THE EFFECT OF COVID-19 LOCKDOWN MEASURES ON AIR QUALITY IN LONDON IN 2020

A note from the Environmental Research Group, King's College London

1 May 2020

KEY MESSAGES

- NO_2 concentrations reduced significantly at busy roadside sites due to reductions in traffic flows of ~53% across London and over 60% in the central area; reductions in average NO_2 concentrations at two busy roadside sites (Marylebone Road and Euston Road) were 55% and 36% respectively. Overall, the mean reduction in hourly NO_2 concentrations were 21.5% across the London roads. The reductions are the difference between the average concentration from 1 January to 12 March and that from 24 March to 22 April.
- Reductions in NO_2 were smaller at outlying roadside sites and at urban background sites. The reduction in average NO_2 at North Kensington was 22% and the mean reduction across all urban background sites was 14%.
- PM_{10} and $PM_{2.5}$ concentrations were higher after lockdown than at any time in 2020 to date, due to several pollution episodes driven by anticyclonic easterly flows suggestive of long-range transport.
- These high PM concentrations are a clear warning that if the UK is to achieve the current WHO $PM_{2.5}$ guideline then as well as actions in the UK, other European countries will need to achieve their emission reduction targets.
- Ozone concentrations were higher post lockdown, partly due to reductions in NO_x but mainly as a result of pollution episodes in easterly anticyclonic air flows. The highest hourly ozone concentration at North Kensington was 129µg/m^3 (~65 ppb) on 24 April.
- Wood burning made a contribution to ambient PM concentrations before and during the lockdown periods. During the lockdown period the evening peak occurred later than in the winter, perhaps reflecting longer daylight hours.
- During the pre-lockdown period (from 12 to 23 March) roadside increments in NO_x, NO_2 had begun to reduce, compared to the January to March average, and continued to reduce in the full lockdown period. This was also true of roadside increments in $PM_{2.5}$ despite the increase in overall $PM_{2.5}$ concentrations.
- Traffic activity as indicated by increases in weekday/weekend ratios of NO_x and NO_2 suggest traffic activity reduced at weekends during the lockdown period. Increases in weekday/weekend ratios of $PM_{2.5}$ and PM_{10} however are probably determined by the occurrence of high PM concentrations mainly on weekdays during the lockdown period.
- The total gaseous oxidative potential (OP) of London's atmosphere, as measured by the sum of ozone and NO_2, increased after lockdown. This was due largely to the incidence of ozone episodes post-lockdown; without these, the gaseous oxidative potential would still probably have increased. Decreases in global ozone as well as decreases in regional ozone episodes and in NO_2 concentrations would be required to reduce the gaseous OP of London's atmosphere.
- One would speculate that the overall OP of London's atmosphere (incorporating pro-oxidant particle associated components) will be heavily influenced by the changes in traffic flow post-lockdown, as many of the key drivers of this activity are metals derived from brake and mechanical wear processes. These concentrations are measured at KCL and could be analysed further.
- Modelling the effects of traffic reductions in London, together with changes in travel behaviours due to the lockdown measures, we estimate reductions in [annual average] personal exposures to NO_2 and $PM_{2.5}$ of 18-27% (NO_2) and 5-24% ($PM_{2.5}$) for children, tube users, professional drivers and hospital staff. The largest benefits were for those who reduced their travel, e.g. tube users and the highest exposure to NO_2 was for professional drivers who

continued to work. Spending an extra 1 hour per day in kitchen environments increased exposure to NO_2 by 2-6% and $PM_{2.5}$ by ~19% for everyone.

- These modelled changes arise purely from the model assumptions about traffic, travel and indoor activities in London and could be modified by changes in these pollutants arising from other sources such as transboundary transport of PM. A more comprehensive analysis for the specific lockdown period, combining changes to European, UK and London emissions as well as a wide range of population subgroups could be undertaken as part of a larger study.

1. Introduction

This note summarises the effects of the social distancing measures introduced in mid-March 2020 to inhibit the spread of the Covid-19 virus. The data for sites in London have been analysed, focusing on particulate matter (PM_{10} and $PM_{2.5)}$, nitrogen oxides (NO_x) and nitrogen dioxide (NO_2) and Ozone (O_3). It should be noted that since the analyses have been done urgently and the data is not in its final ratified status. Nevertheless, a high degree of confidence is justified as a range of automatic and manual quality assurance procedures have been applied and all data is scaled to standards traceable to national and international standards. Moreover we should stress here that this analysis is a preliminary assessment and a considerable amount of further work cold be done using the large amount of data collected by King's College London.

The lockdown period has been split into two sections, namely the 'pre-lockdown' period from 12 to 23 March (inclusive) when the public were strongly urged to observe social distancing, to limit their movements etc; and the 'post-lockdown' period from 24 March onwards when the measures on social distancing, travel etc., were strengthened.

The effects of the measures in both parts of the lockdown period have been complicated by the long periods of anticyclonic weather and relatively high temperatures (particularly in April). This has resulted in easterly air flows and consequent import of PM from other European countries. Temperatures in April have often exceeded 20ºC and these, combined with easterly flows picking up precursor pollutants, have resulted in photochemical production of ozone with hourly values in the region of 55 – 65 ppb.

The analyses below present time series and other data for sites in the London Air Quality Network (LAQN) where the selection criteria were sites with at least 4 of the 5 pollutants.

2. Nitrogen oxides ($NO_X = NO + NO_2$) and NO_2

The data are analysed by roadside and urban background sites, and we deal with both NO and NO_2 together in each category. NO_x concentrations are dominated by traffic sources in London, clearly at roadside sites but also at background locations. NO_x concentration changes are therefore a direct indicator of the change in emissions from traffic sources during the lockdown periods. Changes in NO_2 concentrations would not be expected necessarily to be as large as those in NO_x because of the non-linear chemistry which governs the NO_x to NO_2 conversion. As can be seen from the plots in Figure 1 at some busy roadside sites in Central London (e.g. Marylebone Road, Euston Road) reductions in NO_x are large. The plots show hourly average concentrations together with the LOESS trend line superimposed. In the period up to and including 11 March (i.e. before the 'pre-lockdown' period) the average NO_x concentrations were 177.7 µg/m^3 and 162.5 µg/m^3 at these two sites respectively, while after the lockdown, from 24 March onwards the average NO_x concentrations were 42.9 µg/m^3 and 62.3 µg/m^3, representing reductions of 76% and 62% respectively. Corresponding reductions in NO_2 at these two sites were 55% and 36% respectively.

One would expect a seasonal reduction in NO_x and NO_2 concentrations as improved dispersion conditions become more frequent in spring and summer, and bearing this in mind, the observed reductions in NO_x at these two sites are broadly consistent with reported traffic reductions in Central London of the order of 60%.

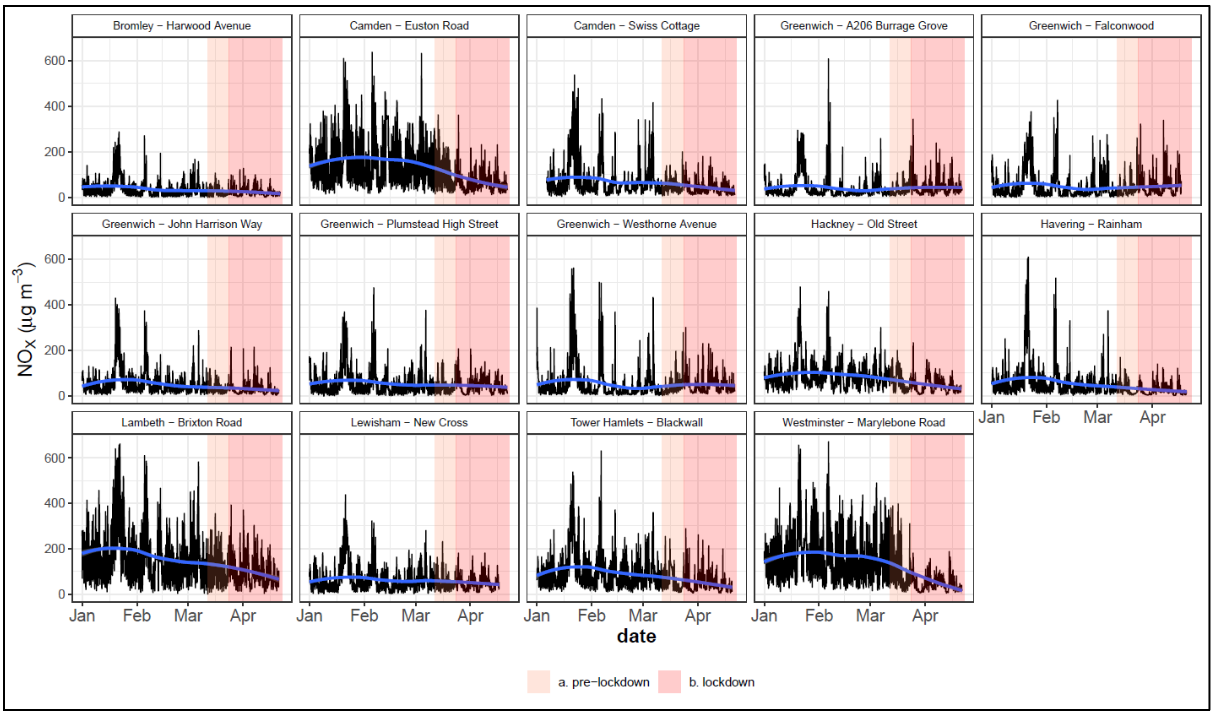
Some sites in outer areas show smaller reductions (the Greenwich sites for example) but overall there appears to have been a widespread reduction in NO_x concentrations across London, albeit to varying degrees. Changes in NO_2 however are even more variable. At most of the sites near busier roads there have been clear reductions in NO_2, at Marylebone Road, Euston Road, Swiss Cottage, Brixton Road, Tower Hamlets and Old Street for example. But at some sites – the Greenwich sites at Westhorne Avenue and the A206 for example – concentrations may even have increased in the few weeks since the lockdown. The extent to which this is due to the predominantly easterly wind flows in the past few weeks will need further investigation.

