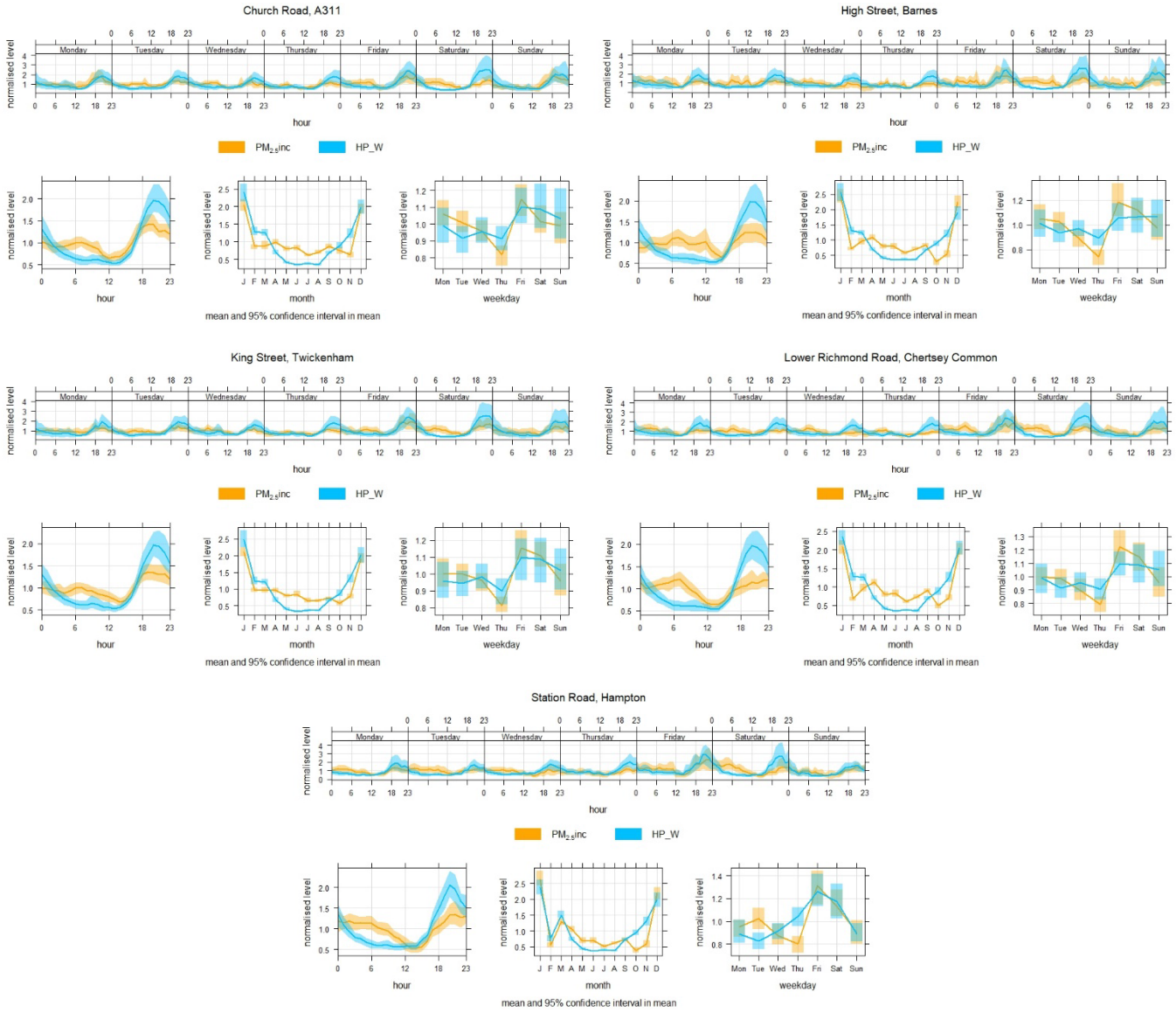
Temporal variations in $PM_{2.5}$ from the sites which were well correlated with wood and solid-fuel burning PM are shown in Figure 5-69. This shows a good match between the times when local $PM_{2.5}$ increment concentrations and wood and solid-fuel burning PM concentrations are greater, particularly in evenings and weekends. There is also a strong seasonal pattern with the greatest concentrations of both metrics in December, January and February. The elevated $PM_{2.5}$ concentrations in the mornings which do not coincide with an increase in wood burning PM are likely due to traffic.

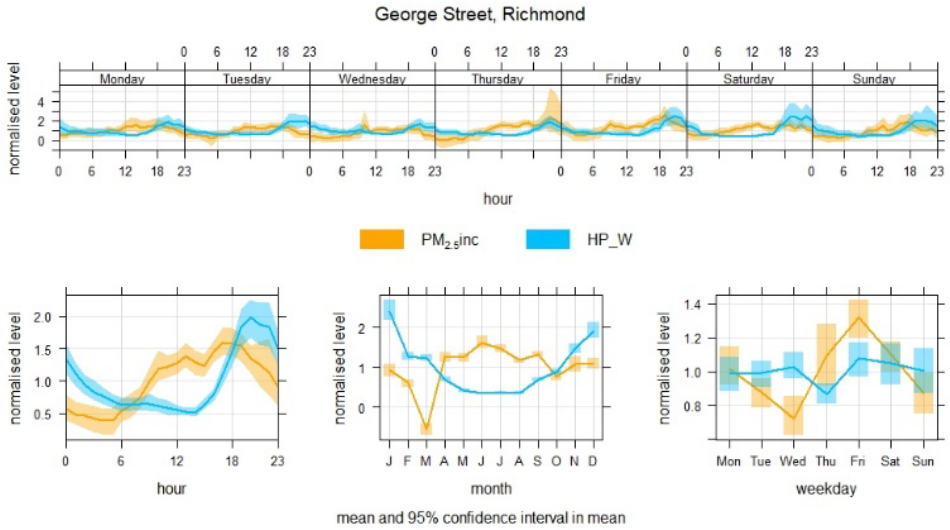
Figure 5-69: Plots showing temporal variations in local $PM_{2.5}$ increment concentrations at Breathe London Richmond sites that are well correlated with wood and solid-fuel burning PM concentrations. Temporal variations in Honor Oak Park wood and solid-fuel burning PM concentrations are shown for comparison. Concentrations are normalised to enable comparison of pollutants on different scales. This is achieved by dividing the concentration of the pollutant by its mean value.



Temporal variations from a site where local $PM_{2.5}$ increment concentrations were poorly correlated with wood and solid-fuel burning PM concentrations are shown for contrast in Figure 5-70. This shows a different pattern, with greater local $PM_{2.5}$ increment concentrations during the daytime, similar

