Impact Of Burning Allotment Waste on Sheffield's Air Quality

MSc Dissertation in Ecology and Conservation

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Abstract

This is the first study investigating how small scale waste fires affect $PM_{2.5}$ concentrations in residential areas of the UK. $PM_{2.5}$ is known to have adverse effects on the environment, climate and human health; highlighting the importance of reducing $PM_{2.5}$ concentrations to below WHO's safe annual limit of 5 μg/m^3. Our study site of Heeley and Meersbrook allotments has a waste fire ban every year between May and September. Using data from SDS011 sensors, we investigated the difference in $PM_{2.5}$ concentrations between when the fire ban is in place, compared to when it is not. We also examined the average $PM_{2.5}$ concentrations among nine nearby sensors, in order to see if there is any significance in spatial distribution from the allotment. Using wind data from a nearby weather station, we created pollution roses for five sensors to investigate the $PM_{2.5}$ concentrations travelling away from the allotments. Surveys were created to investigate the attitudes of nearby residents and allotment holders towards waste fires. Results show that there are lower $PM_{2.5}$ concentrations when there is a fire ban, suggesting that allotment waste fires have a significant effect on $PM_{2.5}$ concentrations. Moreover, our pollution roses illustrate that there are substantial levels of $PM_{2.5}$ concentrations higher than 15 μg/m^3 being released from the allotments. However, we could not find a relationship between the spatial distribution of the sensors - implying that there is an unidentified confounding variable. Survey results show the lack of understanding of the dangers of small scale fires on human health, even to those with pre-existing respiratory diseases. Sheffield City Council should improve their education on air pollutants, rather than immediately implementing a full length ban, to prevent displeasing allotment holders.

Introduction

Particulate matter (PM) is heterogeneous, consisting of a variety of solid particles and liquid droplets. Examples of chemical compounds found in PM include inorganic ions such as sodium and potassium, organic and elemental carbon, metals, particle-bound water and polycyclic aromatic hydrocarbons (WHO, 2013). PM often also contains biological factors such as pollen and microbes. The two methods of PM formation are either primary, which is when it is directly emitted into the air, and secondary, when it is formed via chemical reactions between gases already in the air. When discussing PM, it is critical to refer to the surface area size, as this affects the associated risk to health (Harrison, 2020). This study will focus on fine particulate matter - which includes particles with an aerodynamic diameter smaller than 2.5μm ($PM_{2.5}$).

In the UK, $PM_{2.5}$ concentrations have decreased by 85% since 1970 (Figure 1), when researchers first began discovering the formation and risks associated with air pollution (WHO, 2013). However, 90% of the global population still breathes air that exceeds the World Health Organisation's (WHO) safe annual mean limit of 5 μg/m^3 and daily limit of 15 μg/m^3 (Warren, 2018). Sources of $PM_{2.5}$ include, but are not limited to, transportation, domestic heating, industrial processes, fires, spraying aerosols such as hairspray, cigarette smoke and power generation. The city with the highest global level of $PM_{2.5}$ is Zabol in Iran, which has an annual average of 217µg/m^3, over forty times WHO's safe limit (Van Mead, 2017). The UK's highest $PM_{2.5}$ concentrations are found in London and Birmingham (Figure 2).

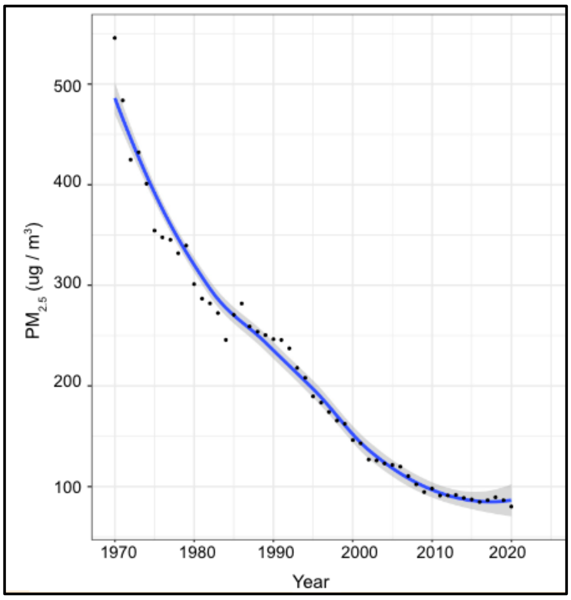

Figure 1*:* $PM_{2.5}$ concentrations *in the UK overtime. Data available from DEFRA (2022).*

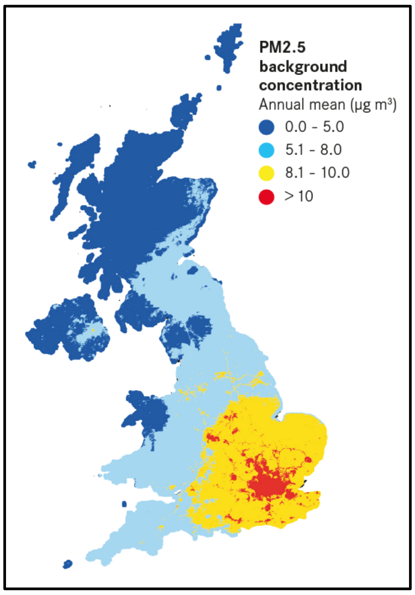

Figure 2*:* $PM_{2.5}$ *Concentrations mapped onto the UK (DEFRA, 2019).*

This report will focus on $PM_{2.5}$ released from domestic, small scale fires. The large majority of research investigating the effect of fires on $PM_{2.5}$ concentrations focuses on large-scale wildfires. These studies have revealed that fires lead to both primary and secondary formations of $PM_{2.5}$. The particles primarily consist of liquid particles of sulphate and organic carbon as well as solid compounds of black carbon - a pure carbon formed after the incomplete combustion of wood (Long, Nascarella and Valberg, 2013).

$PM_{2.5}$ is particularly damaging to human health as it is small enough to travel up the nose and mouth into the lungs, and deposit itself in the bronchioles and alveoli (Schwartz and Dockery, 1996). The deposited $PM_{2.5}$ is then difficult to clear and remains in the lungs causing respiratory problems (Schwartz and Dockery, 1996). Studies have found that asthma-sufferers are far more likely to require hospital treatment on days where there is prescribed burning nearby (Huang *et al.*, 2019). Moreover, due to the fact that $PM_{2.5}$ is smaller than a red blood cell (which typically measures 7µm), it is able to travel around the body via the bloodstream (Cagle, 2022). Research shows that these particles can reach the brain where they are particularly damaging to the cerebellum and hippocampus (Fagundes *et al.*, 2015), as they promote lipid peroxidation and reduce the activity of the enzyme catalase (Fagundes *et al.*, 2015). This leads to neurological illnesses such as Alzheimer's, dementia and Parkinson's (Rhew, Kravchenko and Kim Lyerly, 2021). In Sweden, for instance, 5% of all dementia cases can be directly attributed to $PM_{2.5}$ emissions (Kriit *et al.*, 2021). Moreover, due to the fact that $PM_{2.5}$ can travel around the bloodstream, it is able to affect foetuses, causing premature birth (Guo *et al.*, 2018). Kloog *et al.* (2012) illustrated that a 10 µg/m^3 increase in $PM_{2.5}$ exposure throughout pregnancy causes the child to be 13.8 grams lighter than average at birth. Moreover, being exposed to $PM_{2.5}$ as a foetus has long lasting health impacts. For instance, foetuses exposed to the 1997 Indonesian Forest Fires were 1.2% smaller than average whilst children (Rosales-Rueda and Triyana, 2017). Unsurprisingly, high $PM_{2.5}$ concentrations are also associated with a high mortality rate, due to an increase in respiratory, neurological and cardiovascular disease (G. Chen *et al.*, 2021). Studies have found that $PM_{2.5}$ released by fires have more damaging effects on human health than $PM_{2.5}$ released from transportation, agriculture or industry (Aguilera *et al.*, 2021). This is because wildfire $PM_{2.5}$ is incredibly carbonaceous, giving it a higher oxidative potential and promoting more free radicals (Aguilera *et al.*, 2021). This leads to higher rates of inflammation and is in turn, ten times more harmful than other $PM_{2.5}$ sources (Aguilera *et al.*, 2021). In the UK alone, $PM_{2.5}$ exposure is responsible for up to 36,000 premature deaths annually (Public Health England, 2019) and costs the NHS an estimated £76 million every year (Public Health England, 2018).

As mentioned previously, $PM_{2.5}$ can be released from a number of anthropogenic and natural processes. However Yin *et al.* (2019) found that $PM_{2.5}$ released during burning is significantly more damaging to the environment than $PM_{2.5}$ released during industrial processes or transportation. $PM_{2.5}$ released during burning contains high levels of black carbon (Grieshop *et al.*, 2009). Black carbon has a 600 times stronger warming impact than the equivalent weight of carbon dioxide (Grieshop *et al.*, 2009). Additionally, when black carbon settles on ice and snow, it reduces the surface albedo - darkening the Earth's surface and so absorbing heat - once again contributing to global warming (Hadley and Kirchstetter, 2012). Moreover, $PM_{2.5}$ impacts species in aquatic environments, as shown by Hartono *et al.* (2017), who discovered that higher $PM_{2.5}$ concentrations decreased aquatic snail movement. $PM_{2.5}$ also alters soil health by increasing soil acidity, in turn reducing leaf litter breakdown (Wu and Zhang, 2018) and disrupting nutrient cycling by affecting the rhizosphere bacteria and fungi (Grantz, Garner and Johnson, 2003). $PM_{2.5}$ affects plant growth by coating the stomata, which significantly reduces photosynthesis rates (Yu *et al.*, 2018).

The UK is located in the Temperate Deciduous Forest biome, meaning that it does not typically experience many natural wildfires (Talon *et al.*, 2005). However, anthropogenic burning does occur on heathland in order to clear heather for better grouse shooting conditions (Davies *et al.*, 2016). Moreover, climate change induced dry, hot summers have been linked to a number of rural wildfires (Albertson *et al.*, 2009). Nevertheless, the majority of fires within the UK occur in domestic settings via either log burners or through domestically burning waste. Currently, 43% of the UK's $PM_{2.5}$ emissions are directly linked to domestic burning (Figure 3) (DEFRA, 2021). As yet, there are very few successful methods of removing $PM_{2.5}$ from the atmosphere (Yan *et al.*, 2020). Additionally, the UK has no successful policies or laws restricting individual $PM_{2.5}$ emissions (DEFRA, 2019). Local councils began implementing 'smoke control areas' in the 1950s, which aimed to limit locations of domestic burning. However, few people abide by these policies (DEFRA, 2019). Therefore, this research should focus on understanding what causes high $PM_{2.5}$ concentrations and the policies that should be enforced to reduce them.