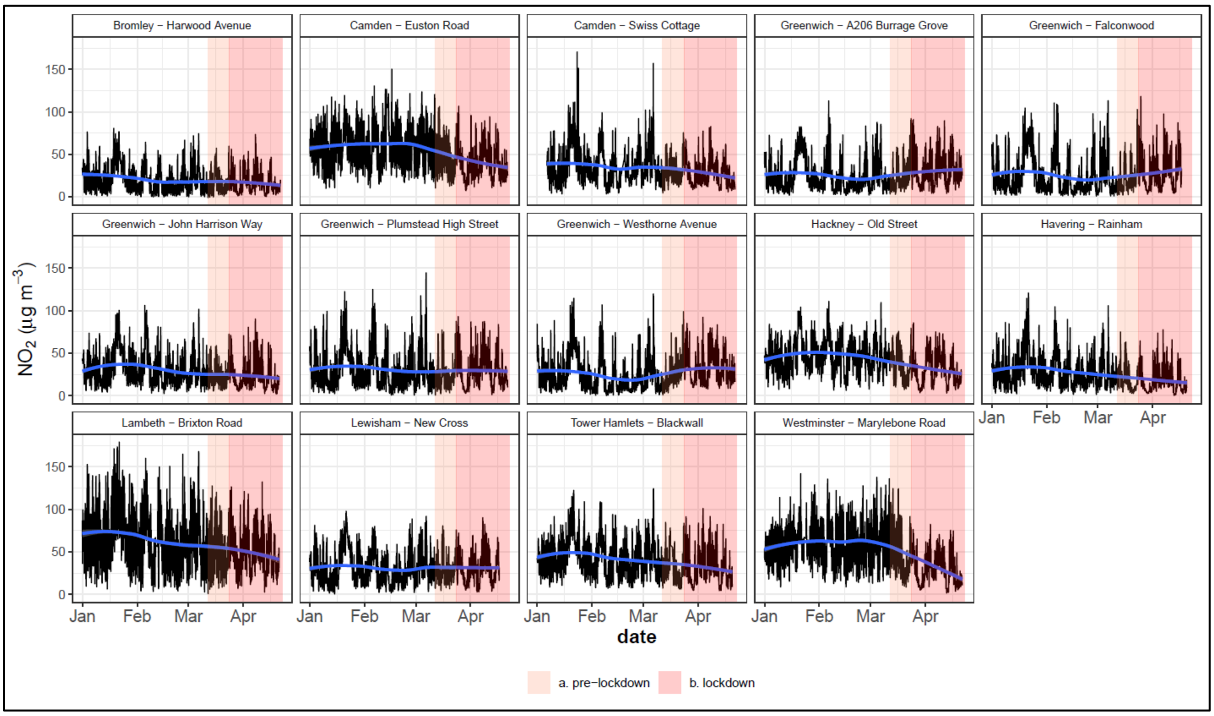
Overall, the mean reduction in hourly NO_X concentrations across the London roads was -44% (ranging from 5% to –75%); for NO_2, the mean decrease was 21.5% (range: 32% to –55%).

The reduction at background locations was smaller compared with that observed at roadside locations. Overall, the background sites observed a decrease of 14% in their NO_2 hourly concentrations, ranging from 30% to –38%.

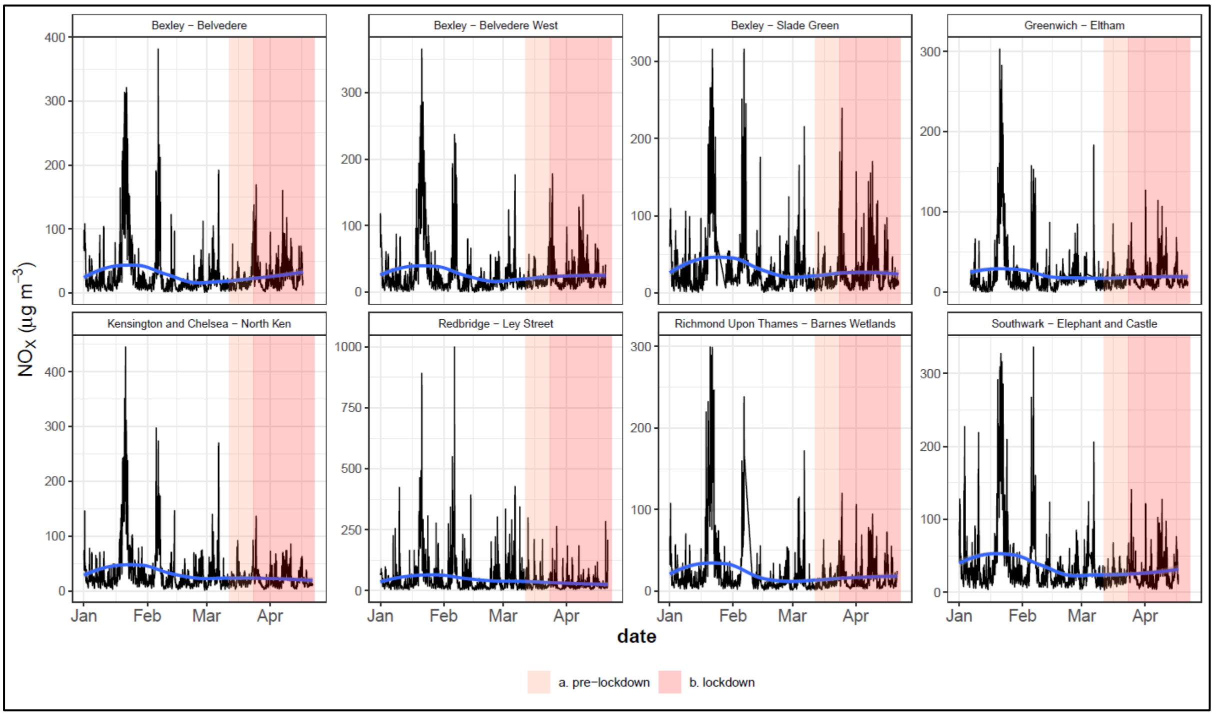
Figure 1 NO_x and NO_2 concentrations at Roadside and Background sites in London