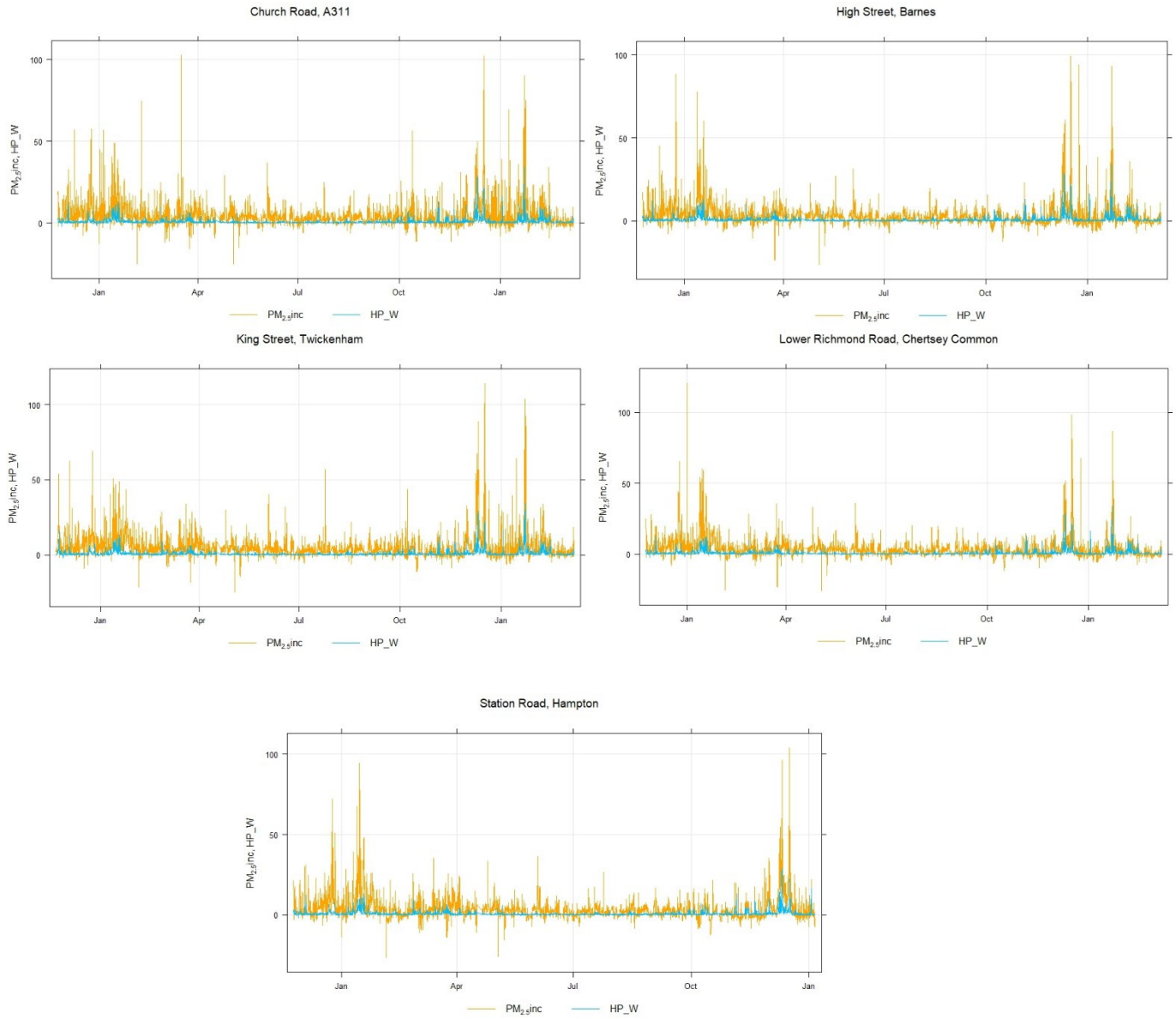
concentrations across weekdays and a less clear seasonal pattern. This could suggest a greater influence of traffic on the local concentrations and less influence from wood and solid-fuel burning.

Figure 5-70: Plots showing temporal variations in local PM2.5 increment concentrations at a Breathe London Richmond site that were poorly correlated with wood and solid-fuel burning PM concentrations. Temporal variations in Honor Oak Park wood and solid-fuel burning PM concentrations are shown for comparison. Concentrations are normalised.



Time series plots of local $PM_{2.5}$ increment concentrations at these sites are shown in Figure 5-71. This shows large spikes in the local $PM_{2.5}$ increment concentrations at similar times to when there were elevated wood and solid-fuel burning PM concentrations at Honor Oak Park and at other times during the winter months. This could indicate the presence of local wood and solid-fuel burning sources. However, in the absence of measurements that can be used to determine the $PM_{2.5}$ source, we cannot have high confidence in this attribution.

Figure 5-71: Time series plots showing local $PM_{2.5}$ increment concentrations at Richmond Breathe London sites with wood and solid-fuel burning PM concentrations from Honor Oak Park



The time series plot of a site where local $PM_{2.5}$ concentrations were not well correlated with wood and solid-fuel burning PM concentrations is shown for contrast in Figure 5-72. This shows a different pattern to the other plots with fewer and smaller local $PM_{2.5}$ spikes in winter compared to the previous plots.

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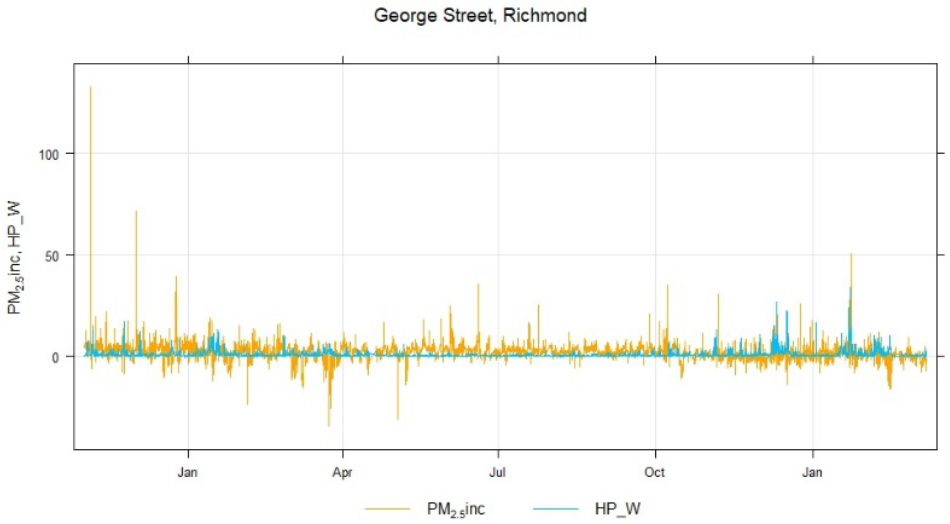
Figure 5-72: Time series plots showing local $PM_{2.5}$ increment concentrations at a Richmond Breathe London site where local PM2.5 increment concentrations were poorly correlated with wood and solid-fuel burning PM concentrations



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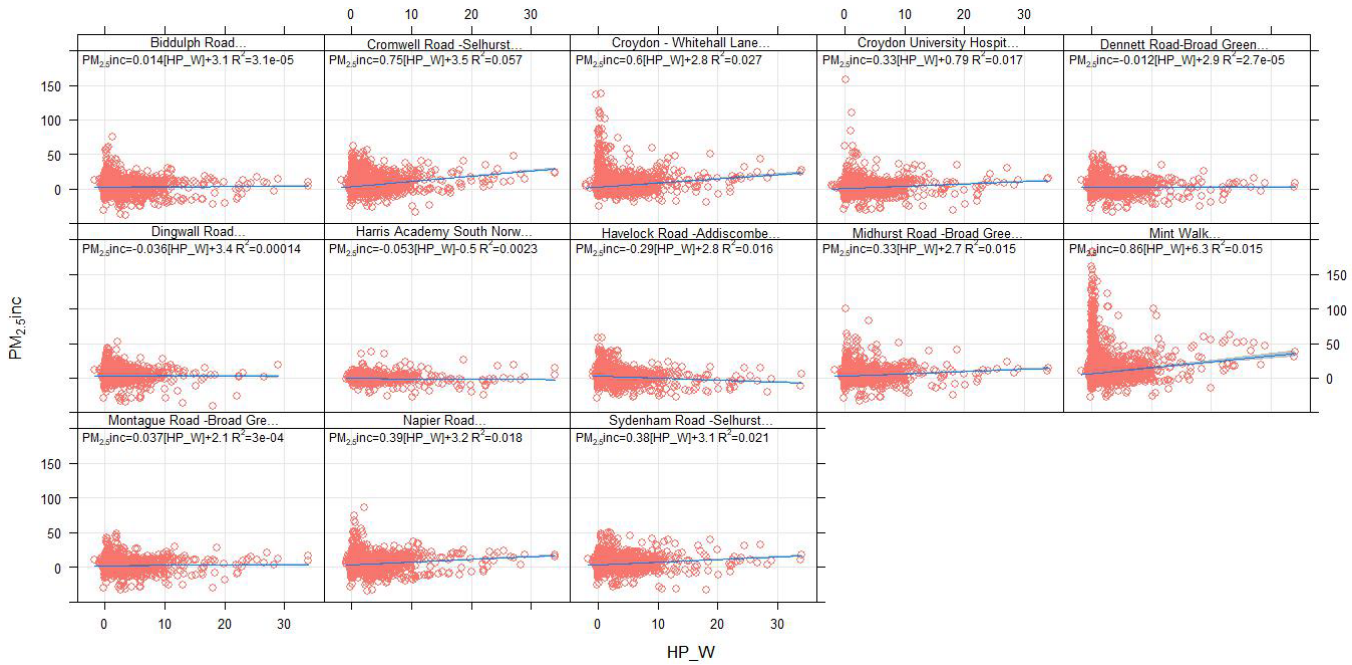
5.4.2 London Borough of Croydon

Scatter plots for local $PM_{2.5}$ increment concentrations at Croydon's Breathe London sites are shown in Figure 5-73.