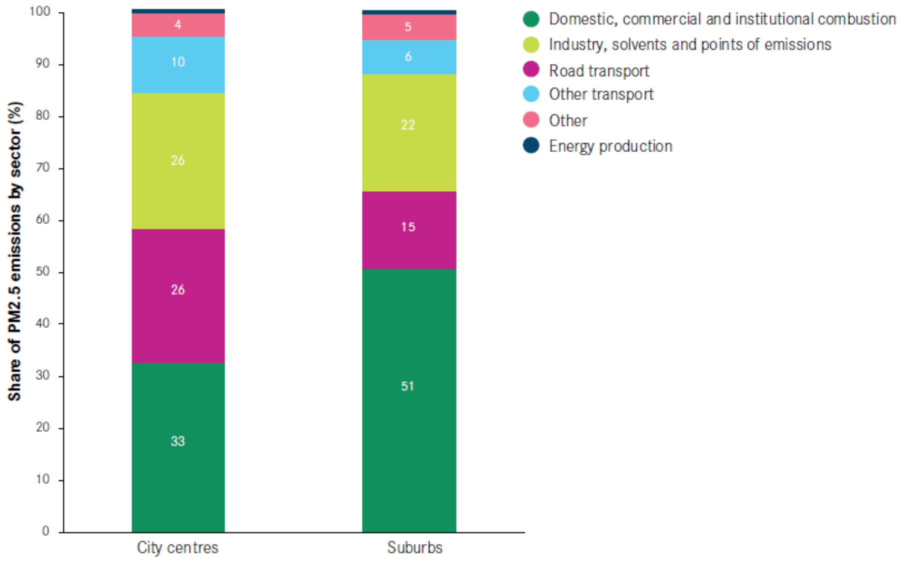

Figure 3*: The proportion of* $PM_{2.5}$ *emissions released by each sector in the UK in 2019, in both cities and suburban areas (NAEI, 2022)*

Here, we investigate the impact of small-scale allotment fires on Sheffield's air quality. There are 500 premature deaths due to poor air quality every year in Sheffield alone (Sheffield City Council, 2015). We hypothesise that even small-scale fires have a significant impact on the concentration of $PM_{2.5}$ in the air. Therefore, we expect to see higher $PM_{2.5}$ concentrations in the allotments compared to in residential areas, and during periods where fires are allowed, compared to when they are banned. We also investigated the attitudes of allotment holders and local residents towards the allotment fires. Our hypothesis is that members of the public with pre-existing respiratory conditions will be more supportive of extending the fire ban compared to their healthy counterparts. We aim to use our results to inform Sheffield City Council as to whether they should extend the Heeley and Meersbrook Allotment fire ban.

<u>Methods</u>

Study Site

Heeley and Meersbrook allotments are located in a suburban area south of Sheffield City Centre, UK (Figure 4). The study site of Heeley and Meersbrook Allotments was chosen due to its size and proximity to residential areas. This site has 436 individual plots and is the largest single allotment site in Europe. Additionally, this site has a number of $PM_{2.5}$ sensors located in and around the allotments, as well as a weather station extremely close to the allotment (Figure 5). There is currently a five month fire ban in place between 1st May and 30th September, which provides ideal data to compare periods of time with fires and without.

Figure 4: *The position of the allotments (represented by the pink pinpoint)* ***a)*** *within the United Kingdom* ***b)*** *in reference to Sheffield City Centre*

Sensors

The sensors used are SDS011 and are proven to be substantially reliable for monitoring $PM_{2.5}$ concentrations (Budde *et al.*, 2018). All sensors were implemented within the last three years by 'Clean Air for Sheffield.' These devices take a number of recordings, including $PM_{2.5}$ concentration, every two minutes. They rely on a solar powered battery so are unable to work under extended periods of cloud cover (Figure 6). The $PM_{2.5}$ data is publicly available (SDS011 Data, 2022).

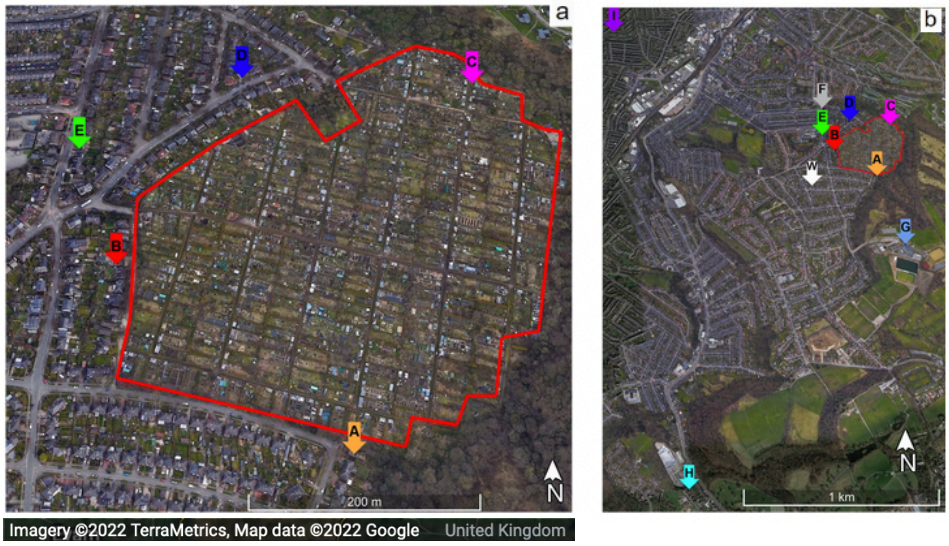

Figure 5: *Maps of the allotment location. Both maps contain a red outline showing the allotment site, as well as a scale and compass.* ***a)*** *An aerial view of the six closest sensors to the allotments. A = sensor 63167, B = sensor 63165, C = sensor 63034, D = sensor 62691, E = sensor 62183.* ***b)*** *a zoomed out view of the wider area, showing F = sensor 29838, G = sensor 64166, H = sensor 62532, I = sensor 64050 and well as the location of the weather station (W).*

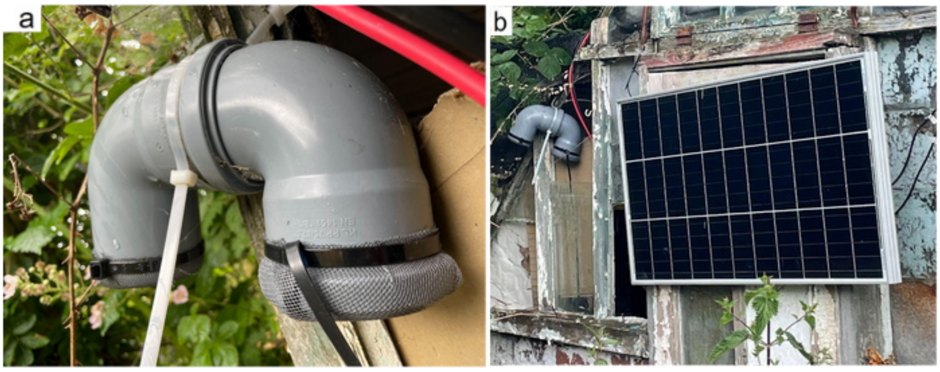

***Figure 6**: **a)** Sensor C enclosed in a waterproof casing **b)** Example of a solar panel used to power the sensor at Heeley and Meersbrook Allotments.*

Wind Data

The wind data used is publicly available (*Davis Weather Data*, 2022) and contains recordings for every 5 minutes from the 1st June 2021 to 1st July 2022. For this study, we used the wind speed and direction data. The weather station is located 230 metres away at a SSW direction from the allotments (Figure 5b).

Surveys

Two surveys were created, one for residents living near the allotment site and one for allotment holders. Both surveys were granted ethics approval by the University of Sheffield's Ethics Department.

The survey for residents included 19 closed-ended questions relating to how often they notice fires coming from the allotments, whether they would support a year-long ban on the fires and the distance and direction they live from the allotments. A link of the Google Forms containing the survey was uploaded to two Meersbrook Resident's Facebook groups, "Only in Meersbrook" which has 7,300 members and "OIM Onision in Meersbrook" which has 5,400 members. 51 residents participated in the survey, which was live for a week between 21st and 28th of June 2022.

The survey for allotment holders was conducted both online through social media and in person. Eleven allotment holders who were present at their sites on Monday 14th of June 2022 were asked the survey questions in person. Eleven allotment holders completed the survey via a Google Form which was accessible via the Heeley and Meersbrook Allotments Facebook page between 15th and 22nd of June 2022. There should be no discrepancies between the answers received via social media and in person. The survey consisted of 21 closed-ended questions, including demographic questions and questions related to how often they burn waste. Copies of both surveys are provided in the Appendix.

Statistical Analysis

A series of statistical R packages were used to analyse the data from the surveys, sensor and weather station (RStudio Team, 2021). Table 1 summarises the different packages used.

***Table 1**: The RStudio packages used, along with the reasoning for their use.*

Package	Statistical Analysis	Reference
ggplot2	Created all graphs (aside from the pollution roses).	(Wickham, 2016)
ggpubr	Increased the quality of all ggplot2 graphs.	(Kassambara, 2020)
lme4	Undertook an lmer to analyse the correlation between wind speed and $PM_{2.5}$ concentrations.	(Bates *et al.*, 2014)
openair	Visualised the $PM_{2.5}$ concentrations from the allotments.	(Carslaw, 2014)
dplyr	Merged the wind data with the $PM_{2.5}$ data.	(Wickham *et al.*, 2015)
mgcv	Created the generalised additive model used to investigate the $PM_{2.5}$ concentrations over time.	(Wood, 2011)
tidymv	Processed and predicted results from the generalised linear model.	(Coretta, 2021)

Results

Allotment Holders' Survey

The allotment holders' survey consisted of twenty one questions. Figure 7 contains the data most relevant in understanding the behaviours and attitudes of allotment holders to waste fires.

A chi-square test revealed no significant relationship between the respondent having a respiratory illness and whether or not they burn waste (X^2 (2, N = 22) = 0.017, p = 0.99). This suggests that allotment holders with pre-existing respiratory illnesses are not disproportionately more affected by high $PM_{2.5}$ concentrations (Figure 7a). An additional chi-square test investigating the relationship between a person's age and whether or not they would prefer a full year ban found a strong significance (X^2 (2, N = 22) = 7.11, p = 0.029), with older allotment holders (56+) being more likely to want a full year ban (Figure 7b). When looking at the relationship between the length of time a person has had their allotment and whether or not they would prefer a full year ban, a chi-square test found that there is significant relationship (X^2 (2, N = 22) = 7.11, p = 0.029). People who have had their allotment for more than 5 years are significantly more likely to favour a full year ban, compared to those that have had their allotment for less than 5 years (Figure 7c). Lastly, a chi-square test found that there is no significance between the importance of environmental issues to the respondent, and whether or not they want a ban (X^2 (2, N = 22) = 2.31, p = 0.31). However, no respondents chose either 1 or 2, meaning that all respondents found environmental issues at least 'mildly important' to them (Figure 7d). Only half of the respondents who rated environmental issues as a 5 on the importance scale said they want a full year ban, implying that they may not be aware of the environmental issues caused by high levels of $PM_{2.5}$ pollution.