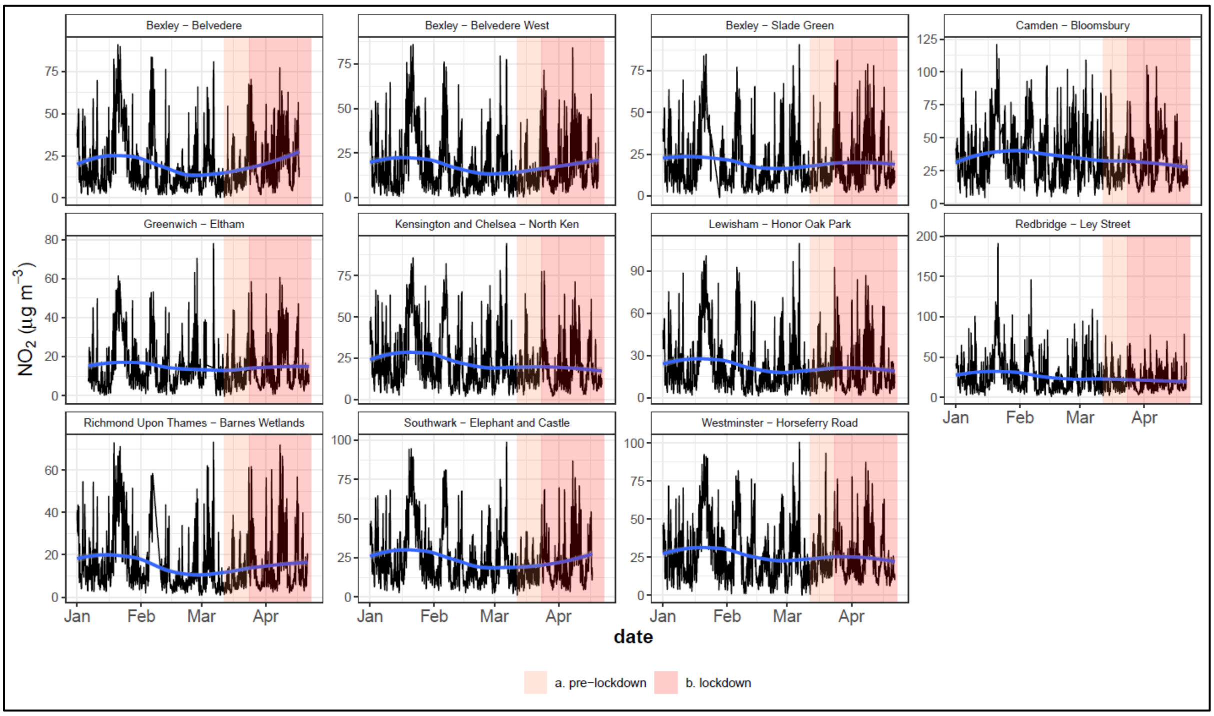
Roadside sites





Background sites



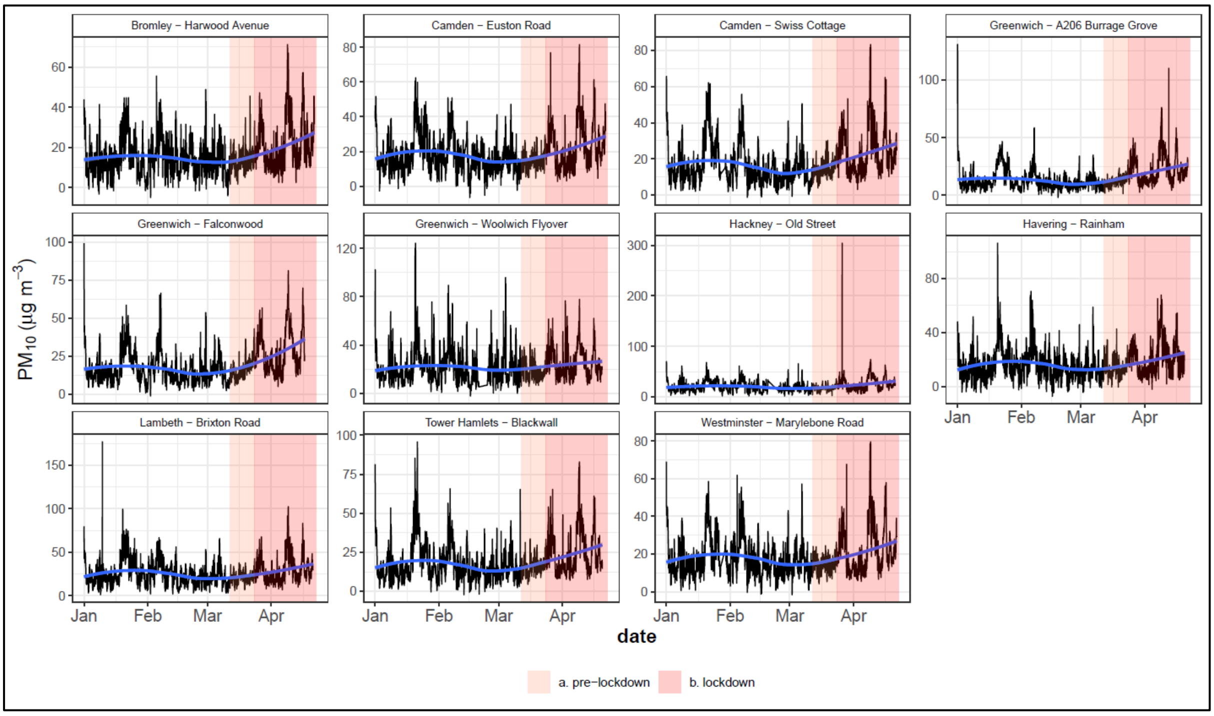


3. Particulate Matter 10 µm (PM_{10})

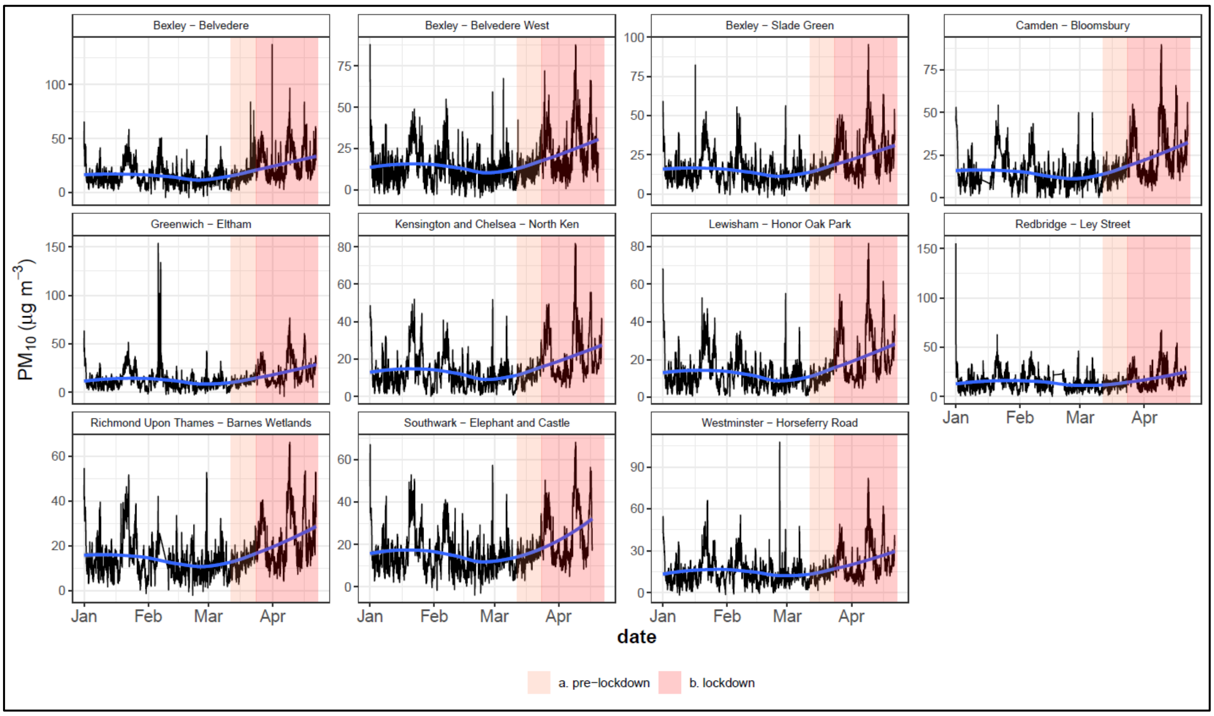
Time series plots of hourly PM_{10} concentrations are shown in Figure 2 below. The effect of easterly winds is immediately apparent with the time series showing the clear effect of a series of pollution episodes near the end of March and in early April, when concentrations higher than any so far seen in 2020 were observed at most sites, at both roadside and background sites. These increased PM_{10} concentrations are a result of the relatively small contribution of road traffic to total mass concentrations of PM_{10}, coupled with the increased contribution from sources outside London and outside the UK. A brief discussion of the more detailed data on the speciation of PM concentrations which King's College London collects is given below.