Figure 5-73: Correlation between local $PM_{2.5}$ increment at Breathe London sites in London Borough of Croydon with Honor Oak Park wood and solid-fuel burning PM



The correlation between the $PM_{2.5}$ increment concentrations at Croydon Breathe London sites and the wood and solid-fuel burning PM at Honor Oak Park is overall much poorer than was seen at Richmond's Breathe London sites. There were no sites with an R^2 value greater than 0.1.

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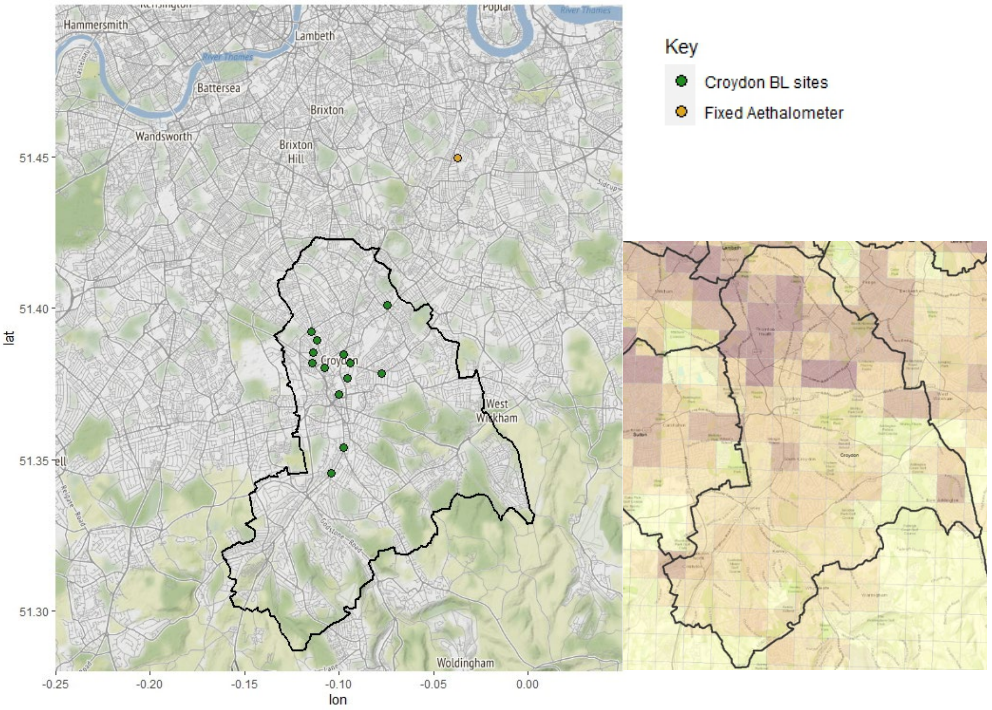
Figure 5-74: Locations of the Croydon Breathe London sites (green) and the fixed aethalometer at Honor Oak Park (yellow).



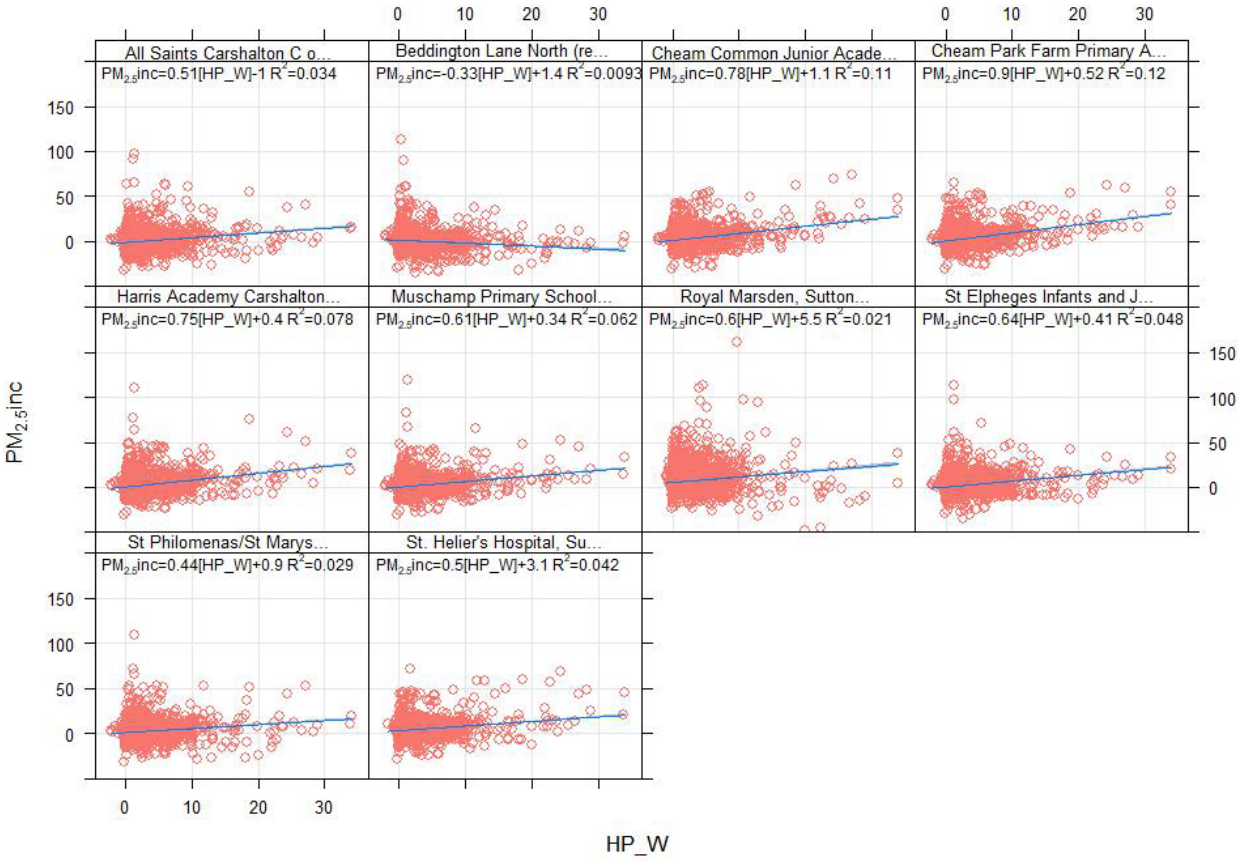
The locations of Croydon's Breathe London sites are shown in Figure 5-74 with the LAEI modelled emissions shown for comparison. This shows that greatest modelled emissions of wood and solid-fuel burning PM are in the north of the borough where few of the Breathe London sensors were located. Overall, the Croydon sites do not show a good correlation between local $PM_{2.5}$ increment concentrations and increased wood and solid-fuel burning PM concentrations at Honor Oak Park. This could indicate the dominance of other local $PM_{2.5}$ sources such as construction or traffic at these locations. There was no evidence to suggest that $PM_{2.5}$ concentrations were greatly influenced by emissions from solid-fuel burning at these locations. These measurements were therefore not examined in more detail.