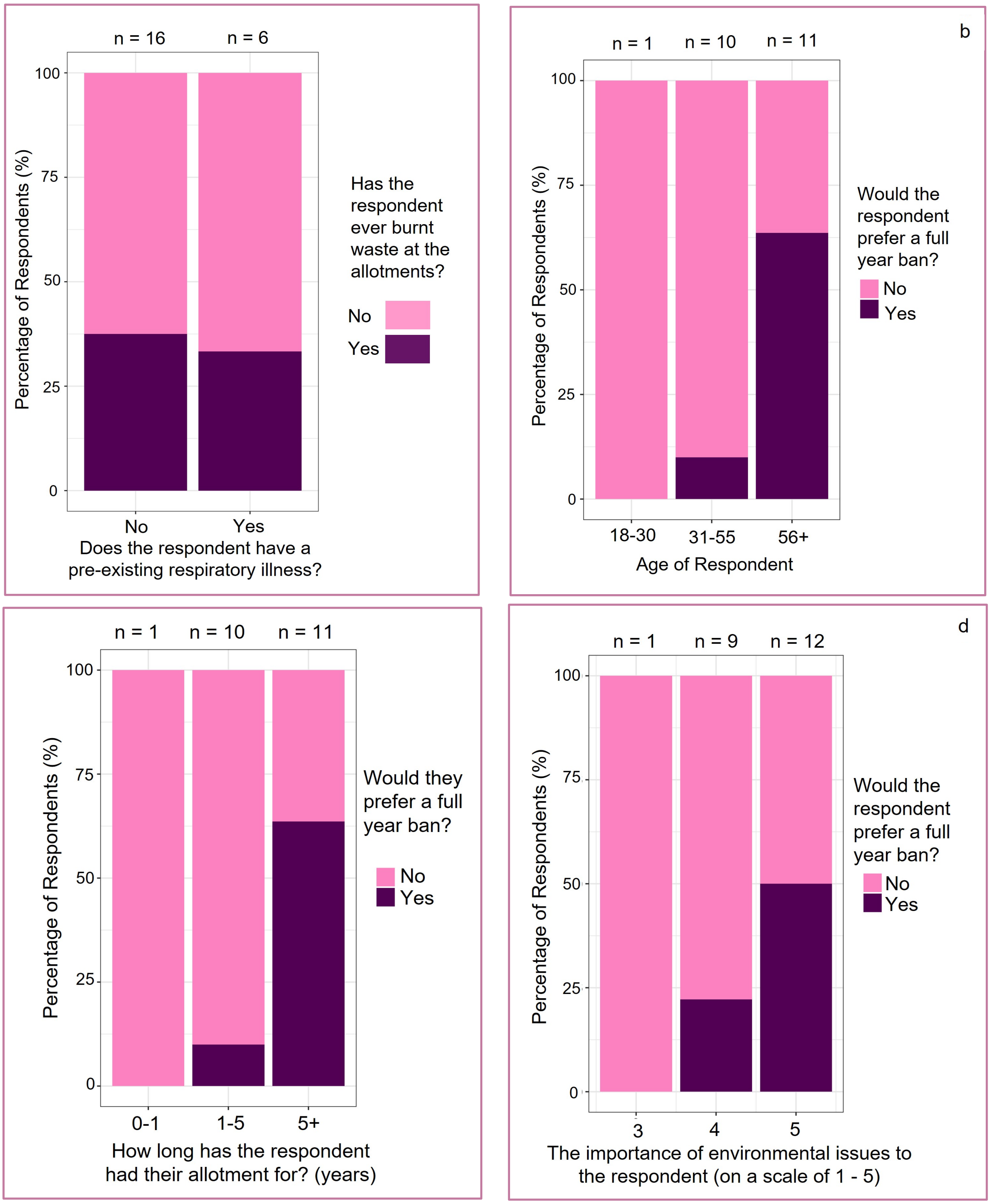

***Figure 7**: **a)** The relationship between whether or not the allotment holder has a pre-existing respiratory condition and if they have ever burnt waste at the allotments. **b)** The relationship between the age of the allotment holder and whether or not they would prefer a full year ban. **c)** The relationship between the length of time the respondent has had their allotment for and whether or not they would prefer a full length ban. **d)** The relationship between the importance of environmental issues (on a scale of 1 to 5, with 1 being 'not at all' and 5 being 'extremely important') to the allotment holder and whether or not they would prefer a full year ban. No respondents selected 1 or 2.*

Residents' Survey

The residents' survey consisted of nineteen questions. Figure 8 contains the data most relevant to understanding how the allotment fires affect local residents and their opinions towards it.

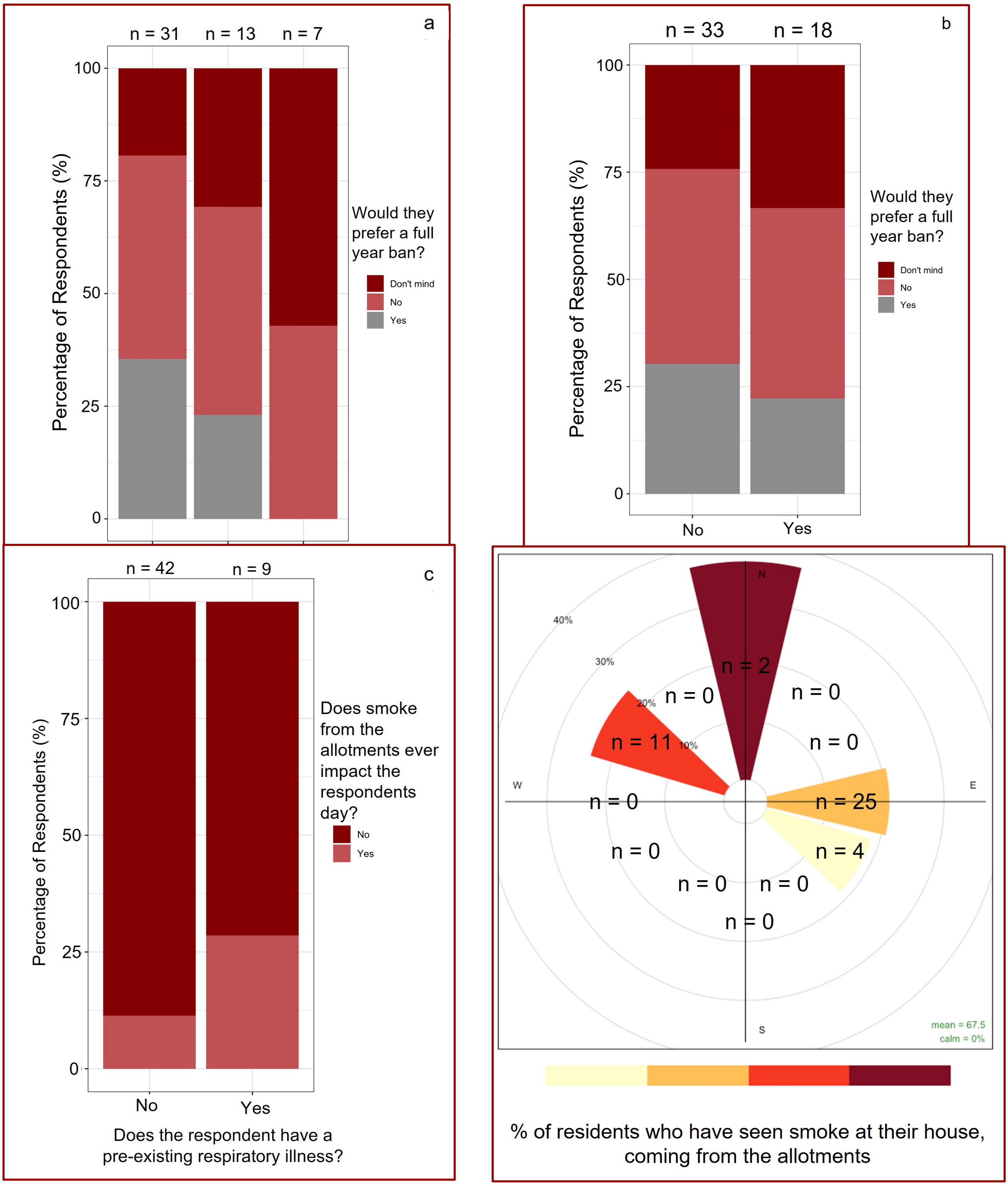

***Figure 8**: **a)** The relationship between the distance of the respondents' house from the allotments and whether or not they would prefer a full year ban. **b)** The relationship between whether the respondents have any dependents under the age of 18 living in the house and whether or not they would prefer a full year ban. **c)** The relationship between whether or not the respondent has a pre-existing respiratory illness and whether or not smoke coming from the allotments ever impacts their day. **d)** The proportion of respondents, living in different directions from the allotments, who have seen smoke coming from the allotments to their house. The total number of respondents who lived in each direction is provided.*

A chi-square test found no significance between the distance of the respondents' house from the allotments and whether or not they would prefer a full year ban (X^2 (2, N = 51) = 0.97, p = 0.62). However, none of the respondents that lived more than 1 mile away from the allotments responded 'Yes' to extending the ban - implying that residents who are more than 1 mile away are less affected by the fires, so less likely to care about the ban (Figure 8a). Moreover, there is no significance between whether or not there is a dependent living in the respondents' house and if they want a full year ban - as shown by a chi-square test (X^2 (2, N = 51) = 0.97, p = 0.62) (Figure 8b). Another chi-square test found no significance between the respondent having a respiratory illness and whether or not smoke coming from the allotments affected their daily life (X^2 (1, N = 51) = 0.41, p = 0.52) (Figure 8c). Figure 8d illustrates that all of the respondents living North of the allotments have seen smoke coming from the allotments. However, this is the case for only 64% of the respondents living West North West, 56% living East and 50% living East South East. This preliminarily suggests that the smoke is primarily travelling North (Figure 8d).

$PM_{2.5}$ data from the SDS011 sensors

Here, we have an example of an allotment fire that occurred on the morning of the 18th of October 2021. Figure 9a illustrates that $PM_{2.5}$ concentrations began rising at 9.30 am and took around three hours to subside. The only sensors to report a change in $PM_{2.5}$ concentrations were B and E, which were the closest sensors to the video. Sensor B (the closest sensor to the fire) reported $PM_{2.5}$ values of 1000 μg/m^3, whilst the maximum $PM_{2.5}$ concentration reported by sensor E was 40 μg/m^3. This shows that one small scale fire is able to increase significantly $PM_{2.5}$ values in the immediate area.

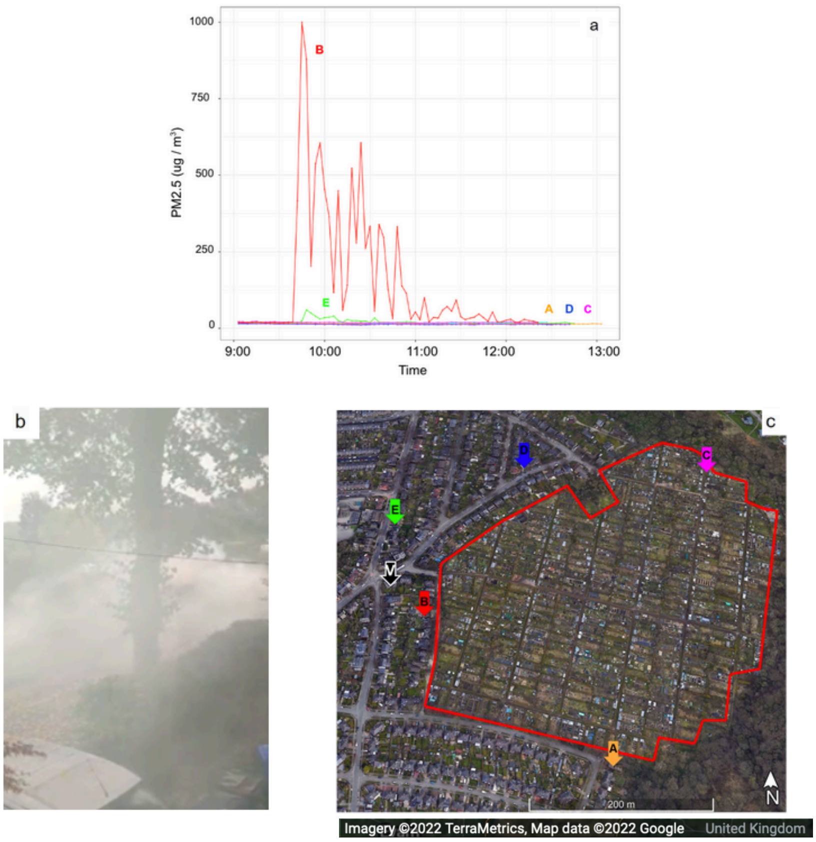

Figure 9**: **a) $PM_{2.5}$ *concentrations on the morning of the 18th of October 2021, for five nearby sensors. **b)** An image taken at 10 am on the 18th of October 2021 by a local resident during a small scale waste fire within the allotment (Hercberg, 2021). **c)** An aerial view showing where the video was taken from (V) in relation to the sensors.*

In order to study the spatial resolution of $PM_{2.5}$ concentrations around the allotments, observations from all nine sensors are summarised in Figure 10. All values were taken from November 2021, when there is no fire ban in place at the allotments. Conversations with the allotment holders during the surveys informed us that November is typically the month with the highest frequency of waste fires - indicating that this would be the best month to analyse the spatial distribution of $PM_{2.5}$ from waste fires. Additionally, only data from between 10 am and 5 pm was used, in order to reduce the impact of domestic wood burning stoves as a confounding variable.