Figure 2. Hourly PM_{10} concentrations at roadside and background sites in London

Roadside sites



Background sites

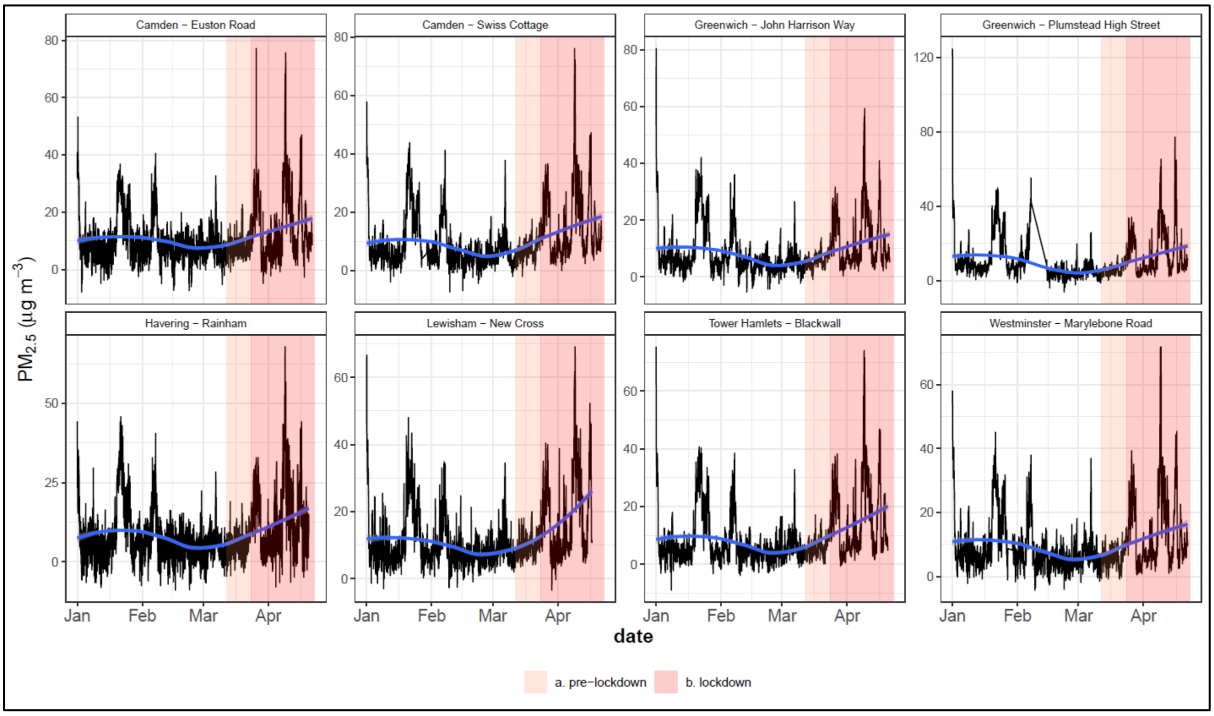


4. Particulate Matter 2.5 µm ($PM_{2.5}$)

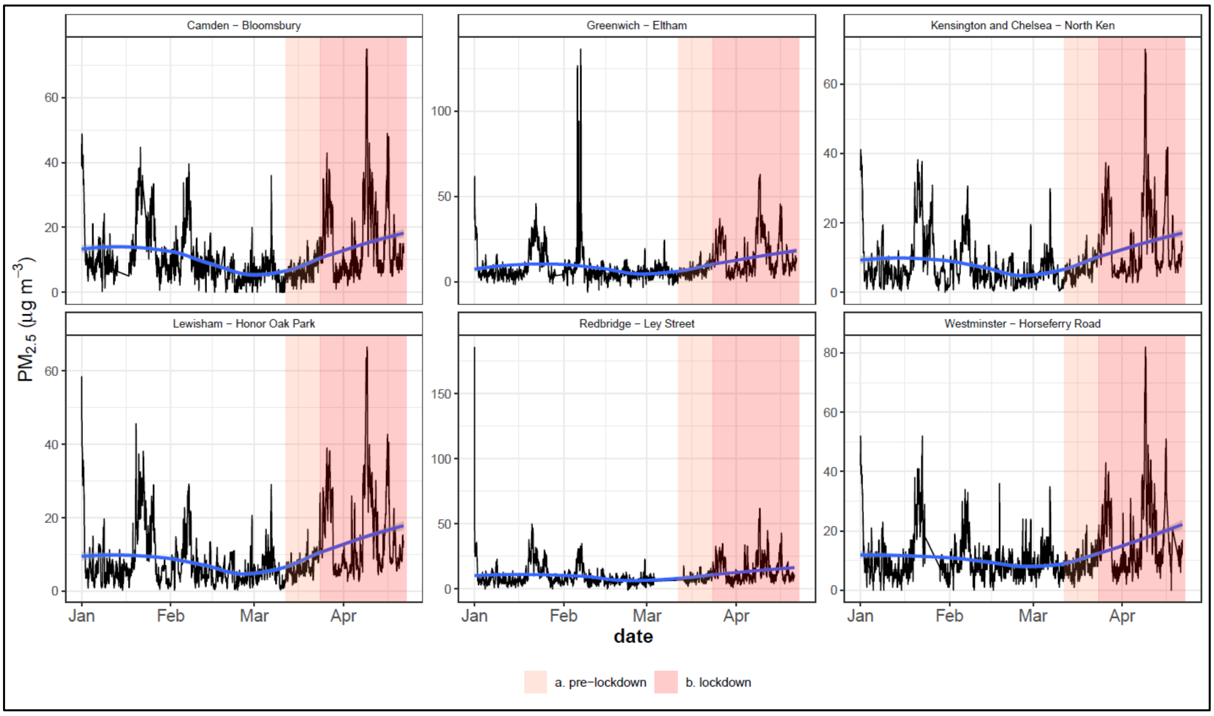
A similar picture also applies for $PM_{2.5}$ where concentrations post-lockdown demonstrated little evidence of an impact from the local reductions in traffic, due to the episodes of easterly winds, with the observed concentrations higher than that at any period during the current year.

Figure 3. Hourly $PM_{2.5}$ concentrations at roadside and background sites in London

Roadside sites

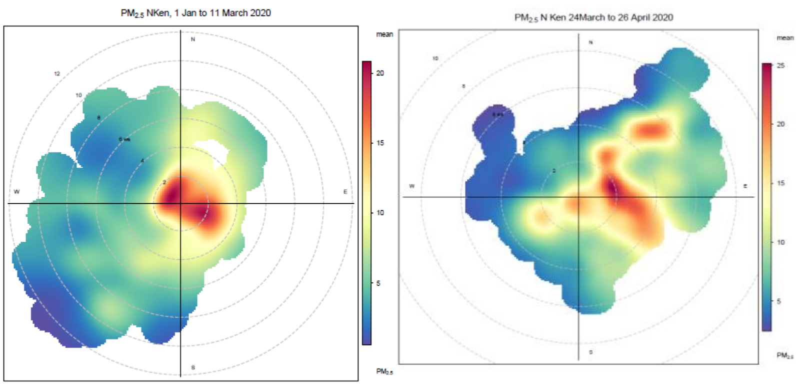


Background sites



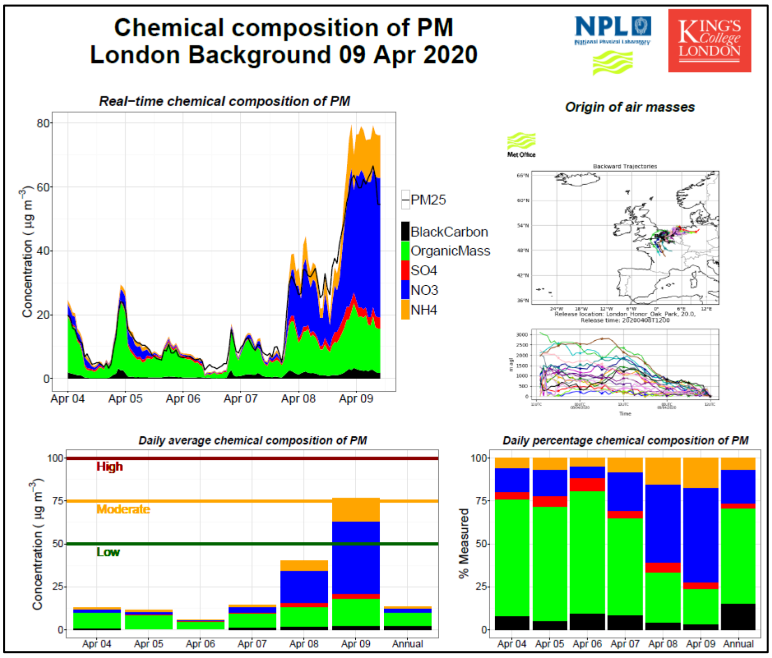
The influence of easterly flows and potential long-range transport can be seen in the two polar plots in Figure 4 below. The plot for the period before the pre-lockdown period shows highest concentrations on relatively low wind speeds with a more uniform directional dependence than the plot for the post lockdown period (from 24 March to 26 April). The low wind speed dependence in the pre-lockdown period is consistent with elevated contributions from local sources. More detailed chemical analysis could shed more light on these contributions. The plot for the post-lockdown period shows a much stronger influence of easterly winds and on higher wind speeds, both consistent with long range transport of particles and their precursors into the UK.

Figure 4. Polar plots of hourly $PM_{2.5}$ at North Kensington, left plot data from 1 Jan to 11 March and right plot from 24 March to 26 April 2020.