This part of the analysis aims to identify previously unknown potential wood and solid-fuel burning hotspots without prior detailed knowledge of the measurement location characteristics. The sites have not been located with the aim of measuring emissions from wood and solid-fuel burning. An inferred lack of influence of wood and solid-fuel burning on $PM_{2.5}$ concentrations at these particular locations does not mean that there is no solid-fuel burning in the borough. There may be locations where more wood and solid-fuel burning takes place which do not have Breathe London sensors.

5.4.3 London Borough of Sutton

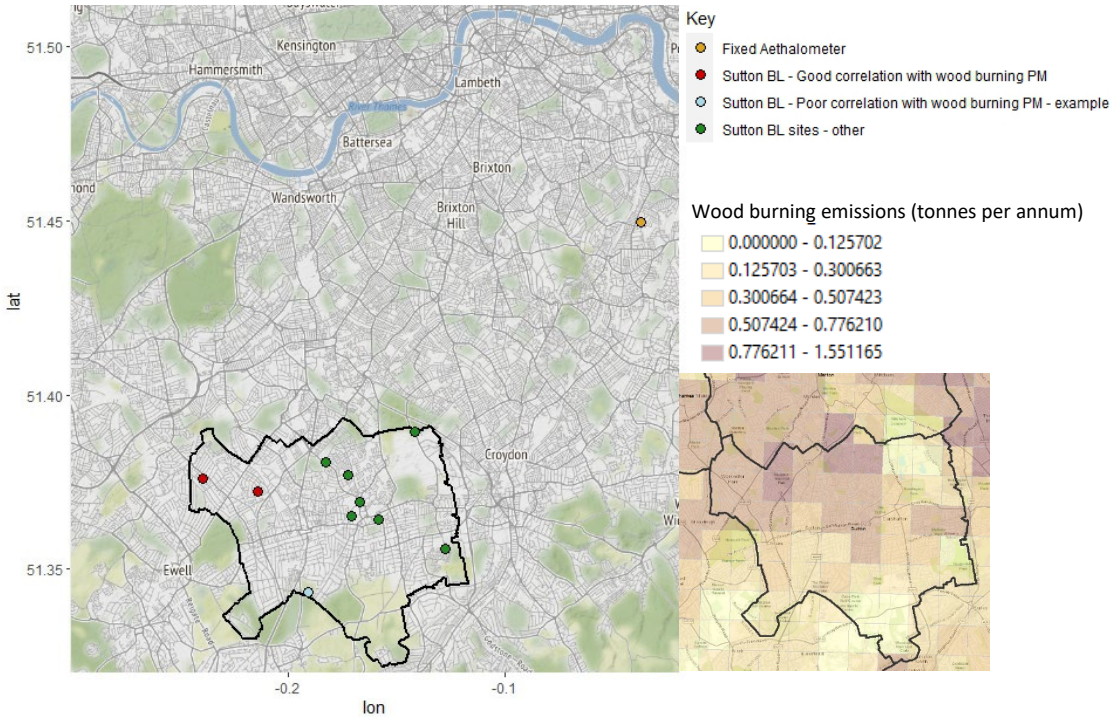
Scatter plots for local $PM_{2.5}$ increment concentrations at Croydon's Breathe London sites are shown in Figure 5-75.

Figure 5-75: Correlation between local $PM_{2.5}$ increment at Breathe London sites in London Borough of Sutton with Honor Oak Park wood and solid-fuel burning PM.



The correlation between the $PM_{2.5}$ increment concentrations at the Sutton sites with the Honor Oak Park wood and solid-fuel burning PM concentrations was also poorer than that found for Richmond's Breathe London sites. However, two sites had an R^2 value greater than 0.1: Cheam Common Junior Academy and Cheam Park Farm Primary Academy. These sites were chosen for more detailed examination. Royal Marsden, Sutton was chosen as an example site with poor correlation between $PM_{2.5}$ increment concentrations and Honor Oak Park wood and solid-fuel burning PM concentrations.

Figure 5-76: Locations of the Sutton Breathe London sites (green) and the fixed aethalometer at Honor Oak Park (yellow). The two sites where $PM_{2.5}$ increment concentrations correlated relatively well with the Honor Oak Park wood and solid-fuel burning PM are shown in red and the example comparison site which had a poor correlation with wood and solid-fuel burning PM is shown in light blue.



There is some agreement between locations with greater modelled wood and solid-fuel burning emissions and where $PM_{2.5}$ increment concentrations correlated relatively well with wood and solid-fuel burning PM concentrations from Honor Oak Park as shown in Figure 5-76. However, sites in the central north part of the borough which had greater modelled concentrations did not show a good correlation with wood and solid-fuel burning PM. These could be influenced more by other sources, such as traffic.

Temporal variations in local $PM_{2.5}$ increment concentrations at the Sutton Breathe London sites which were best correlated with wood and solid-fuel burning PM are shown in Figure 5-77. This shows an increase in $PM_{2.5}$ increment concentrations in the evenings although this is not as clear as at the Richmond sites, as would be expected by the poorer correlation. The seasonal pattern is also less clear and there is no obvious increase in daily mean concentrations at weekends which is normally expected for wood and solid-fuel burning. This suggests a weaker influence of wood and solid-fuel burning on local $PM_{2.5}$ in Sutton than was seen in Richmond. However, there is a clear contrast with the pattern seen at the Royal Marsden site where local $PM_{2.5}$ increment concentrations were poorly correlated with wood and solid-fuel burning PM concentrations, shown in Figure 5-78.

Figure 5-77: Plots showing temporal variations in local $PM_{2.5}$ increment concentrations at Breathe London Sutton sites that are relatively well correlated with wood and solid-fuel burning PM concentrations. Temporal variations in Honor Oak Park wood and solid-fuel burning PM concentrations are shown for comparison. Concentrations are normalised.