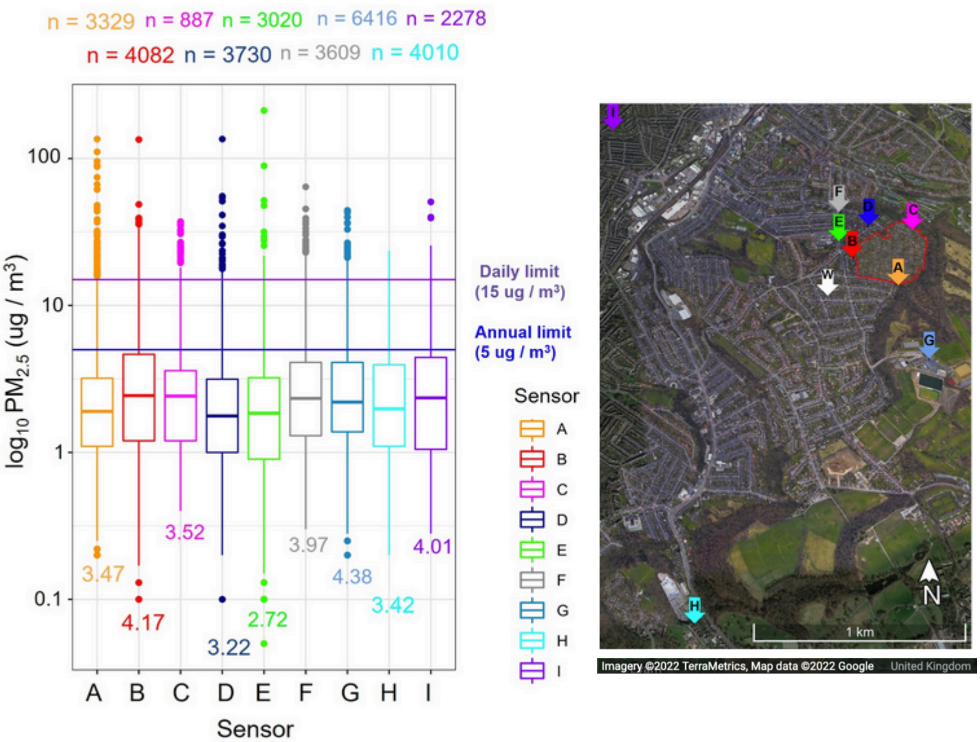

***Figure 10**: $PM_{2.5}$ concentrations for all nine sensors from 10 am to 5 pm for November 2021 . The data were logged for clarity. The number of recordings within each sample is shown, as well as the mean value of the sensor for the month. WHO's daily and yearly safe $PM_{2.5}$ limits are displayed. A copy of Figure 5b is also provided to allow direct comparison between the $PM_{2.5}$ values and their respective location.*

Results from a one way anova show that there is significant difference in the $PM_{2.5}$ concentrations between all nine sensors (df = 8, f = 43.08, p = <0.01). Sensor G has the highest mean $PM_{2.5}$ concentration of 4.38 µg/m^3, which is still under WHO's safe annual limit of 5 µg/m^3. The lowest average $PM_{2.5}$ level is from sensor E at 2.72 µg/m^3. Perpexingly, this is incredibly close (< 150 metres away) from sensor B, which has the second highest $PM_{2.5}$ mean of 4.17 µg/m^3. Sensor C, which is the only sensor directly inside the allotment site, had the median $PM_{2.5}$ average between all 9 sensors. Figure 10 alone does not indicate that there is a higher $PM_{2.5}$ concentration within the allotments, compared to within residential areas.

To determine if the burning ban significantly affects the $PM_{2.5}$ concentrations throughout the year, data from 24th July 2021 to 10th June 2022 were analysed in Figure 11. Data from sensor C was used, as this is the only sensor directly in the allotments.

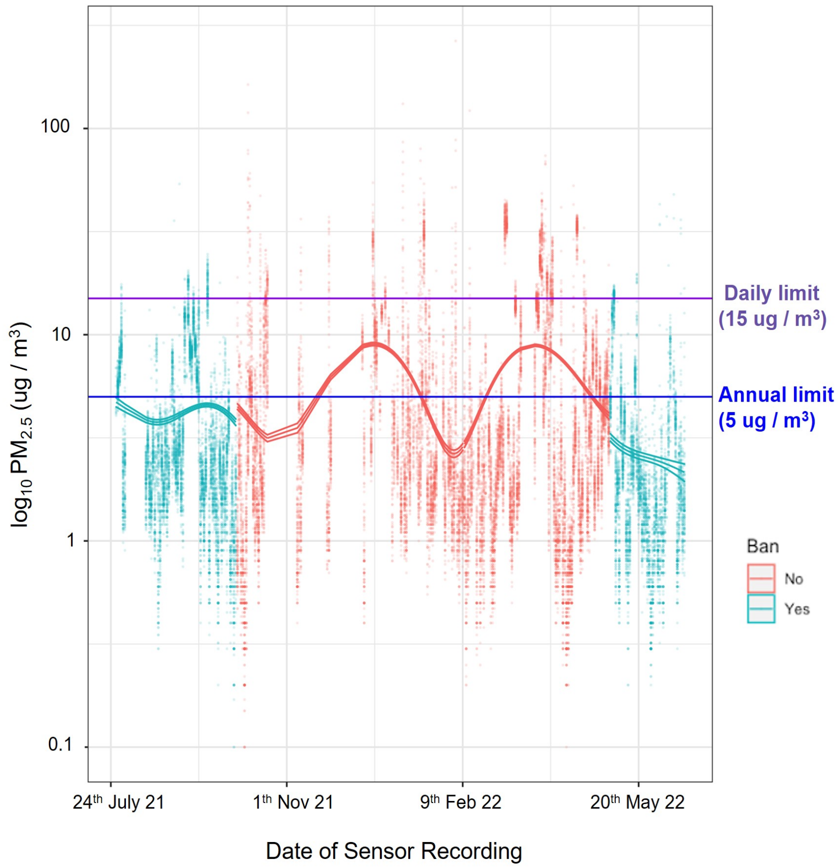

***Figure 11**: $PM_{2.5}$ data from sensor C were logged for clarity and better data visualisation. WHO's safe daily and annual $PM_{2.5}$ limits are displayed. Once again, only data from recordings between 10 am and 5 pm were used. A line of best fit is shown.*

Results from a generalised additive model show that there is a significant difference in $PM_{2.5}$ concentrations throughout the year, with May to September having a higher $PM_{2.5}$ value than October to April (p-value = 0.0001, R-sq.(adj) = 0.0798, Dev explained = 8.01%, n = 33926). Figure 11 illustrates that during the ban, the line of best fit is below WHO's annual limit of 5 μg/m^3 , whereas for a large proportion of the time during no ban the line of best fit is over the annual limit. Moreover, we can see an unexplained dip in the $PM_{2.5}$ concentration at the start of February 2022.

Relationship between $PM_{2.5}$ and wind data

To assess whether wind conditions affect $PM_{2.5}$ concentrations, wind data (direction and speed) from a nearby weather station were analysed with the $PM_{2.5}$ sensor data. Figure 12 shows $PM_{2.5}$ concentrations for each sensor and the geographical direction the wind was travelling from at the corresponding time.

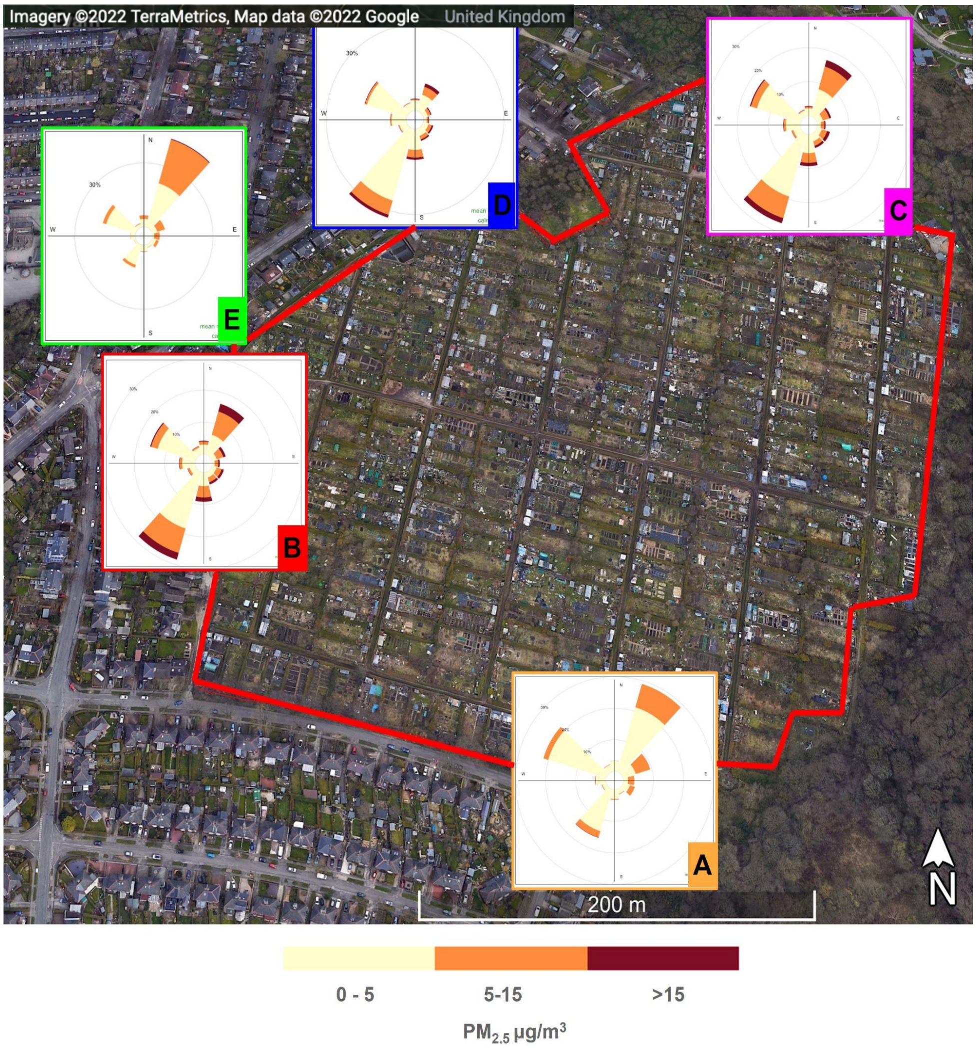

Figure 12*: Pollution roses for sensors A, B, C, D and E and their position from their allotments. Once again, only data from the month of November, between 10 am and 5 pm were used. The segment placement shows the direction the wind is coming from. The colouration is divided into WHO's* $PM_{2.5}$ *safe limits. The size of the segment shows their relative proportion to the overall recorded* $PM_{2.5}$ *of that sensor. The outer grid line represents 30% of the data. Full size versions of each pollution rose are available in the Appendix.*

A large proportion (30%) of the wind blowing towards Sensors A and C are from the direction of the allotments. These winds contain a significant proportion of $PM_{2.5}$ over 5 µg/m^3. The wind blowing towards sensor C in particular contains a small proportion of $PM_{2.5}$ over 15 µg/m^3. Sensors B and D only have a small amount of wind blowing from the direction of the allotments. However, these winds have a significantly high proportion $PM_{2.5}$ over 15 µg/m^3. This suggests that the allotments are often responsible for $PM_{2.5}$ concentrations over the WHO's annual limit.