Further detail on the composition of $PM_{2.5}$ is afforded by the NERC-funded 'supersite' operated by King's College London at Honor Oak Park. Data from the aerosol mass spectrometer and aethalometer along with backtrack trajectories are shown in Figure 5 for 9 April when concentrations of $PM_{2.5}$ were elevated. The influence of nitrate and organic aerosol on the elevated concentrations observed is clear.

Figure 5. Chemical composition in $PM_{2.5}$ measured at Honor Oak Park with King's pollution forecast and backtrajectory information from the Met office-NAME model.

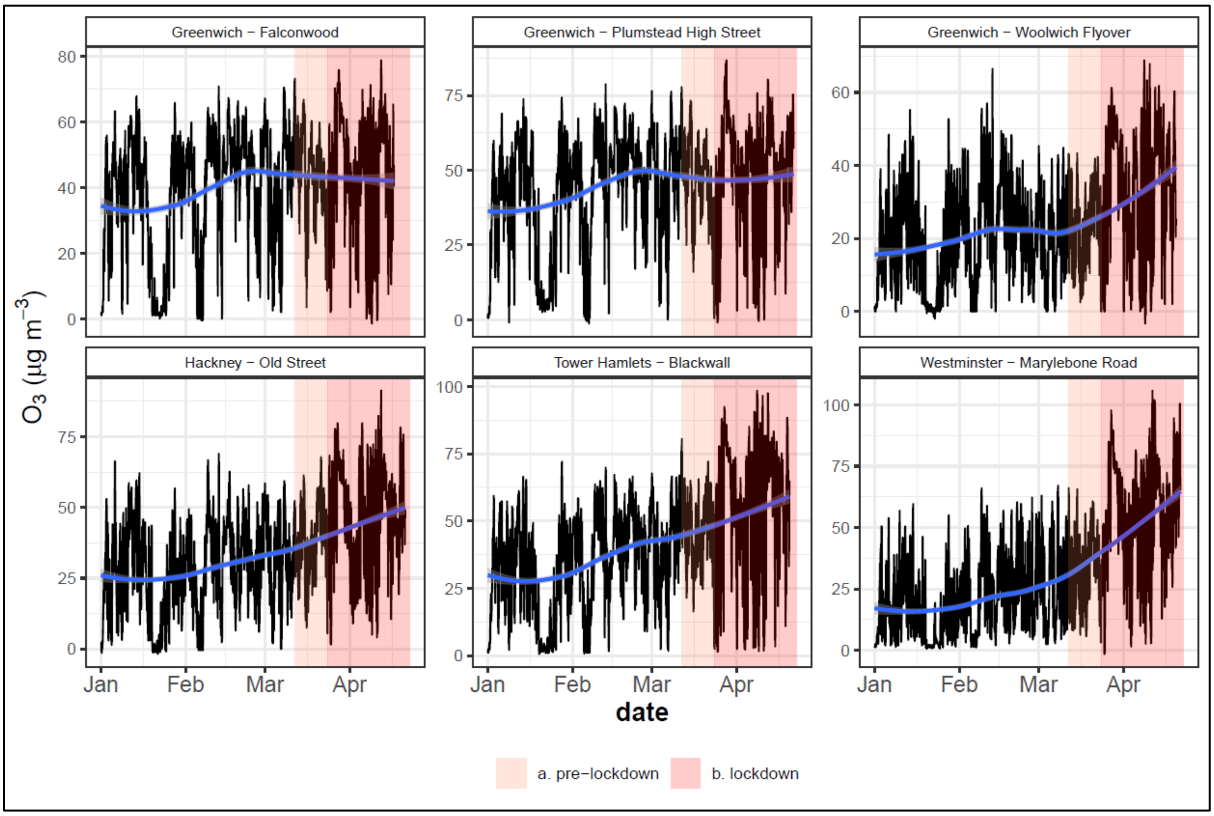


5. Ozone (O_3)

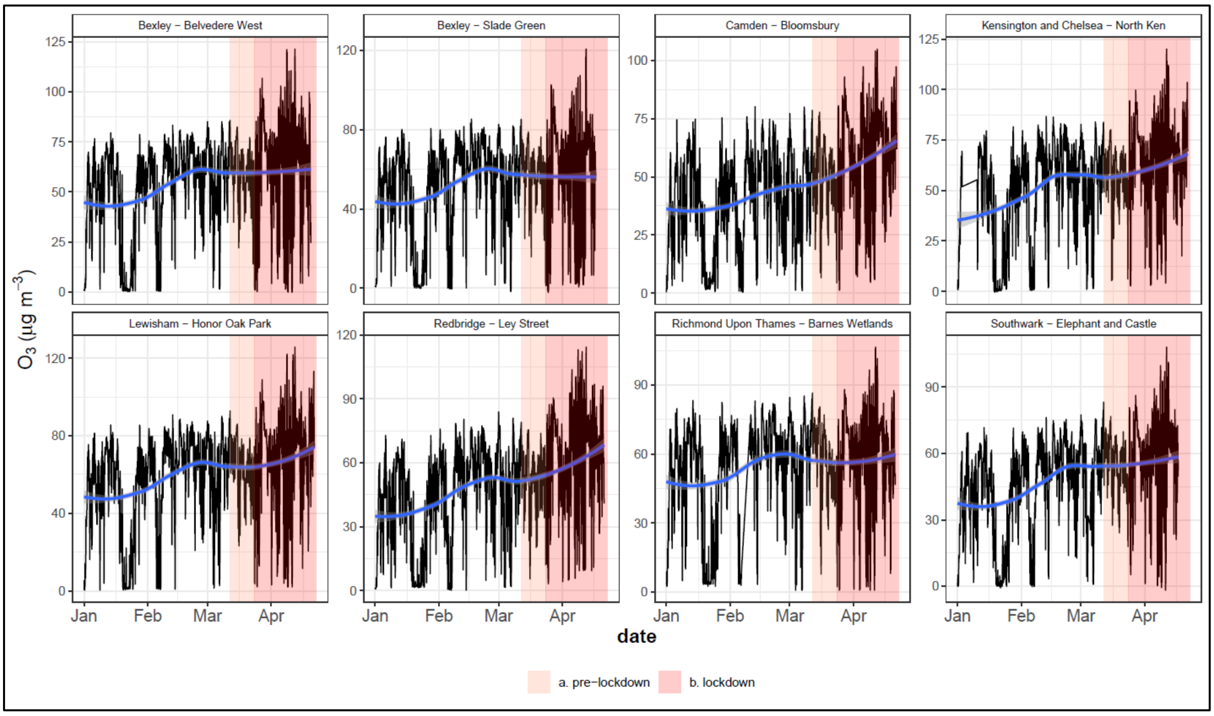
During the post-lockdown period meteorological conditions – elevated temperatures, easterly flows – were conducive to increased photochemical activity, leading to hourly concentrations occasionally exceeding 60 ppb at some urban background sites, with rural concentrations of a similar magnitude, see Figure 6 below.

Figure 6. Hourly ozone concentrations in London

Roadside sites

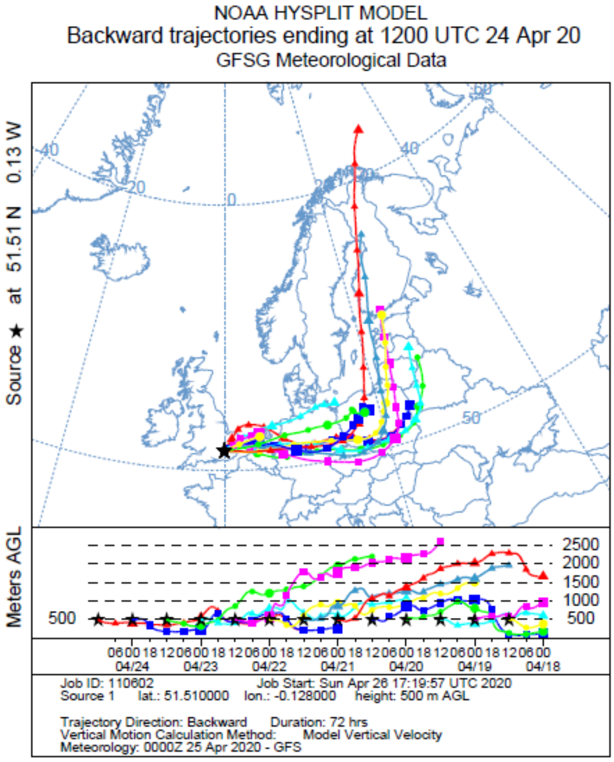


Background sites



As noted for $PM_{2.5}$ and PM_{10}, if the UK is to achieve reductions in ozone concentrations then both the UK and the rest of Europe will need to honour their emission reduction obligations within the EU and the UNECE/CLRTAP, see Figure 7 below. This shows a backtrack trajectory for noon on 24 April when hourly ozone concentrations at North Kensington reached 129 µg/m^3 (65 ppb) at 3 pm.