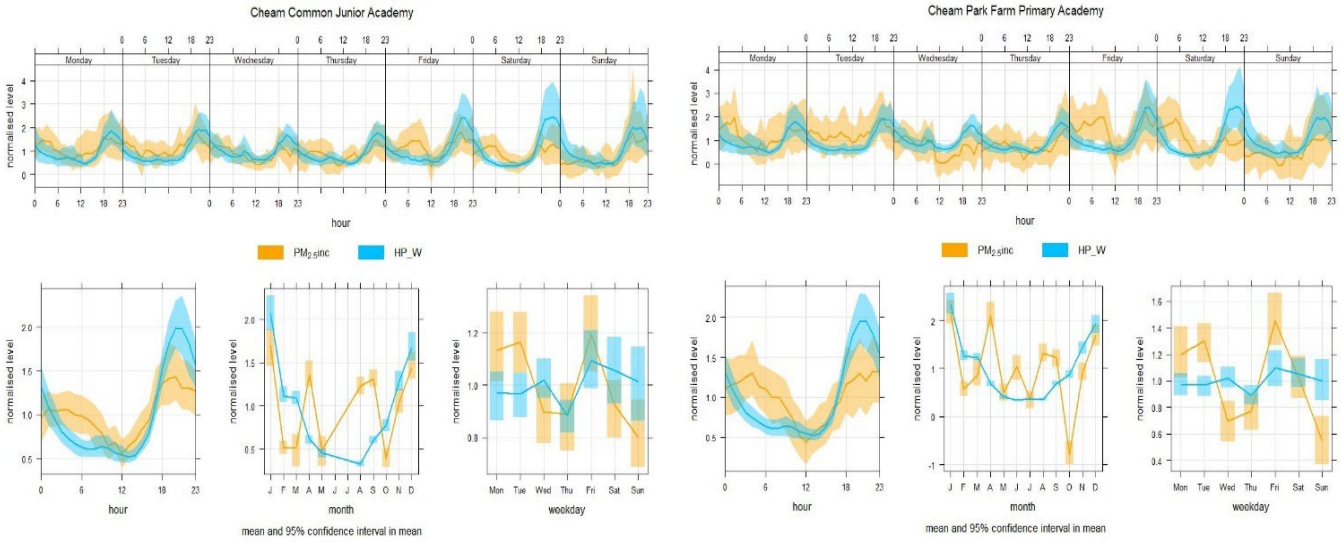
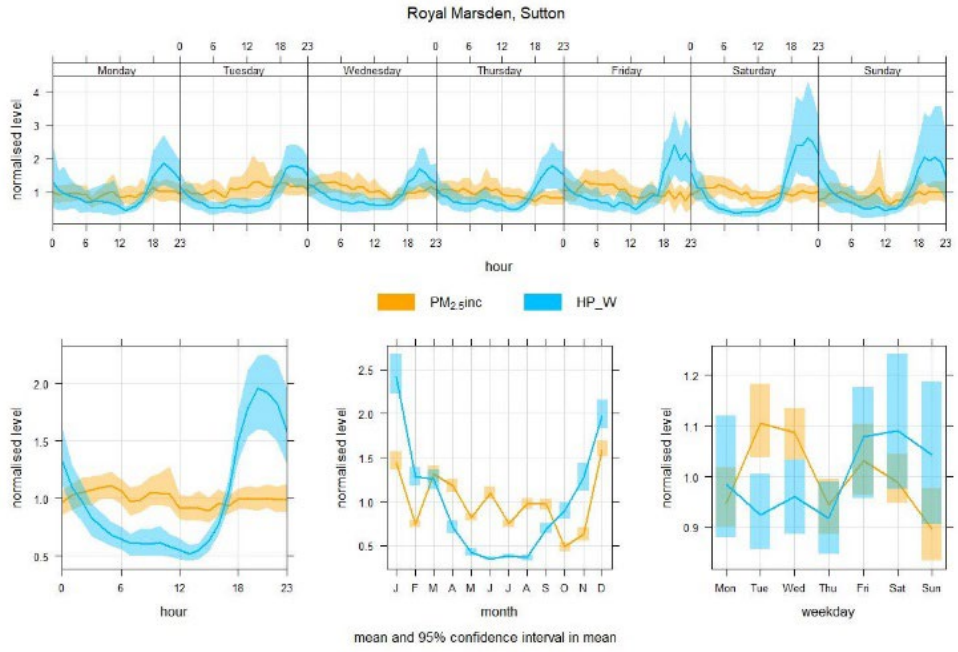


Figure 5-78: Plots showing temporal variations in local $PM_{2.5}$ increment concentrations at a Breathe London Sutton site that was poorly correlated with wood and solid-fuel burning PM concentrations. Temporal variations in Honor Oak Park wood and solid-fuel burning PM concentrations are shown for comparison. Concentrations are normalised.



The time plots for Cheam Common Junior Academy and Cheam Park Primary Academy in Figure 5-79 show increased $PM_{2.5}$ increment concentrations when wood and solid-fuel burning PM concentrations were elevated at Honor Oak Park. The Cheam Common Junior Academy plot shows that some data was missing between May and September which could partly account for the lower correlation with wood and solid-fuel burning PM. However, at Cheam Park Farm Primary Academy, local $PM_{2.5}$ increment spikes continue throughout the summer. This could suggest that the spikes are less likely to be caused by domestic wood and solid-fuel burning. They may indicate another local $PM_{2.5}$ source.

Figure 5-79: Time series plots showing local $PM_{2.5}$ increment concentrations at Sutton Breathe London sites with wood and solid-fuel burning PM concentrations from Honor Oak Park

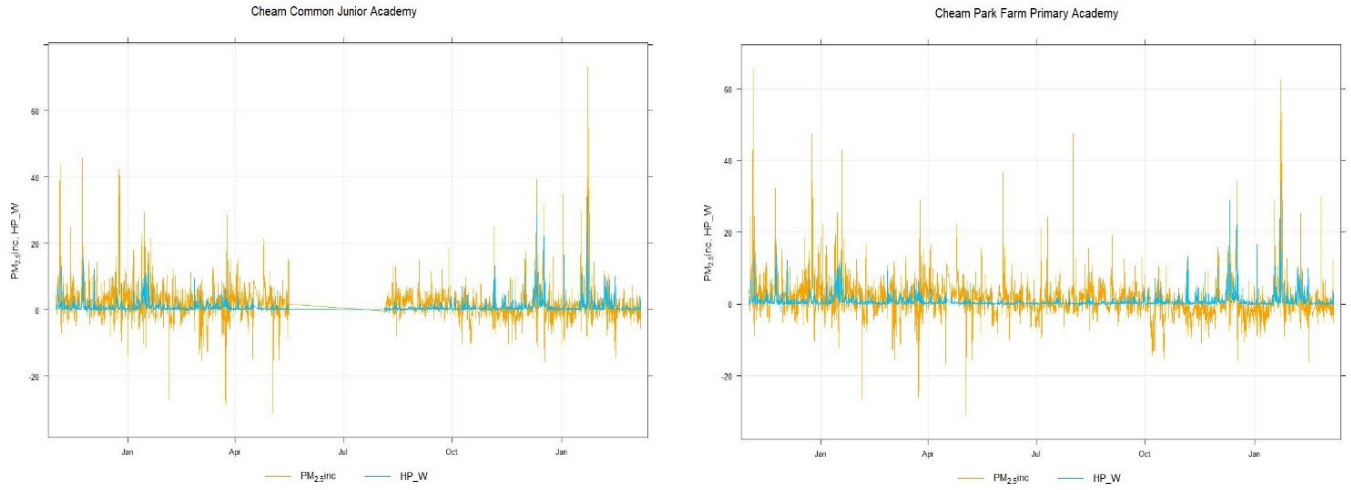
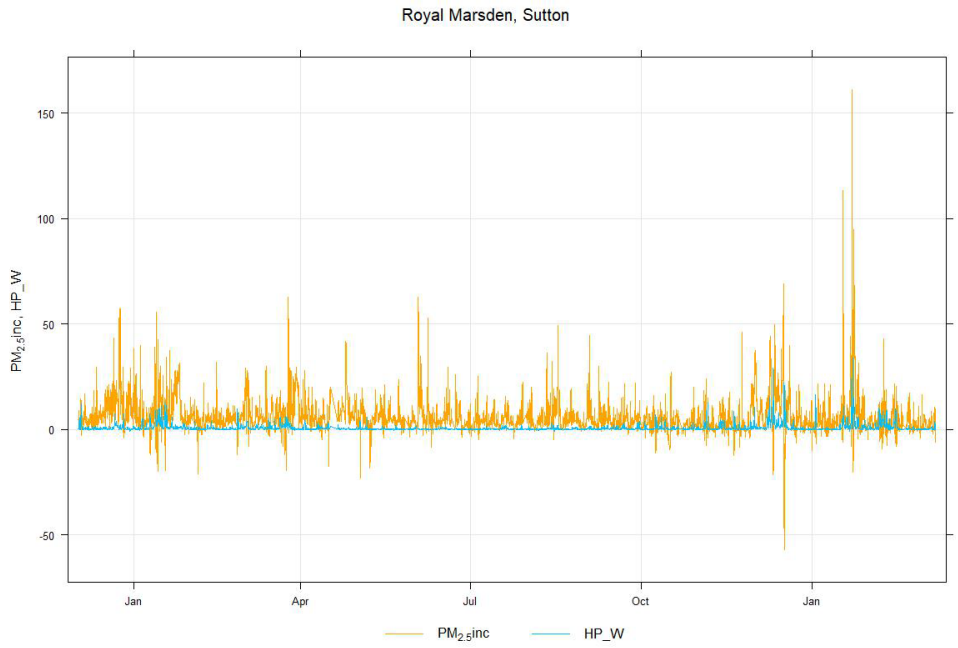


Figure 5-80 shows the time series plot for Royal Marsden which had a poor correlation between $PM_{2.5}$ increment concentrations and times when wood and solid-fuel burning PM had greater concentrations at Honor Oak Park. There are increases in local $PM_{2.5}$ concentrations when wood and solid-fuel burning PM is elevated. However, local $PM_{2.5}$ spikes occur throughout the year, suggesting there are other sources which have a greater influence on measured concentrations.