To investigate whether wind speed affects $PM_{2.5}$ concentration, we analysed the relationship between $PM_{2.5}$ and wind speed. Once again, sensor C was used as this is the only sensor directly in the allotments.

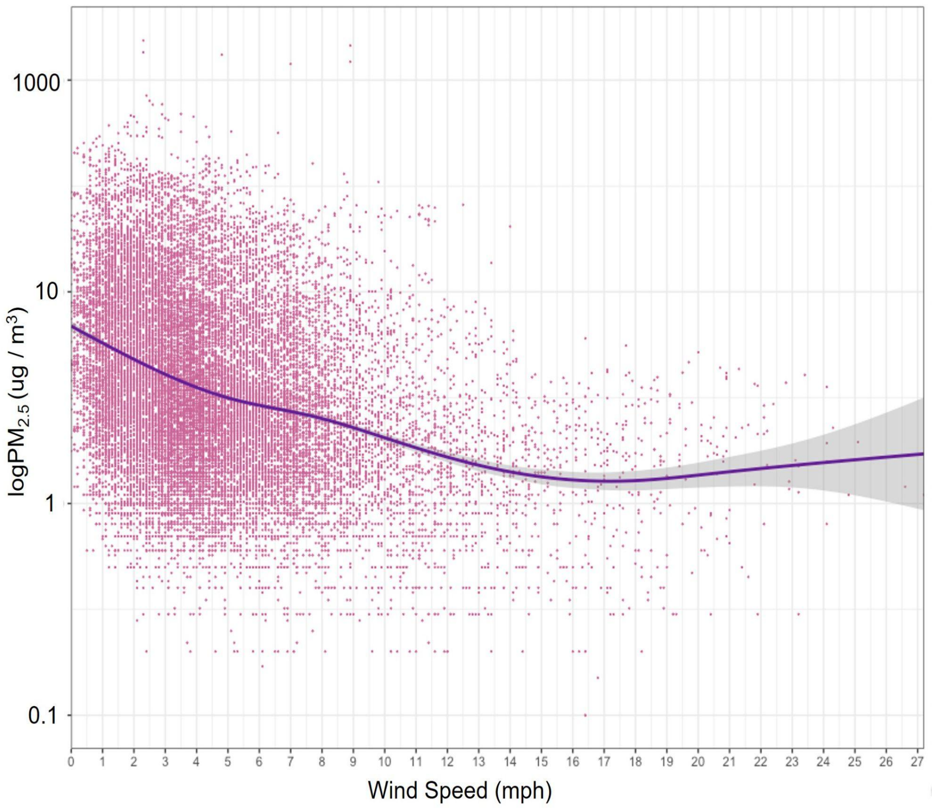

***Figure 13**: $PM_{2.5}$ concentration from sensor C and associated wind speed in mph, along with a line of best fit and confidence intervals (shown by the grey shading). Data points are from 1st June 2021 - 1st June 2022. $PM_{2.5}$ data were logged for clarity.*

A linear mixed effect model, controlling for date and time, found that there is a negative association between $PM_{2.5}$ and wind speed (Figure 13). For every 0.2 unit decrease in $PM_{2.5}$ concentration, there is a 1 unit increase in wind speed ($t = -12.21$, $f = 149.22$, $p < 0.01$). Therefore, as the wind speed increases, $PM_{2.5}$ disperses and dilutes into the atmosphere, resulting in a decreased concentration for that specific location (Verma and Desai, 2008).

Discussion

Overall, our results indicate that waste fires within Heeley and Meersbrook Allotments significantly increase the $PM_{2.5}$ concentration within the immediate area (Figure 9). Therefore, when the fire ban is not in place, there is a significantly higher $PM_{2.5}$ concentration compared to when the ban is enforced (Figure 11). It is important to note that the $PM_{2.5}$ concentrations present during the months with no ban are still under WHO's safe limits. Surprisingly, there is no relationship between the location of the sensor from the allotment and the $PM_{2.5}$ concentration (Figure 10), indicating that the allotments do not have significantly higher concentrations of $PM_{2.5}$ compared to neighbouring residential areas. Meteorological conditions, such as wind speed and direction do significantly impact $PM_{2.5}$ concentration, so could possibly be taken into account when discussing altering the ban (Figure 12, 13). However, public knowledge of the impact of fires on health and the environment is very low, meaning that most allotment owners and local residents are not in support of extending the ban (Figure 7, 8).

Allotment holders with pre-existing respiratory conditions, such as Chronic Obstructive Pulmonary Disease (COPD) or asthma, are just as likely to burn waste as healthy allotment holders (Figure 7a). One reason for this may be a lack of public understanding regarding the health impacts of fire induced air pollution (Ramírez *et al.*, 2019). Another possible explanation is that the allotment holders have no other options when removing their waste. Whilst speaking to allotment holders during the in person surveys, many of them mentioned that there is no other way to dispose of waste. Therefore, in order for people with respiratory problems to not feel required to burn their waste, the council must provide better waste management facilities. Nonetheless, we are still unclear if having a pre-existing respiratory disease makes you more vulnerable to $PM_{2.5}$ (Nakao *et al.*, 2016). Studies show that $PM_{2.5}$ pollution does exacerbate conditions such as asthma and COPD (Hansel *et al.*, 2013; Huang *et al.*, 2019). However there are very few studies directly comparing the effect of $PM_{2.5}$ on people with pre-existing health conditions and without. The few studies that have attempted to make a direct comparison have been unable to reach a definite conclusion as to whether $PM_{2.5}$ affects people with pre-existing respiratory diseases disproportionately more than healthy individuals (T. Chen *et al.*, 2021). Therefore, solutions for enticing people with pre-existing respiratory problems to burn less waste include improved education, as well as the council implementing more waste removal options. However, as yet, we are unsure if people with pre-existing respiratory conditions should be burning less than their healthy counterparts.

Our result, which suggests that people over the age of 56 are more likely to want a full year fire ban (Figure 7b), are supported by copious amounts of research literature stating that $PM_{2.5}$ is more harmful to elderly members of this public (particularly those aged 65 and over) (Jiménez *et al.*, 2009). This is because $PM_{2.5}$ exacerbates diseases that the elderly are already vulnerable to, such as cardiovascular and respiratory diseases (Fischer *et al.*, 2003; Simoni *et al.*, 2015; Wang *et al.*, 2015). This indicates that elderly allotment holders are aware of the harmful health impacts of high $PM_{2.5}$ concentrations.

Figure 7c illustrates that the longer allotment holders have had their allotment for the more likely they are to want a full year fire ban. A potential explanation for this is that people who have had the allotments for longer have had more interactions with high $PM_{2.5}$ concentrations, so are more aware of the negative effects of $PM_{2.5}$. For instance, people who have had their allotments for less than a year may not have encountered many days with lots of fires and high $PM_{2.5}$ levels. On the other hand, allotment holders who have had their site for longer than 5 years will recall the time before there was any ban and fires were allowed everyday.

There is also the paradox of there being no significance between people who care a lot about environmental issues and whether or not they want a full year ban (Figure 7d). This highlights the idea that members of the general public do not associate $PM_{2.5}$ released from fires as being harmful to the environment (Ramírez *et al.*, 2019). Studies suggest that there is a lack of adequate education and communication on the environmental impacts of fires, and that the existing information does not reach vulnerable people (Ramírez *et al.*, 2019). Therefore, many of the allotment holders who are burning waste may be unaware of the detrimental impacts they are inflicting on the environment. Improved education is a feasible solution to this paradox.

Figure 8a suggests that people who live further than a mile from the allotments are not affected by the $PM_{2.5}$ concentrations. We have inferred this from our results, which state that none of the residents living more than a mile away from the allotments chose ‘Yes’ when asked whether or not they would prefer a full year ban, whereas people who lived less than a mile away did (Figure 8a). Calculating how far smoke travels is a complicated process and involves knowing exactly when the fire was lit, the temperature, humidity and wind of that day, whether there are any obstructions (such as buildings) in the way, the materials being burnt, and how long the fire was lit for (Damoah, Spichtinger and Forster, 2004). However, our survey results suggest that it is only the houses within a mile radius of the allotments that are affected.

Moreover, we initially hypothesised that residents who had young dependents living in the house would be more likely to want a full year fire ban, compared to residents without dependents. This is because people with children are typically more environmentally conscious (Brochado, Teiga and Oliveira-Brochado, 2017). However, our results of no significance between having dependents in the house and wanting a full year ban, once again imply that the local residents do not associate fires, and the subsequent high $PM_{2.5}$ concentrations, as being environmentally damaging (Figure 8b).

The results from our survey also illustrated the paradox of local residents with pre-existing respiratory conditions being just as impacted by $PM_{2.5}$ as healthy residents (Figure 8c). A potential reason is that residents with respiratory diseases do not directly associate the smoke coming from the allotments as being the reasons for any exacerbations of their illness. As mentioned previously, members of the public, particularly those who are vulnerable, are not aware of the impacts of $PM_{2.5}$ (Ramírez *et al.*, 2019). Therefore, they may not have linked any exacerbations in their illnesses to the high levels of smoke. Another potential explanation is that the questions were quite ambiguous. For instance, a ‘pre-existing respiratory disease’ may be mild asthma for one respondent, whilst for another respondent it may be severe COPD. Moreover, asking the residents if ‘smoke coming from the allotments ever impacts their daily life’ is equally ambiguous. Some respondents may have their visibility affected or may just dislike the smell of smoke in the air - and say that this affects their everyday life. Whilst another respondent who does have a respiratory disease may be house-bound with severe short term respiratory problems due to the smoke and would also say that their daily life is affected. Therefore, future research should use less ambiguous closed-ended questions. Nonetheless, the obvious conclusion, and one that is supported by previous literature, is that residents with respiratory illnesses are not affected disproportionately more by high $PM_{2.5}$ concentrations compared to their healthy counterparts (T. Chen *et al.*, 2021). This conclusion suggests our results are in fact reliable and accurate, and residents with pre-existing health conditions are not significantly more impacted by smoke from the allotments.

Lastly, Figure 8d implied that the largest proportion of $PM_{2.5}$ was travelling North - which significantly contradicts results from Figure 12, which states that most $PM_{2.5}$ is travelling from either North East or South West. In order for the residents' survey results to correlate with Figure 12, the majority of $PM_{2.5}$ would need to be travelling from the South to the North. Reasons for this discrepancy may be that the residents' data was too unevenly distributed to provide reliable results. For instance, there were 25 respondents living East of the allotments, and only 2 living North. There were no respondents living either North East or South West, the two directions that would corroborate with the results from Figure 12. Further survey responses are required in future to assess the impact of $PM_{2.5}$ in different geographical directions.