Figure 7. 72-hour backtrajectories for London, 24 April 2020, from the NOAA Hysplit model (courtesy of the Met Office).



6. Roadside increments in NO_x, NO_2 and $PM_{2.5}$

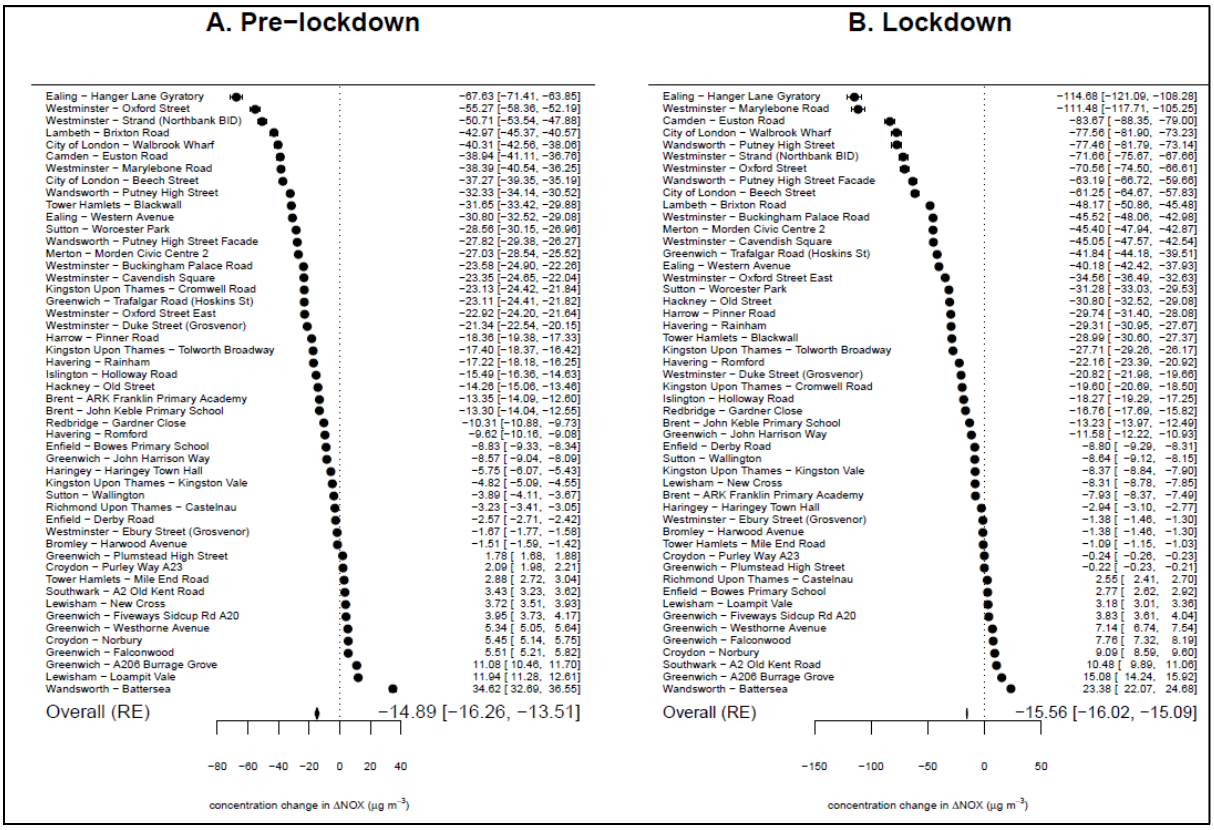
Quantifying the impact of the measures is not straightforward as London has benefited from significant reductions in traffic emissions due to the accelerated adoption of emission reduction technology through the Ultra Low Emission Zone in 2019 as well as cleaning up London's bus and taxi fleet. Simply comparing 2020 to previous years to account for seasonal and meteorological variability would therefore lead to an overestimation of the impact of the lockdown. Where appropriate, we have attempted to control for meteorology by subtracting the measurements made as a representative London urban background station from the measurements at the roadside station.

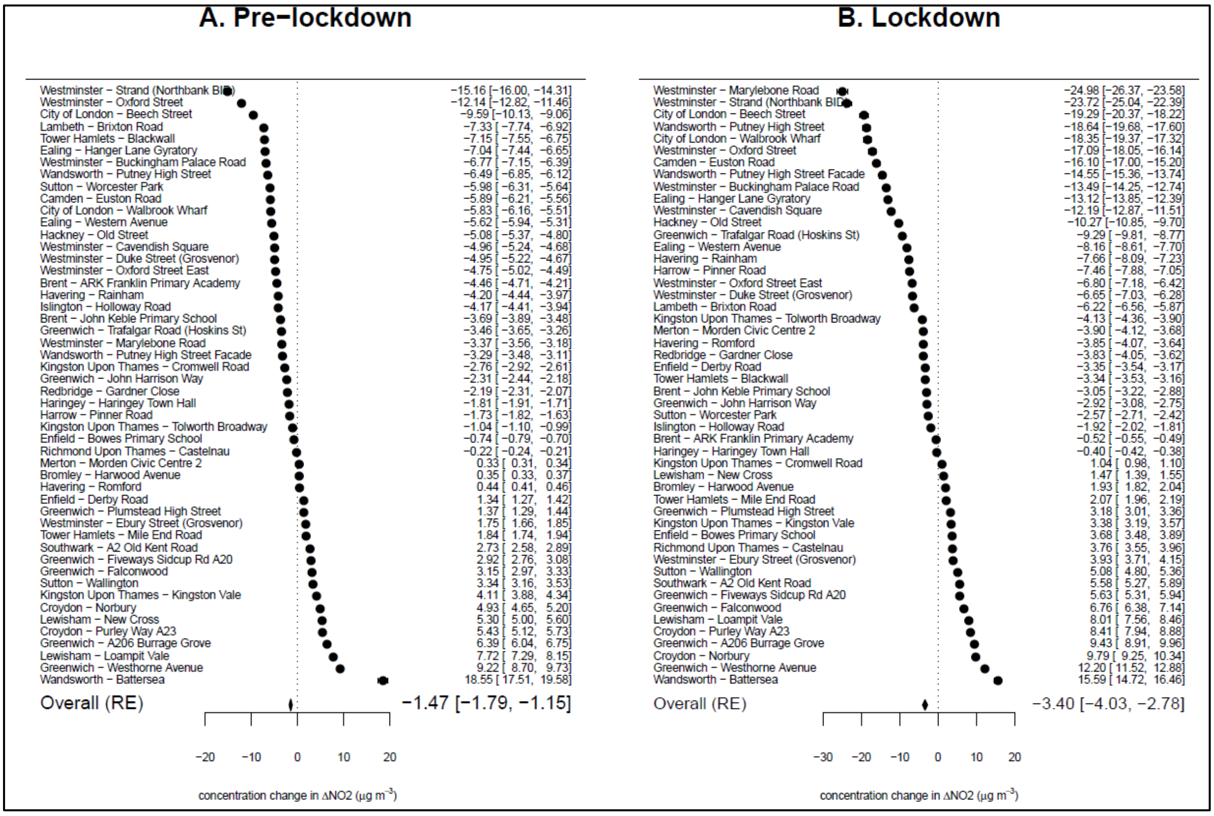
The forest plots in Figure 8 show the change in the roadside increment (concentration measured at the roadside minus the concentration measured at urban background – Kensington and Chelsea North Kensington) measured during the pre-lockdown period (12 to 23 March) and lockdown period (24 March onwards) compared to the mean concentrations measured Jan to March. 2020.Confidence intervals in the plots were calculated using the uncertainty based on the measurement method on the annual concentration. Sites with lower increments might have more weight in the meta-analysis result.