Figure 5-80: Time series plots showing local PM2.5 increment concentrations at a Sutton Breathe London site where local PM2.5 increment concentrations were poorly correlated with wood and solid-fuel burning PM concentrations



5.4.4 Part 4: Key findings

- The analysis sought to make use of a relatively new measurement resource with a large number of measurement locations to investigate its potential to provide information on wood and solid-fuel burning emissions.
- Combining examination of Breathe London $PM_{2.5}$ measurements with comparison to fixed aethalometer measurements may help to identify potential hotspots where wood or solid-fuel burning have a greater influence on $PM_{2.5}$ concentrations. This could be used as a screening method to find areas for further investigation using instruments such as micro-aethalometers to better understand the PM composition.
- There is scope for further work on hyper-local $PM_{2.5}$ measurements using methods developed for this study.

6 Conclusions

- There was clear evidence of air pollution inside homes from stoves and fireplaces especially when fire lighting and refuelling. However, indoor concentrations were less than those from cooking and cigarette smoking.
- There was clear evidence that solid-fuel burning can cause short-term pollution peaks outdoors in the immediate area, typically around 10m from the chimney and these peaks were mainly linked to fire lighting and refuelling. This was the case even for the appliance which was the highest rated for efficiency and low emissions.
- There may be some benefits for outdoor air quality of using more modern wood burning appliances, highly-rated for efficiency and low emissions although these still have an impact on outdoor air quality.
- Measurements of indoor and outdoor pollutant concentrations in homes where wood and solid-fuel are burnt do not suggest that "smokeless" fuels, including those authorised for use by Defra in Smoke Control Areas produce less pollution than seasoned wood. Wood is not permitted to be burnt in open fires or non-exempt appliances in Smoke Control Areas. Participants also noted difficulty with use of these "smokeless" fuels which may lead to increased indoor pollution from more interaction with the fire or appliance.
- There was evidence that solid-fuel burning was leading to new street scale air pollution hotspots.
- Methodologies developed through this, and previous studies provide opportunities for further research. Measurements from the Breathe London hyperlocal sensor network may be used to identify areas for further investigation. Portable aethalometer measurements have successfully identified solid-fuel burning hotspots that agree well with modelled emissions. These methods could be combined to cover other areas of interest.
- Good correlation between mapping solid-fuel burning smells and $PM_{2.5}$ measurements and wood and solid-fuel burning PM, shows that encountering a solid-fuel burning smell means particulates are being inhaled.
- At a London-wide scale domestic solid-fuel burning is contributing to $PM_{2.5}$. This is mainly during winter evenings and on Friday, Saturday and Sundays. Concentrations were much lower in summer months when outdoor burning is more common.
- This highly seasonal source of $PM_{2.5}$ has greater concentrations in winter, with mean concentrations at Honor Oak Park in south-east London of up to 1.5 µg m^{-3} in winter months. Therefore, exposure to this harmful combination of substances is a particular concern at these times of year.
- During the planning of the study, it was noted that complex information, categories, requirements, and regulations for wood and solid-fuel burning can be difficult to understand and may lead to non-compliance, both intentional and unintentional.
- The correlation of solid-fuel burning smells with measured concentrations suggests that public complaints related to solid-fuel burning should be taken seriously. Portable measurements in locations where complaints have been received could aid enforcement.
- Further restrictions on domestic wood and solid-fuel burning would be beneficial to enable progress towards meeting WHO air quality guidelines (WHO, 2021), especially for $PM_{2.5}$. The guideline value is 5 µg m^{-3} as an annual mean. The estimated annual mean measured contribution of wood and solid-fuel burning from urban areas of London was 0.46 µg m^{-3} in 2022 and is the biggest source of $PM_{2.5}$ emissions that can be influenced on a local level.

This report is the independent expert opinion of the author(s).

Appendix 1 – Ethics Documents

Advert

Imperial College London is looking for volunteers to help with research on solid fuel burning

We are looking for people who burn solid-fuel in their homes, such as wood logs or smokeless coal, who would be willing to take part in collecting air quality measurements this winter as part of an innovative research project. We would like to take measurements in homes where solid fuel is burned in an open fireplace or a stove.

We will test a variety of fuel types, which will be provided, over a five-day period at your home. Our research team will set up equipment at the start of the week and provide instructions and return to collect the equipment at the end of the week. Checks on the equipment will be made once or twice during the week. The equipment consists of a pair of small mobile monitors (each up to 20 cm in length - see photo) to be placed inside and a pair to be placed outside.

We are planning to take the measurements between January and March 2023. No personal details will be included in the study outputs and reporting will refer to an approximate location only. If you would like to take part in this exciting research, please email us at londonwoodburning@imperial.ac.uk. Please include in your email which type of solid-fuel burning appliance you use, including the manufacturer and make/model, if available, and where in South East England you live.

The aims of the project are to contribute to improving scientific understanding about how different types of solid fuel burning appliances and fuels can affect indoor and outdoor air quality and will inform guidance on the safest ways to use such appliances.

We are offering a £20 gift voucher as a token of thanks to participants.

PARTICIPANT INFORMATION SHEET

London Wood Burning Project – Monitoring air pollution at home when solid fuel is burned

You are being invited to take part in a research study. Before you decide to take part, it is important for you to understand why the research is being done and what it will involve. Please take time to read the following information carefully and discuss it with others if you wish. Ask us if there is anything that is not clear or if you would like more information. All data collected as part of this study will be reported anonymously. We will not include information about your exact location or any personal details. Take time to decide whether you wish to take part. Thank you for reading this.

What is the purpose of the study?

In the UK, air pollution is the largest environmental risk to public health. Tiny particles such as PM10 - particles less than 10 micrometres in diameter, and PM2.5 - particles less than 2.5 micrometres in diameter (invisible to the naked eye) - are a particular concern due to the evidence of adverse health effects. Home burning of solid fuel is a major source of PM emissions in the UK, most of which comes from burning wood in closed stoves and open fires. Black carbon and other types of particles are also produced by solid fuel and wood burning. This part of the study will seek to identify differences in indoor and outdoor pollution from using different types of solid fuel burning appliances and different fuel types. Measurements inside and outside homes will contribute to improving understanding of the emissions and exposure from different appliances and fuels.

Measurement of air quality in homes is one part of a larger project led by the London Boroughs of Camden and Islington and funded by Defra (the 'London Wood Burning Project') on behalf of 13 additional London boroughs. The Environmental Research Group (ERG) at Imperial College London has been awarded a contract to carry out the air quality data collection element of this project which will investigate the impacts of domestic solid fuel burning on internal and external air quality, including in real-world settings. Other parts of this element include outdoor measurements across two transects in London expected to have varying amounts of wood burning, analysis of fixed PM2.5 measurements in London and analysis of fixed black carbon measurements to identify emissions from wood burning and the contribution from London sources. There are two further elements of the overall project: Surveys of residents' current knowledge and opinions on domestic solid fuel burning and health impacts evaluation to seek to quantify the impacts of domestic solid fuel burning in London upon public health. These are being carried out by separate contractors.

Why have I been invited to take part?