To the best of our knowledge, this is the first study to look at outdoor small scale fires and their impact on $PM_{2.5}$ concentrations. Figure 9 is an excellent example of how one small scale fire can affect $PM_{2.5}$ concentrations in the immediate area. This corroborates results from Figure 8a, which states that people who live more than a mile away from the allotments are not particularly affected by the resulting $PM_{2.5}$ concentrations. Figure 9 shows that only the two closest sensors, B and E experienced peaks in $PM_{2.5}$. However, the next closest sensor, D, which is only 250 metres (0.16 miles) away, shows no changes in $PM_{2.5}$ concentrations. Therefore, we can conclude that small scale waste fires at the allotment do cause extremely high concentrations of $PM_{2.5}$, however this is only in the immediate vicinity. As mentioned previously, it is extremely complex to measure how far $PM_{2.5}$ will travel from a fire due to the different compounding factors involved. Additionally, due to the fact that there is no current literature investigating small scale waste fires in the UK, it is difficult to accurately measure how far $PM_{2.5}$ travels. Nevertheless, this case study implies that small scale fires will only alter $PM_{2.5}$ concentrations incredibly close-by. Our results also allow us to safely state that the sensors used are far enough away from each other to not experience pseudoreplication.

Even though we did find a significant difference in average $PM_{2.5}$ concentrations between the nine different sensors, we found no spatial patterns in $PM_{2.5}$ concentration (Figure 10). The highest average $PM_{2.5}$ concentration is from sensor G, which is located 500 metres south of the allotments in the grounds of Newfield Secondary School. Schools typically have very high levels of indoor air pollution (Konstantinou *et al.*, 2022) and high concentrations of $PM_{2.5}$ during school drop off and pick up times due to the number of parked vehicles with their engines left on (Adams and Requia, 2017). However, this study only used $PM_{2.5}$ concentrations between 10 am and 5 pm, meaning that any $PM_{2.5}$ released during drop offs would not be included. In future, studies assessing the impact of small scale waste fires on air pollution should only use data from 10 am to 2.30 pm, to remove school pick ups from influencing $PM_{2.5}$ concentrations. It is particularly worrying that a school, where developing children spend a large proportion of their time, has the highest $PM_{2.5}$ concentration. Nevertheless, this sensor's average was still below WHO's safe annual limit. This illustrates that the other sensors near to the allotments, still have, on average, safe $PM_{2.5}$

concentrations. As mentioned previously, sensor C, which is the only sensor located within the allotments, experienced the median average $PM_{2.5}$ concentration. However, Figure 12 illustrates that a significant proportion of the $PM_{2.5}$ recorded by this sensor was travelling from the allotments. The lowest average $PM_{2.5}$ concentration was recorded by sensor E, which is 90 metres to the North West of the allotments and does not receive much air pollution from the allotments (Figure 12). These results raise the question of what is affecting the $PM_{2.5}$ concentrations in order for them to have such spatially variable average concentrations. An important spatial property that we have not accounted for that increases $PM_{2.5}$ concentrations is being near busy roads (Harrison *et al.*, 1997). Sensor H is the closest sensor to a heavily trafficked road, however it has one of the lowest average $PM_{2.5}$ concentration. Therefore, future research must investigate reasons behind this spatial distribution.

We are able to accept our hypothesis that there will be higher $PM_{2.5}$ concentrations between October and April, when there is no fire ban, compared to the rest of the year when there is a ban (Figure 11). Enforcing a ban on burning waste ensures that the $PM_{2.5}$ line of best fit stays below WHO's annual recommended safe limit of 5 μg/m^3. However, when there is no ban the line of best fit reaches 9 μg/m^3, which is beyond the annual safe limit. Moreover, whilst there is no ban, there are far more extreme highs - presumably due to the fires from the allotments. This figure alone shows that the ban is successful in reducing $PM_{2.5}$ concentrations, and if extended throughout the year may bring the annual average down to 5 μg/m^3. However, there are unexplainable peaks and troughs in this figure. For instance, during the start of February the $PM_{2.5}$ concentrations drop significantly. As yet, we have no explanation for this. However, future research should investigate what happened to create this trough, and if we can learn anything from this event to try and keep $PM_{2.5}$ concentrations down throughout the year. Overall, if the ban continued as it is, the $PM_{2.5}$ concentrations would still be at a relatively safe level. Therefore, careful consideration must be taken before making any new decisions regarding the length of the ban.

Figure 12 highlights the wind conditions under which the highest concentrations of $PM_{2.5}$ occur. It is evident that the wind carries air pollution primarily from the South West and North East (Figure 12). 30% of sensor A's recorded $PM_{2.5}$ is travelling from the allotments (NNE). A large proportion of this $PM_{2.5}$ has a concentration higher than 5 μg/m^3. Similarly, sensor C has just under 30% of its recorded $PM_{2.5}$ travelling from the direction of the allotments with a high proportion of $PM_{2.5}$ concentration over WHO's daily limit of 15 μg/m^3. This suggests that the levels of air pollution being released from the allotments are above WHO's recommended safe levels. Additionally, both sensors D and B have a small proportion of their wind blowing from the direction of the allotments, and these winds carry a significant proportion of $PM_{2.5}$ concentrations above 15 μg/m^3. Sensor E is the only sensor which has such a small proportion of its wind blowing from the allotments that it is difficult to assess the proportion of the wind's $PM_{2.5}$ concentration that is safe. Overall, Figure 12 allows us to infer that the allotments do release significant amounts of high concentrations of $PM_{2.5}$ into the atmosphere. This corroborates with previous findings, that have looked at the impact of large scale wildfires on air quality and found that fires release a disproportionate amount of highly concentrated $PM_{2.5}$, compared to other air pollutant sources (Yin *et al.*, 2019).

The results from our wind speed study corroborate with existing literature (Lu and Fang, 2002; Verma and Desai, 2008; Li, Feng and Liang, 2017). There is a negative association between wind speed and $PM_{2.5}$ concentrations (Figure 13). This is due to the fact that increased wind speed disperses $PM_{2.5}$, diluting it into the atmosphere rather than concentrating it in one place (Verma and Desai, 2008). Wind speed has been labelled the predominant meteorological factor driving the dispersion and dilution of air pollutants (Verma and Desai, 2008). This raises the question as to whether the fire ban should be based on the wind speed of that particular day, rather than the time of year. The ban is currently set between May and September as this is the most popular time of the year for allotment holders to visit their site. Therefore, people are able to burn waste between October and April when there are less people at the allotments. However, this current rule does not take into account any meteorological factors that affect the $PM_{2.5}$ concentration. Whereas, if the ban was implemented on a day by day basis, depending on the wind speed, $PM_{2.5}$ concentrations would be reduced within and around the allotments. For instance, $PM_{2.5}$ concentrations begin to plateau at 15mph, so this may be a suitable cut off point for the ban to be lifted (Figure 13). However, this would be difficult to implement. Firstly, in 2019 there were only seven days in Sheffield where the average daily wind speed exceeded 15 mph (*Davis Weather Data*, 2022). Typically, within one day, Sheffield experiences fluctuations in wind speed. These fluctuations mean that any periods with high wind speeds have their daily averages lowered by long periods of low wind speeds. So even though the wind speed frequently exceeds 15mph, the daily average does not. This makes it hard to implement as the ban would have to be for hourly periods. Additionally, it would be hard to implement rules that change so rapidly. Half of the allotment holder survey respondents were over the age of 56. This suggests that they may not be adept enough with technology to be looking online and at social media for hourly updates as to whether or not they can light fires. Moreover, it makes it difficult to police, as the ban may be implemented whilst people's fires are still alight from when the ban was lifted.

Our study yielded a number of reliable results, however there were some limitations to the study. As mentioned previously, there were no sensors to the East of the allotments (Figure 5b), meaning that we are unable to see the $PM_{2.5}$ concentration in that direction. Future studies should ensure that there are sensors in all directions of the allotments to fully understand how $PM_{2.5}$ travels. This is particularly important considering that 56% of people living to the East of the allotments report having seen smoke from the allotments at their house (Figure 8d).

Additionally, SDS011 sensors are found to be less effective when the humidity is above 80% (Liu *et al.*, 2019). Between September and March, Sheffield's humidity is typically over 80% - reaching an average of 88% in January 2022 (*Davis Weather Data*, 2022). Therefore, the sensors may not be functioning properly during the months where there is no ban. Due to this, all of our results that use the months of September to March must be taken with caution and future studies investigating the impact of small scale fires on $PM_{2.5}$ concentrations should consider using more advanced sensors.

This study provides the opportunity for a number of additional analyses associated with investigating the release of $PM_{2.5}$ from small scale fires in residential areas. Results from the allotment holder survey suggest that there were a number of residents who said they would not burn waste due to environmental reasons, however frequently lit BBQs (Figure S1d). This suggests that these people do not believe that BBQs affect $PM_{2.5}$ concentrations at the same rate as burning waste, even though most available research contradicts this claim (Lenssen *et al.*, 2022). Therefore, future research should investigate how domestic BBQs affect $PM_{2.5}$ concentrations in suburban areas and whether they are less damaging than burning allotment waste. Moreover, this investigation did not particularly focus on the materials that were being burnt during the fires. During the in person allotment holder surveys, brief comments were made stating that the majority of waste was dead plant matter, such as weeds or larger pieces of wood. However, a few allotment holders said that they also burnt plastic, such as packaging and bottles. Therefore, a future study should focus on whether burning different waste materials affects resulting concentrations and composition of $PM_{2.5}$. Current literature suggests that burning plastic produces the highest concentrations of $PM_{2.5}$, however few studies have used organic waste, such as weeds, as a comparison (Yan *et al.*, 2016). Moreover, this study focuses on $PM_{2.5}$ from small scale waste fires, however we should use the findings from this report to help us better understand how large scale waste incinerators affect $PM_{2.5}$ concentrations. At present, there are a few items of literature investigating $PM_{2.5}$ concentrations near to waste incinerators (Yan *et al.*, 2016; Jalili, 2020). However, there are already 90 incinerators in the UK, with at least 50 more being developed (Laville, 2021), highlighting the need for continued research into this topic.

The overall aim of this study was to ascertain whether or not the Heeley and Meersbrook Allotment fire ban should be extended to a full year. Our conclusion is that no immediate action should be taken to extend the ban. Even though the data shows that the allotment fires release significantly high concentrations of $PM_{2.5}$ (Figure 9, 11, 12), the levels are still similar to residential areas away from the allotments (and in turn, away from the fires) (Figure 10). Moreover, neither the allotment holders or local residents are in full support of extending the ban (Figure 7, 8). This is due to a lack of understanding as to the impacts of high $PM_{2.5}$ concentrations on a person's health, as well as there being no other option to remove waste from allotments. Therefore, before any further discussions on extending the ban occur, Sheffield City Council should implement additional waste removal strategies, educate residents on the harmful effects of high $PM_{2.5}$ concentrations and conduct further research to investigate why, if we know allotment fires release significant levels of $PM_{2.5}$, there is no significance between the mean $PM_{2.5}$ concentration next to the allotments compared to within residential areas.

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Appendix

Survey A: Questionnaire for Heeley & Meersbrook Allotment Users

This is an MSc study funded by the University of Sheffield Bioscience Department. We are investigating the impacts of allotment fires on air pollution within Sheffield. The survey is anonymous, but please do not feel pressured to answer any questions you are uncomfortable with.