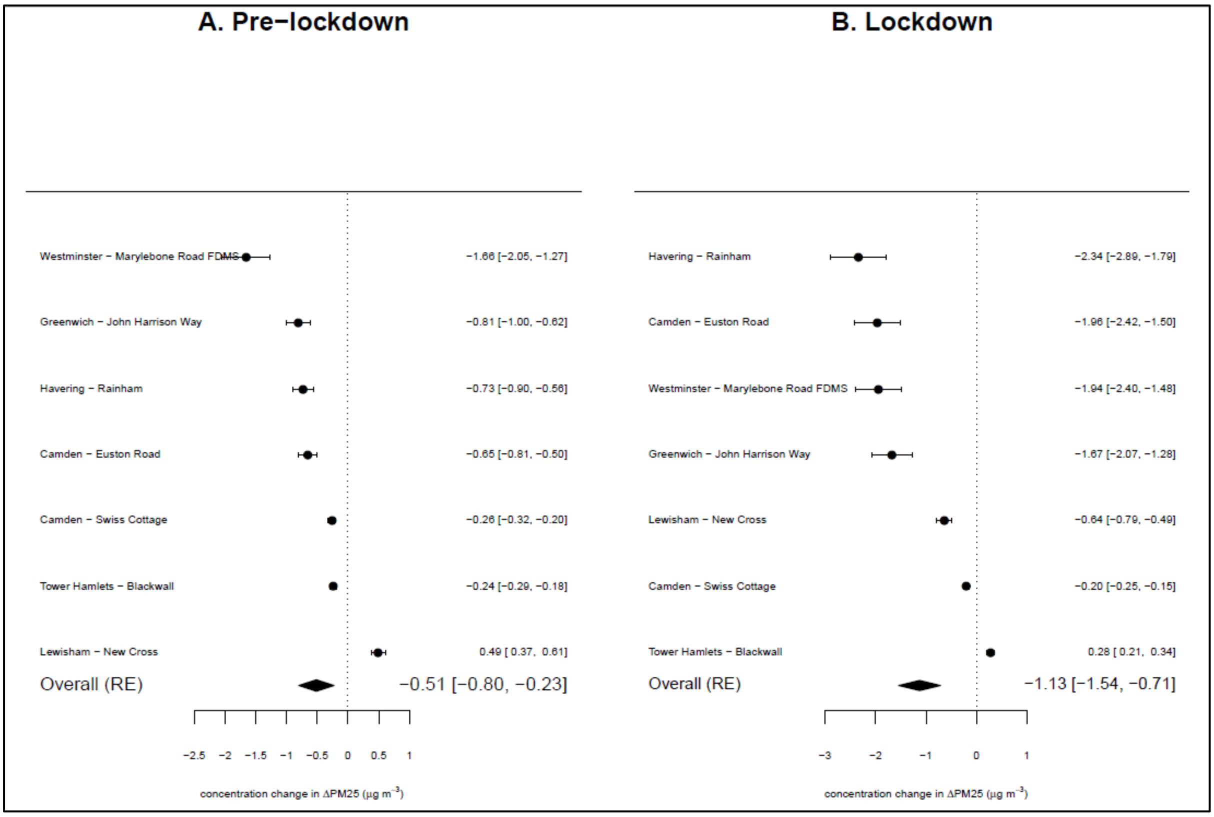
The plots for all three pollutants suggest that there was a reduction in traffic activity in London in the pre-lockdown phase (when measures were 'recommended'), but that this reduced further when the full lockdown measures were strengthened. However not all roadside sites showed decreases in NO_x and NO_2. Two factors could affect this finding; first there may well have been an increase in traffic at some sites, but also the predominance of easterly winds in both periods may have meant that the contribution of the road emissions was less during lockdown because of the relative orientation of the wind direction, the road and the monitoring site location.

The plots focusing on the roadside increment of $PM_{2.5}$ demonstrate the effect of local traffic measures in reducing concentrations, despite the overall increase in $PM_{2.5}$ during the lockdown period, largely due to long range transport.

Figure 8. Forest plots of changes in roadside increments (Δ) of NO_x, NO_2 and $PM_{2.5}$ at London roadside sites.



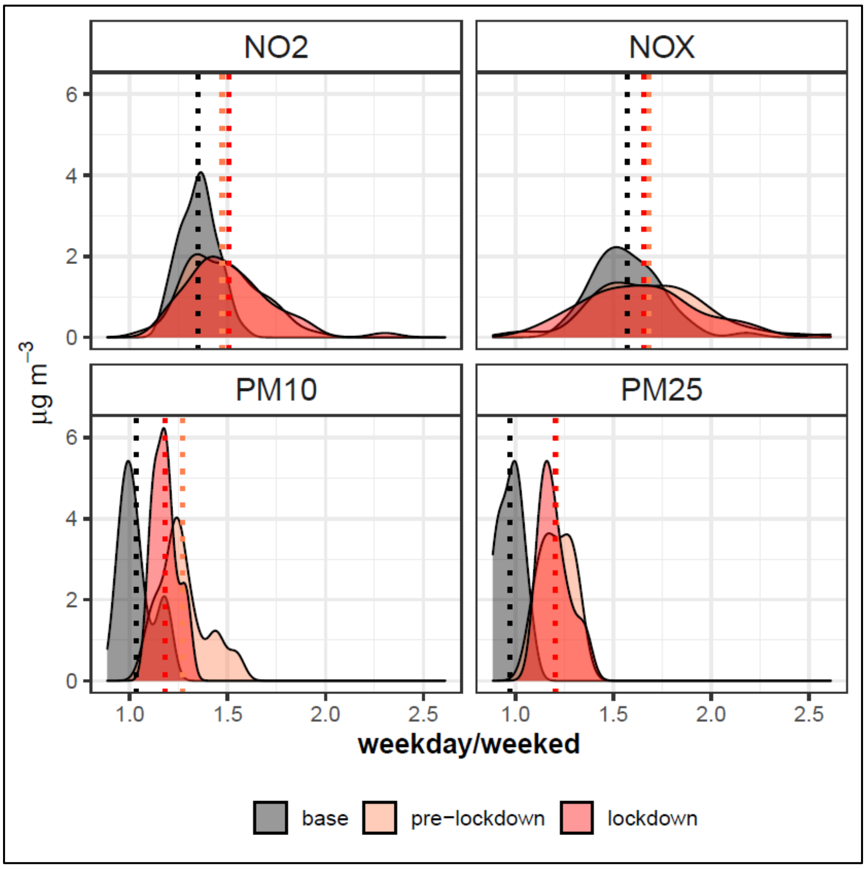



A. Pre−lockdown
Westminster − Marylebone Road FDMS
Greenwich − John Harrison Way
Havering − Rainham
Camden − Euston Road
Camden − Swiss Cottage
Tower Hamlets − Blackwall
Lewisham − New Cross
Overall (RE)
−1.66 [−2.05, −1.27]
−0.81 [−1.00, −0.62]
−0.73 [−0.90, −0.56]
−0.65 [−0.81, −0.50]
−0.26 [−0.32, −0.20]
−0.24 [−0.29, −0.18]
0.49 [0.37, 0.61]
−0.51 [−0.80, −0.23]
−2.5 −2 −1.5 −1 −0.5 0 0.5 1
concentration change in ΔPM25 (μg m−3)
B. Lockdown
Havering − Rainham
Camden − Euston Road
Westminster − Marylebone Road FDMS
Greenwich − John Harrison Way
Lewisham − New Cross
Camden − Swiss Cottage
Tower Hamlets − Blackwall
Overall (RE)
−2.34 [−2.89, −1.79]
−1.96 [−2.42, −1.50]
−1.94 [−2.40, −1.48]
−1.67 [−2.07, −1.28]
−0.64 [−0.79, −0.49]
−0.20 [−0.25, −0.15]
0.28 [0.21, 0.34]
−1.13 [−1.54, −0.71]
−3 −2 −1 0 1
concentration change in ΔPM25 (μg m−3)

7. Weekend/weekday differences

Figure 9 shows the distribution of weekdays/weekend ratios for NO_2, NO_x, PM_{10} and $PM_{2.5}$ for the three periods: base (January to mid-March), pre- and post-lockdown. For NO_2 and NO_x, the ratios >1 indicate higher concentrations over the weekdays compared to weekends. When the lockdown measures were implemented, there is a shift to higher ratios. That might indicate that traffic emissions during weekends (and bank holidays) have probably decreased; and some work-related traffic is still taking place Monday to Friday. For PM_{10} and $PM_{2.5}$ a clear shift in the ratio means were observed, from 1 during the base period, to 1.2-1.3 during the lockdown. This change in the ratio is probably due to the PM episodes taking place predominantly during weekdays.