You are being invited to participate in this study as you replied to an advert requesting volunteers. Your response to the advert included information on your home burning appliance and your location, which were of particular interest to the project. Based on this initial expression of interest and the information supplied you were asked to fill in a questionnaire requesting more detailed information. A review of the completed questionnaire highlighted you as a potentially suitable participant in the study and this was subsequently confirmed during a follow-up phone conversation. During the phone conversation a visit by a project team researcher to your home was arranged, to carry out a final assessment of suitability. At this visit the suitability of your home to participate in the study can be confirmed. At the visit this participant information sheet is provided and any questions you may have can be addressed. You then have up to one week to consider if you wish to take part.

What will happen if I take part?

If you agree to take part in this project, the following will take place:

1. We will ask you to sign a consent form to participate in the study.

2. We will deliver the solid fuel to be burned during the study period.

3. We will install two air quality monitoring packs at your home. One will be in the same room as your fire/appliance, and one will be located on your property at an outside location. Air quality monitors in these monitoring packs will be switched on by the researcher and will monitor air pollution continuously during the week while the study is in progress. The air monitoring packs will be connected to a mains power supply socket. If that is not possible outdoors, then a portable power source will be installed alongside the air monitoring pack for outdoor monitoring. Each air quality monitoring pack will include the two portable air monitors shown in Fig 1. The cost of electricity to run one of the air monitoring packs on mains supply is approx. £2 for five days. (Oct 2022).

Each air quality monitoring pack contains a Sidepak AM520 for measuring PM2.5 particulates and an Aethlabs MA300 or MA350 for measuring black carbon and UV particulate matter.

Fig.1. Air quality monitoring pack equipment

4. You will be required to burn each of the five provided fuels separately over five days. according to instructions on a supplied protocol. The five solid fuel types are.
    - Seasoned kiln-dried wood.
    - Non-seasoned/kiln-dried wood,
    - 'Smokeless' coal,
    - Authorised manufactured solid fuels.
    - Exempt manufactured solid fuels.

   You will be required to burn each of the provided fuels in an open fire or stove which will be one of the following.
    - Open fireplace.
    - Non-DERFA-exempt stove.
    - DEFRA-exempt Eco-Design stove.
    - ClearSkies stage 5 stove.

5. The air pollution monitoring week in your home will take place on five days between **Monday and Sunday** of a week identified by you in the questionnaire and by a phone conversation, as being suitable. You will be asked to record time and any interaction with the fire/appliance during the study on an activity form. You will also be asked to record time and any activity that may result in particulates being generated at your home during the study (examples of such activities will be described in the protocol). The activity forms will be used to match different activities to air quality measurements.

6. A researcher will arrange to visit on one day while monitoring is in progress at a time to be arranged, to check that the air quality monitoring packs are operating correctly.

7. At the end of the week at a time to be arranged a researcher will visit to collect the monitoring equipment and any unused fuel. The researcher will also collect the reporting forms completed by the participants during the study week.

8. Following the air quality data gathering we will inform you of the publication of the study results. We will send you a copy of the results for your home and a summary of the overall findings. We can also discuss the results with you if you wish. We will let you know if any of the results indicate dangerous concentrations of pollutants in your home. We are also offering a £20 gift voucher as a token of thanks for taking part.

Do I have to take part?

Participation is completely voluntary. You should only take part if you want to.

What are the possible disadvantages or risks?

There are very few risks to you participating with this study in addition to the existing risks of domestic solid fuel burning. Emissions from domestic solid fuel burning can be harmful to health and the environment. We will be asking you to use your fire or stove as you typically would do, to burn different types of solid fuel. Burning different fuel types may result in increased or decreased emissions compared to those when using your usual preferred fuel. However, it has been established that all fuel types provided are safe to burn in your appliance/fireplace and the burning of the different fuel types will be short-term, required for one evening each. Nothing in the air quality monitoring packs is dangerous or can harm you in any way.

What are the possible benefits of taking part?

The benefits of taking part in this study are that you will help us to measure typical levels of air pollution people can be exposed to during a normal evening indoors when a fire or stove is in use. If you wish we will give you a copy of the results summary for your home once we have processed the data, which you might want to use to look at ways to avoid high levels of pollution. If you would like to know more about the ways that air pollution can affect your health, there is information on these websites:

Health effects of exposure to above normal levels of pollution on sensitive groups: (e.g., Sufferers from lung diseases, such as chronic obstructive pulmonary disease [COPD] and asthma, as well as heart disease. Children and the elderly.
http://www.londonair.org.uk/LondonAir/Guide/SensitiveEffects.aspx
Short-term health effects of exposure to above normal levels of pollution:
http://www.londonair.org.uk/LondonAir/Guide/ShortTermEffects.aspx
Long-term health effects of exposure to above normal levels of pollution::
http://www.londonair.org.uk/LondonAir/Guide/LongTermEffects.aspx

What if I change my mind about taking part?

Even if you have decided to take part, you are still free to stop your participation at any time during the study and to have research data and information relating to you withdrawn without giving any reason up to 1 month after the monitoring week, after which withdrawal of your data will no longer be possible.
All your reported data will be anonymised. Please do not include any personal identifiable information on your activity forms or the photos you submit.

This report is the independent expert opinion of the author(s).

What will happen to the results of the study?

A report will be produced combining data from four participating homes with conclusions on how air quality in homes is affected by burning different solid fuel types in a fire or stove. The report will also investigate how air quality outside the home is affected by burning different solid fuel in different appliances. The report will investigate if solid fuel burning emissions outside the home are detected inside the home. The findings from this study may be presented at relevant conferences and published in a relevant peer reviewed journal. The anonymised data may also be shared with other researchers in Imperial College London.

How is the project being funded?

The project is being funded by the Department for Environment Food and Rural Affairs (DEFRA).

Who has reviewed the study?

This study has been approved by the Head of Department and been given a favourable opinion by Imperial College Science, Engineering and Technology Research Ethics Committee (SETREC).

Photography consent

We may take photos of your fireplace/stove or the installed air quality monitoring packs on our visit to your home during the monitoring week. We will also ask you to take some photos of fuel being added to the fire/stove during the monitoring week. The photos will not include people living in the home. They will be used to illustrate instrument set-up, fuels used and/or the fuel burning appliance. These images may be used by the Research Team for information relating to the study and for academic publications, presentations and/or other display materials directly relating to the study. Participants and location will not be identifiable from the photos. Please note that whether you consent or not to photographing, you are still welcome to take part in the air pollution study. GDPR (General Data Protection Regulations) will apply to all information gathered (air pollution data and activity reporting forms) and held on password-locked computer files and locked cabinets within Imperial College London. No data will be accessed by anyone other than the Research Team.

What if something goes wrong?

If you are harmed by taking part in this research project, there are no special compensation arrangements. If you are harmed due to someone's negligence, then you may have grounds for a legal action. Regardless of this, if you wish to complain, or have any concerns about any aspect of the way you have been treated during the course of this study then you should immediately inform the Investigators, Louise Mittal louise.mittal@imperial.ac.uk and/or John Casey john.casey@imperial.ac.uk If you are still not satisfied with the response, you may contact the Imperial College Research Governance and Integrity Team (rgitcoordinator@imperial.ac.uk).

Who should I contact for further information?

If you have any questions or require more information about this study, please contact us using the following contact details:

Ms Louise Mittal
Email: louise.mittal@imperial.ac.uk - Telephone: +44 02075943310

Mr John Casey
Email: john.casey@imperial.ac.uk - Telephone: +44 02075946723 or +44 07964188578

How do I enrol in the study?

If you do decide to take part in this study, please keep a copy of this information sheet and sign the consent form attached.

Thank you for reading this information sheet and for considering taking part in this research.

TRANSPARENCY NOTICE

HOW WILL WE USE INFORMATION ABOUT YOU?

Research Study Title: London Wood Burning Project – Monitoring air pollution at home when solid fuel is burned
Study number: 6374539

Imperial College London is the sponsor for this study and will act as the data controller for this study. This means that we are responsible for looking after your information and using it properly. Imperial College London will keep your personal data for:

- 10 years after the study has finished in relation to data subject consent forms.
- 10 years after the study has completed in relation to primary research data.