1. What is your gender?

Male	Female	Other	Prefer not to say

2. What age group are you in?

Under 18	18-30	31-55	56+	Prefer not to say

3. How often do you visit the allotments?

once a year	once a month	once a fortnight	once a week	more than once a week

4. Do you have an allotment here

Yes	No - it's someone else's

5. How long have you used this allotment for?

less than a year	between 1-5 years	more than 5 years

6. How important are environmental issues to you

1- Not important at all	2- slightly important	3- a bit important	4- quite important	5- extremely important

7. How important is good air quality to you

1- Not important at all	2- slightly important	3- a bit important	4- quite important	5- extremely important

8. Do you have any illnesses that impact your breathing such as COPD or asthma?

No	Yes

9. How do you typically remove your waste?

Burning	Composting	Take it home	I have no waste	Other:

10. Do you ever burn waste at the allotments

Yes	No

11. If yes, how often do you burn waste

Once every 5 years	Once a year	Every 6 months	Every month	Every week

12. Do you burn waste between May and September

Yes	No

13. Do you ever have BBQs at the allotments

Yes	No

14. If so, do you have BBQs at the allotments between May and September

Yes	No

15. Has the amount of smoke / burning ever made you leave the allotments early or put you off visiting

Yes	No

16. If yes, how often does this happen?

once a year	once a month	once a fortnight	once a week	more than once a week

17. Have you ever noticed breathing difficulties after there has been a fire at the allotments

Yes	No

18. If yes, how often does this happen?

once a year	once a month	once a fortnight	once a week	more than once a week

19. Would you support a full year ban on fires at the allotments?

Yes	No	Don’t mind

20. Would you like to see more alternatives to burning (provided by the allotment site)?

Yes	No	Do not mind

21. What alternative would you be most likely to use?

Individual composting	Regular waste removal	Larger composting	None- I will continue with my method

22. Please leave any additional comments below

Survey A2: Questionnaire for Meersbrook Residents

This is an MSc study funded by the University of Sheffield Bioscience Department. We are investigating the impacts of allotment fires on air pollution within Sheffield. The survey is anonymous, The survey is anonymous, but please do not feel pressured to answer any questions you are uncomfortable with.

1. What is your gender?

Male	Female	Other	Prefer not to say

2. What age group are you in?

Under 18	18-30	31-55	56+	Prefer not to say

3. How best describes your house?

Flat or apartment	Terraced or semi - detached house	Detached house

4. Is there anybody under the age of 18 living at your address?

Yes	No

5. How far away do you live from the allotments?

0 - 0.5 miles	0.5 - 1 miles	1 - 3 miles	> 3 miles	unsure

6. How important are environmental issues to you

1- Not important at all	2- slightly important	3- a bit important	4- quite important	5- extremely important

7. How important is good air quality to you

1- Not important at all	2- slightly important	3- a bit important	4- quite important	5- extremely important

8. Do you have any illnesses that impact your breathing such as COPD or asthma

No	Yes

9. What direction do you live from the allotments

North	East	South	West	North East	South East	North West	South West	Unsure

10. Do you currently have an allotment at ‘Heeley and Meersbrook Allotments’

Yes	No

11. Have you ever noticed smoke or witnessed fires at Heeley and Meersbrook allotments?

Yes	No

12. If yes, how often do you notice smoke or fires coming from the allotments?

> once a day	> once a week	> once a month	> once every 6 months

13. Do you notice a difference in the amount of fires between May and September and the rest of the year?

Yes	No

14. Do the fires or smoke coming from the allotments ever impact your day to day life?

Yes	No

15. Have the fires ever impacted your breathing?

Yes	No

16. Would you support a full year ban on fires at the allotments?

Yes	No	Don’t mind

17. Do you ever light fires in your garden (including bonfires, fireworks, BBQs or a chiminea)

Year	No

18. If yes, how often do you light fires?

> once a week	> once a fortnight	> once a month	> once every 6 months	< once a year

19. What would you say is the largest air pollutant affecting the Meersbrook area?

Vehicle pollution	Industrial pollution	Fires	None	Other

Additional analysis from the allotment owner survey results

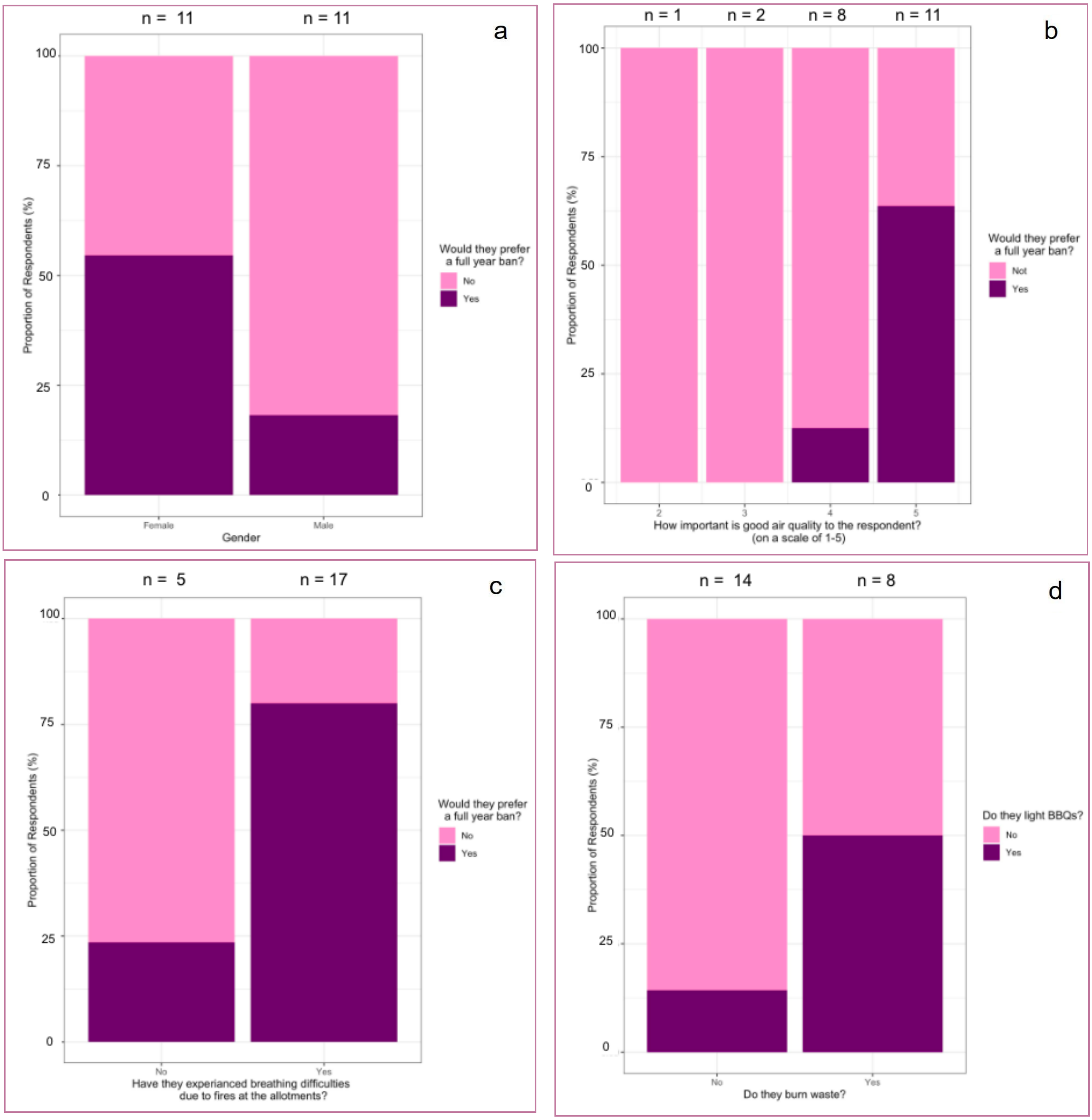


*Figure S1: **a**) The relationship between the gender of the allotment owner and whether or not they would prefer a full year ban. **b) T**he relationship between the importance of good air quality (on a scale of 1 to 5, with 1 being 'not at all' and 5 being 'extremely important') to the allotment owner and whether or not they would prefer a full year ban. No respondents selected 1. **c)** The relationship between whether or not the respondent has experienced breathing difficulties at the allotments and if they would prefer a full year ban. **d)** The relationship between whether or not the allotment owner burns waste and whether or not they light BBQs.*

Additional analysis from the Meersbrook resident's survey results

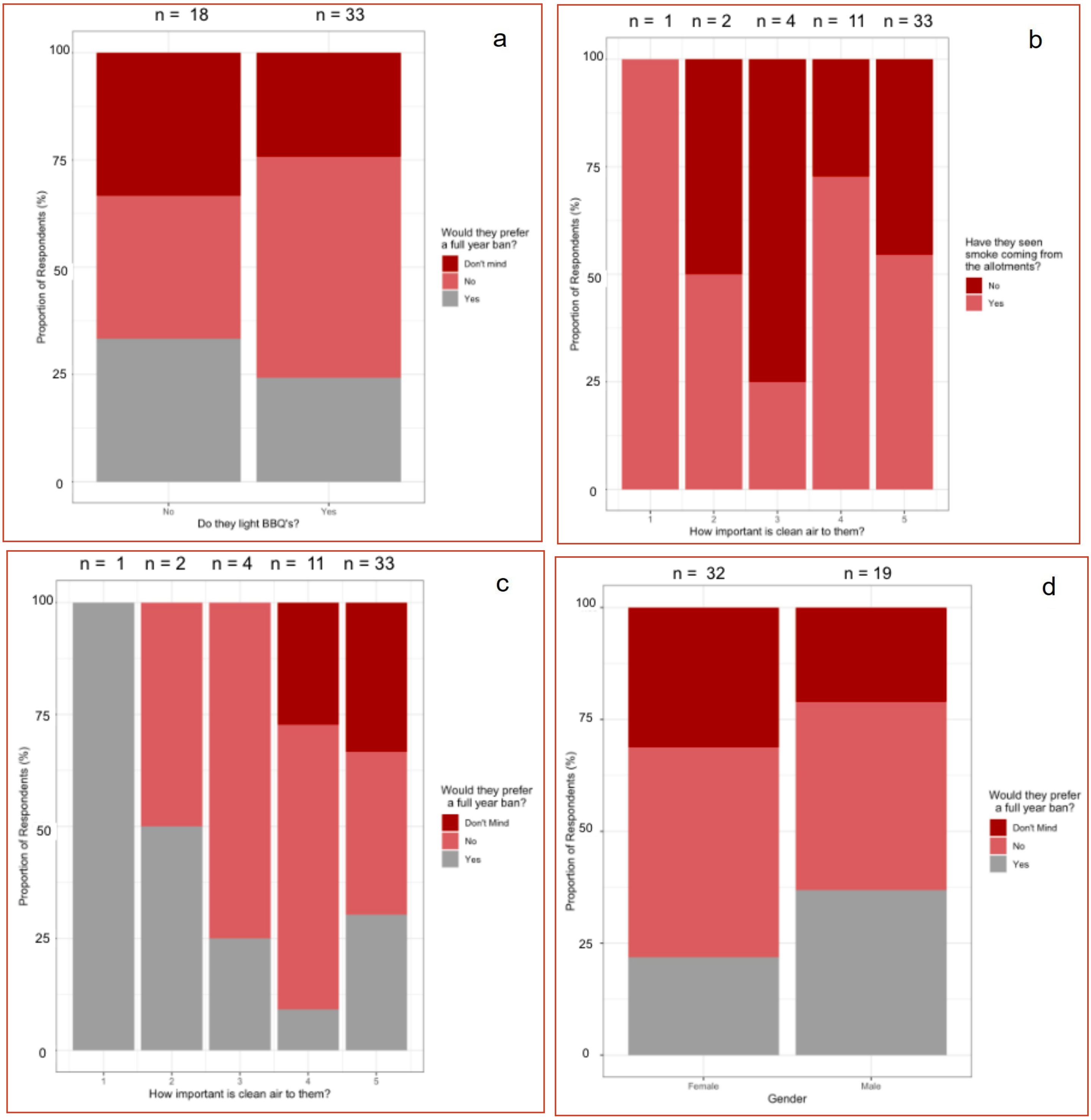


Figure S2: ***a)*** *The relationship between whether or not the local resident lights BBQs and whether or not they would prefer a full year fire ban.* ***b)*** *The relationship between the importance of good air quality (on a scale of 1 to 5, with 1 being 'not at all' and 5 being 'extremely important') to the local resident and whether or not they have ever seen smoke coming from the allotments.* ***c)*** *The relationship between the importance of good air quality (on a scale of 1 to 5, with 1 being 'not at all' and 5 being 'extremely important') to the local resident and whether or not they would prefer a full year ban.* ***d)*** *The relationship between the gender of the local resident and if they would prefer a full year ban.*

Figure 11 using unlogged $PM_{2.5}$

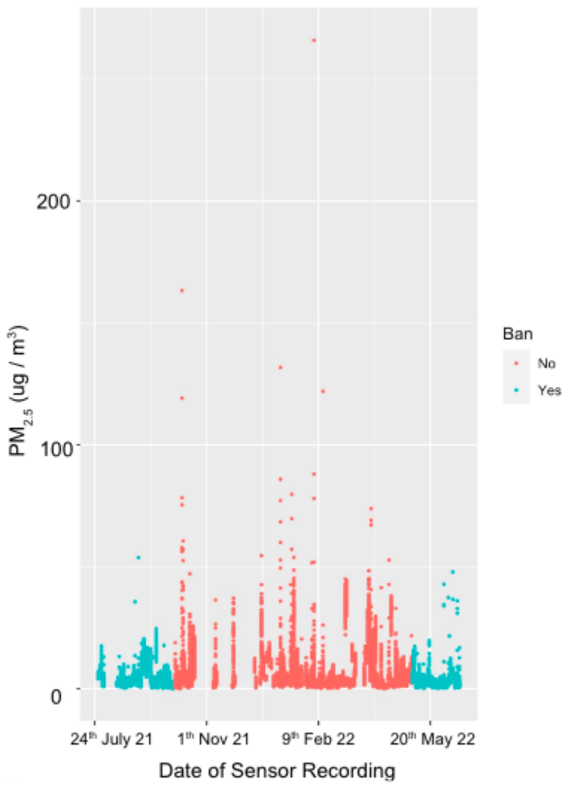


Figure S3: $PM_{2.5}$ data from sensor C. Only data from recordings between 10 am and 5 pm were used.

Figure 13 using unlogged $PM_{2.5}$

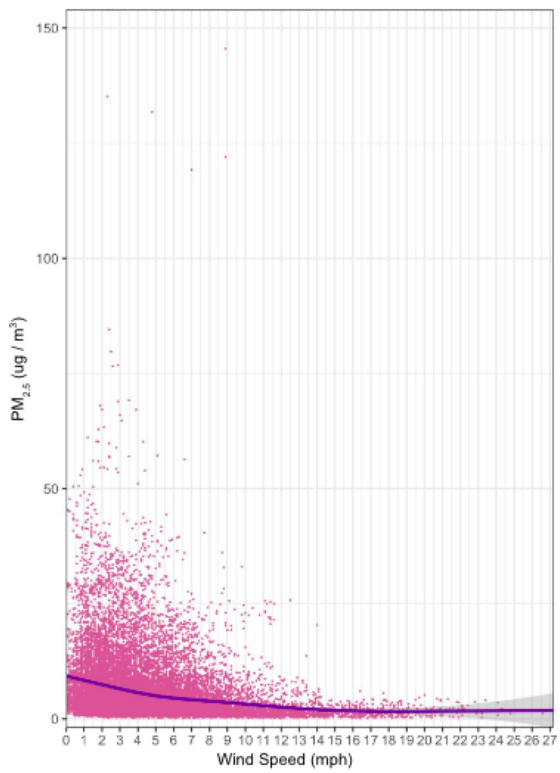


Figure S4: $PM_{2.5}$ data from sensor C and associated wind speed, along with a line of best fit. Data used are from 1st June 2021 - 1st June 2022.

Figure 10 using unlogged $PM_{2.5}$

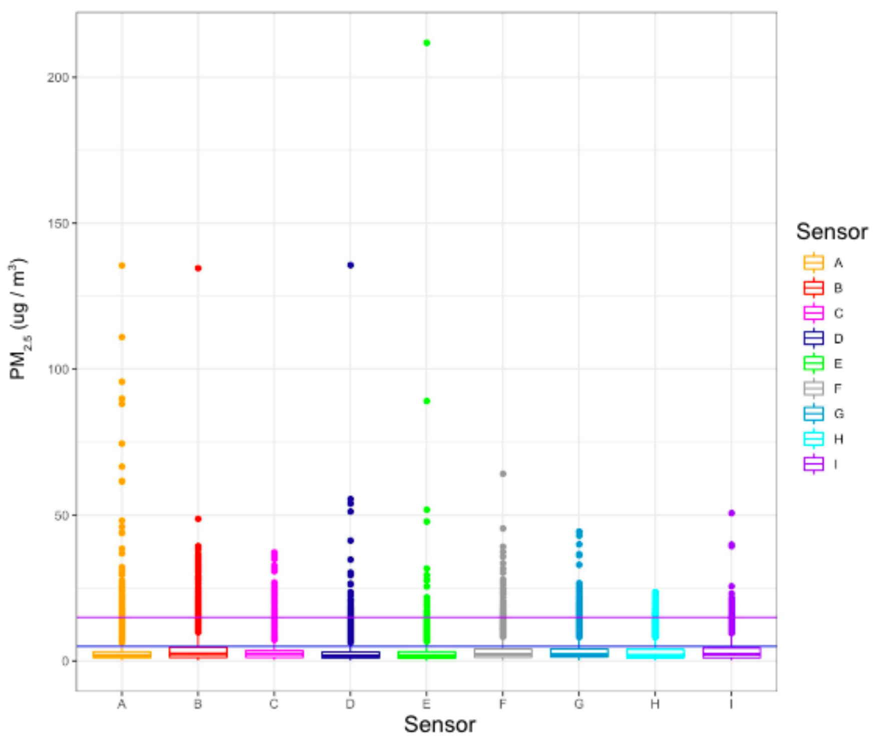
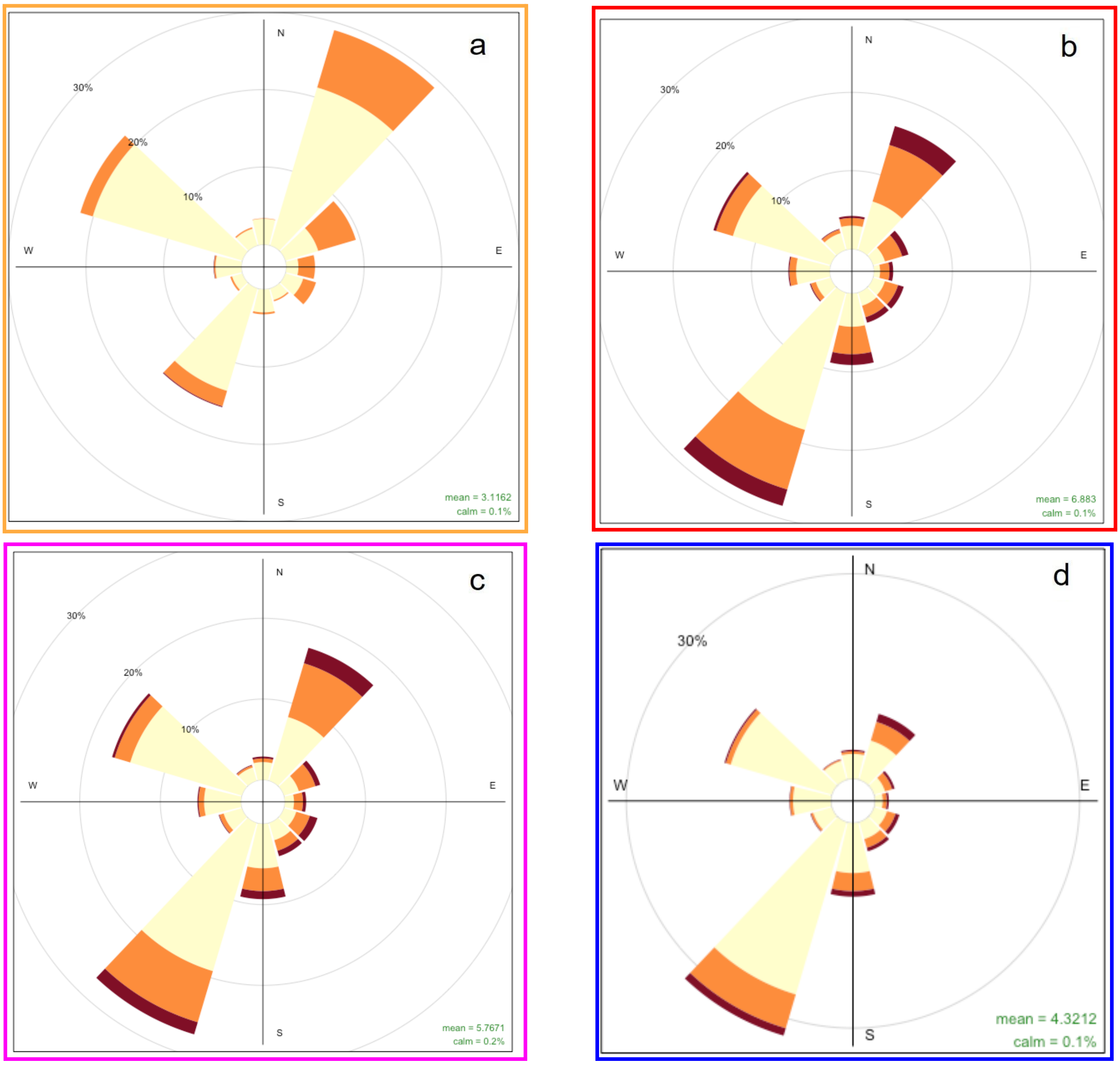


Figure S5: $PM_{2.5}$ concentrations for all nine sensors between 10 am to 5 pm for November 2021.

Individual pollution roses from Figure 12



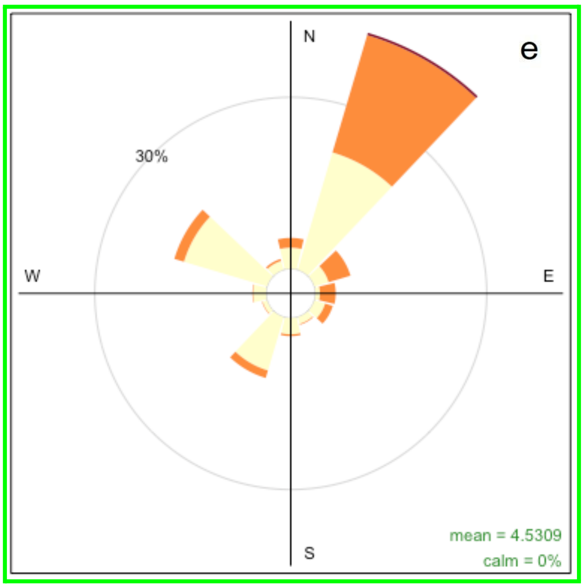


Figure S6: Individual pollution roses from sensors A, B, C, D and E showing the wind conditions under which the highest concentrations of $PM_{2.5}$ occur.