We will need to use information from you for this research project.
This information will include your:

- Home burning appliance
- Activity form data

People will use this information to do the research or to check your records to make sure that the research is being done properly.
People do not need to know who you are and will not be able to see your name or contact details. Your data will be assigned to an appliance type and solid fuel burned type. We will keep all information about you safe and secure. Once we have finished the study, we will keep the data so we can check the results. We will write our reports in a way that no-one can work out that you took part in the study.

LEGAL BASIS

As a university we use personally identifiable information to conduct research to improve health, care and services. As a publicly funded organisation, we have to ensure that it is in the public interest when we use personally identifiable information from people who have agreed to take part in research. This means that when you agree to take part in a research study, we will use your data in the ways needed to conduct and analyse the research study.
Health and care research should serve the public interest, which means that we have to demonstrate that our research serves the interests of society as a whole. We do this by following the UK Policy Framework for Health and Social Care Research

INTERNATIONAL TRANSFERS

This report is the independent expert opinion of the author(s).

There may be a requirement to transfer information to countries outside the European Economic Area (for example, to a research partner). Where this information contains your personal data, Imperial College London will ensure that it is transferred in accordance with data protection legislation. If the data is transferred to a country which is not subject to a European Commission (EC) adequacy decision in respect of its data protection standards, Imperial College London will enter into a data sharing agreement with the recipient organisation that incorporates EC approved standard contractual clauses that safeguard how your personal data is processed.

SHARING YOUR INFORMATION WITH OTHERS

For the purposes referred to in this privacy notice and relying on the bases for processing as set out above, we will share your personal data with certain third parties.

- Other College employees, agents, contractors and service providers (for example, suppliers of printing and mailing services, email communication services or web services, or suppliers who help us carry out any of the activities described above). Our third-party service providers are required to enter into data processing agreements with us. We only permit them to process your personal data for specified purposes and in accordance with our policies.
- The following Research Collaborator.
  - Third Party Company – The anonymised data may be shared with the manufacturer of the air pollution monitors, so they can test the performance of the monitors.

WHAT ARE YOUR CHOICES ABOUT HOW YOUR INFORMATION IS USED?

Even if you have decided to take part, you are still free to stop your participation at any time during the study and to have research data and information relating to you withdrawn without giving any reason up to 1 month after the completion of the monitoring, after which withdrawal of your data will no longer be possible as all data will be anonymised.

We need to manage your records in specific ways for the research to be reliable. This means that we won't be able to let you see or change the data we hold about you.

WHERE CAN YOU FIND OUT MORE ABOUT HOW YOUR INFORMATION IS USED

You can find out more about how we use your information

- On this participant Information sheet
- by asking one of the research team
- by sending an email to louise.mittal@imperial.ac.uk or john.casey@imperial.ac.uk

COMPLAINT

If you wish to raise a complaint on how we have handled your personal data, please contact Imperial College London's Data Protection Officer via email at dpo@imperial.ac.uk, via telephone on 020 7594 3502 and/or via post at Imperial College London, Data Protection Officer, Faculty Building Level 4, London SW7 2AZ.

If you are not satisfied with our response or believe we are processing your personal data in a way that is not lawful you can complain to the Information Commissioner's Office (ICO). The ICO does recommend that you seek to resolve matters with the data controller (us) first before involving the regulator.

PARTICIPANT CONSENT FORM

Full Title of Project: London Wood Burning Project

Name of Principal Investigator: Dr Mohammed Mead

Name: ……

Please initial box

1. I confirm that I have read and understood the participant information sheet version 0.3 - dated 04/01/2023 for the above study and have had the opportunity to ask questions which have been answered fully.	
2. I understand that emissions from domestic solid fuel burning can be harmful to health and the environment and that burning different fuel types may result in increased or decreased emissions compared to my usual preferred fuel.	
3. I understand that my participation is voluntary, and I am free to withdraw at any time within one month of the completion of monitoring, without giving any reason and without my legal rights being affected.	
4. I understand that personal information collected about me will not be shared beyond the project team.	
5. I give/do not give (delete as applicable) consent for information collected about me to be used to support other research or in the development of a new test, medication, medical device or treatment (delete as applicable) by an academic institution or commercial company in the future, including those outside of the United Kingdom (which Imperial has ensured will keep this information secure).	
6. I understand that data collected from me are a gift donated to Imperial College and that I will not personally benefit financially if this research leads to an invention and/or the successful development of a new product or service.	
7. I understand that confidentiality and anonymity will be maintained, and it will not be possible to identify me in any research outputs	
8. I understand that the data collected from the monitoring equipment and activity forms will be published in a report. No personal information of the participant will be included in the report.	
9. I agree to taking part in this study	

This report is the independent expert opinion of the author(s).

Photography consent (optional)	
a. *I authorise Imperial College London to take photos of the monitoring equipment and fuel burning appliance in place at my home I understand that these images* may be used by the Research Team for academic publications, presentations and/or other display materials directly relating to the study. Participants and location will not be identifiable in photos included in reports or publications.	
b. *I understand that photos submitted of fuel and my burning appliance, by myself the participant* may be used by the Research Team for academic publications, presentations and/or other display materials directly relating to the study. Participants and location will not be identifiable in photos included in reports or publications.	

_____	_____	_____
Name of participant	Signature	Date
_____	_____	_____
Name of person taking consent (if different from Principal Investigator)	Signature	Date
_____	_____	_____
Principal Investigator	Signature	Date

1 copy for participant; 1 copy for Principal Investigator

Protocol.

London Wood Burning Project – Monitoring air pollution at home when solid fuel is burned.

Five fuels are provided, to burn in your fire/stove appliance. These include, seasoned kiln-dried wood, non-seasoned/kiln-dried wood, 'Smokeless' coal, authorised manufactured solid fuels. exempt manufactured solid fuels.

Please burn only one individual fuel type each evening. Do not mix the fuels during burning. The stove/fire should be cleaned out each day before re-lighting.

We ask that when initially starting the fire/stove on a test day, the firelighters and kindling provided are used.

Allow the fire to establish and then top up **at least once** over the course of the evening. However, you may top up the fire/stove as many times as you wish.

When topping up, please add an amount of fuel similar to what you would typically add when topping up.

If possible please can you take a photo of the fire before starting and the amount of fuel being added each time the fire/stove is topped up. These photos can be emailed to John Casey a researcher with the project team. john.casey@imperial.cac.uk

Paper activity forms are provided to record burning activities and other activities which may affect particulate levels indoors. These forms will be collected by the researcher at the end of the test week.

Please record **all** times, activities and comments for any interaction with the fire/stove on the activity form. A new activity form should be used for each day - (provide as much detail as possible).

Example of fire/stove typical activity entries with times and comments durning burning.

18:04	*Lit kindling and solid fuel*	*(small escape of smoke)*
18:18	*Closed stove door*	
19:55	*opened stove door and added fuel to stove*	*(noticable smell of smoke)*
20:00	*closed stove door*	

Please also record **all** times, activities and comments on the day's activity form for any other activity which may affect particulate concentrations in the room where air quality monitoring is taking place. These activities may include but are not limited to (cooking, lighting candles, smoking, use of aerosols or air freshners, ventilation etc – provide as much detail as possible)

Example of typical activity entries with times and comments.

18:30	*Started cooking*	*stir fry and oven use for baking, extraction fan on. (noticable smell of oil burning)*
18:40	*Finished frying*	
18:59	*Oven turned off*	*door opened and pie removed.*
19:15	*Finished cooking*	
19:30	*Lit candle*	
19:32	*Added fuel to stove*	
20:00	*Opened window*	

Thank You.

Imperial College London
Projects

Contact us:

Louise Mittal, Environmental Research Group.
Email: louise.mittal@imperial.ac.uk

Imperial Projects
Email: iproj@imperial.ac.uk