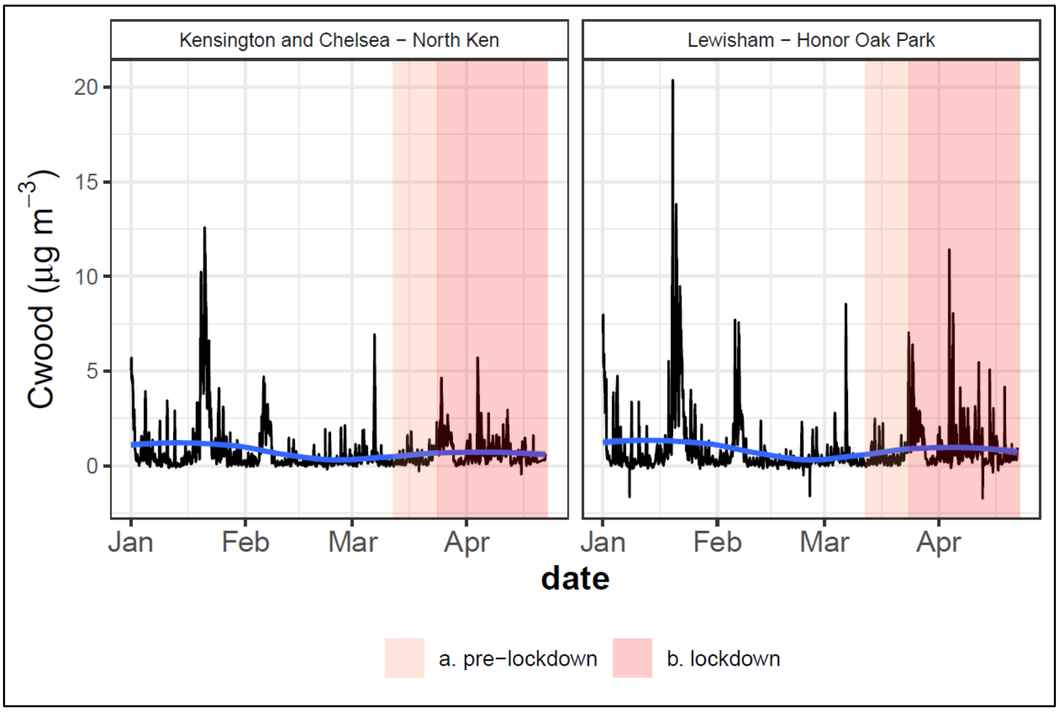
Figure 9. Density plots showing the ratio between weekday/weekend concentrations measured across the London roadside sites. Vertical lines denote the mean ratio for each period.

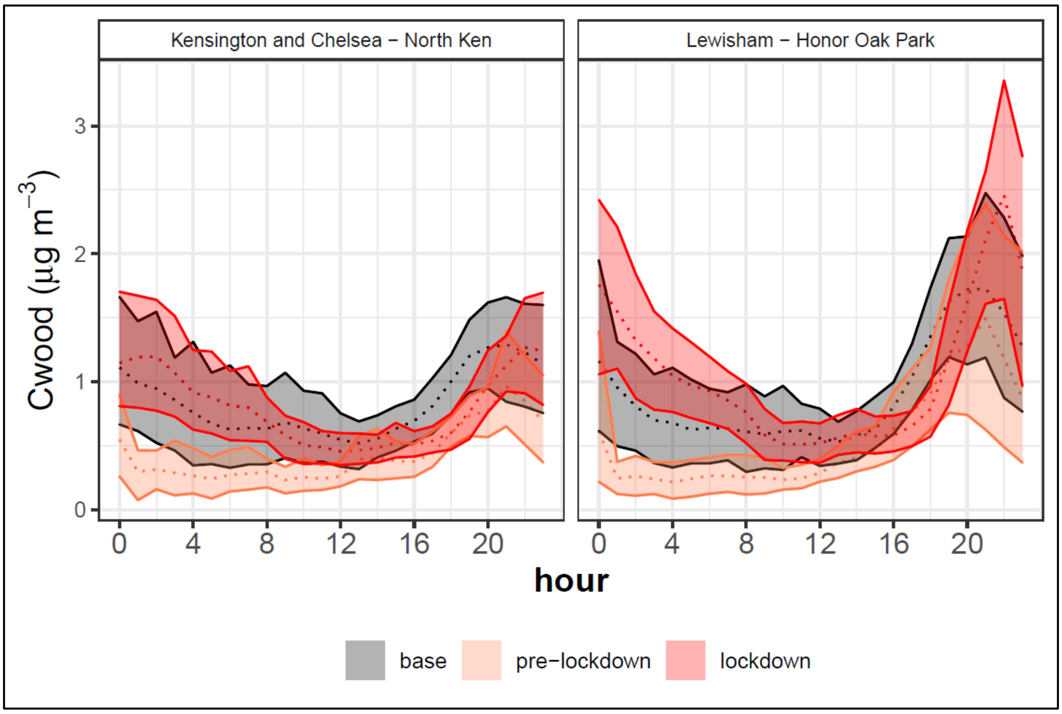


8. Wood burning contributions to PM concentrations

PM from wood burning (Cwood) has been calculated from aethalometer data using the Sandradewi et al. (2008) method, consistent with Font and Fuller et al (2017). Hourly time series of the Cwood concentration at the London background sites and the mean hourly diurnal variation for each period are shown. A series of peaks up to 5 and 10 µg m^{-3} were observed at the start of the lockdown period at North Kensington and Honor Oak Park, respectively. Greater concentrations were measured during the winter months; however, we expect a decrease in springtime. Diurnal plots show similar mean concentrations during lockdown to those measured in the 'base', but with a later evening peak, perhaps due to later use of home heating due to longer daylight hours.

Figure 10. Hourly time series in PM from wood burning (Cwood) and mean hourly variation per each period.




Kensington and Chelsea − North Ken
Lewisham − Honor Oak Park
Cwood (μg m⁻³)
0
1
2
3
0
4
8
12
16
20
hour
base
pre−lockdown
lockdown

9. Implications for health effects

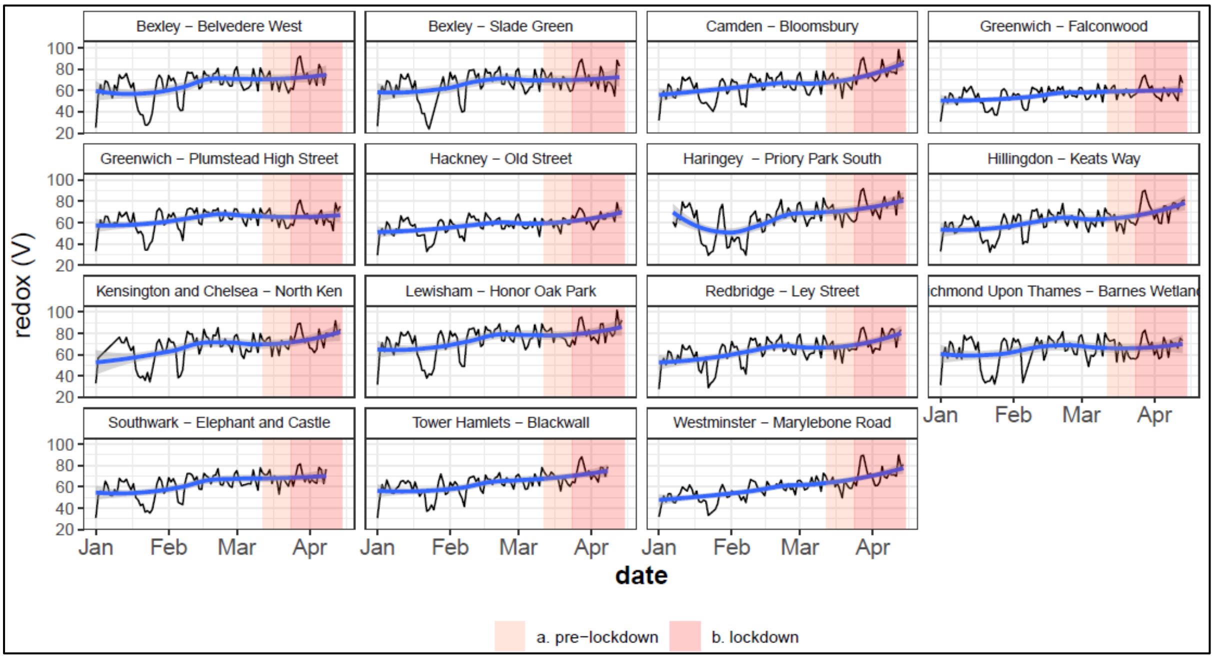
In normal circumstances the increases in $PM_{2.5}$ levels in the post lockdown period would suggest an increase in life years lost and increased morbidity. However, given the special circumstances of the Covid-19 outbreak, the application of standard concentration-response functions and even baseline rates of mortality and disease in health impact assessment would be questionable. This is because health impact assessment relies on the assumption that the population and location characteristics applying to the epidemiological studies from which the concentration-response functions were derived also apply to the population and location to which they are being applied. For example, standard concentration-response functions apply to all-cause mortality but represent the typical relative proportions of respiratory and cardiovascular deaths. Respiratory deaths will be much higher than usual during the COVID-19 outbreak. Concentration-response functions for cause-specific mortality could be used but they would still come from studies of populations that were not experiencing an epidemic. For baseline rates, the exact question would need to be defined. If using the air pollution changes as a model for future air pollution reductions many years ahead, it could be argued that typical baseline rates (perhaps with adjustment for expected mortality trends irrespective of COVID-19) would be most appropriate. If modelling the expected actual changes in air-pollution associated health outcomes, then real baseline rates in this period might be used (although they may not yet be available). However, it would still be in the absence of knowledge about how air pollution affects those with COVID-19, something that is difficult to study to a high standard in a short timescale. With this providing a significant proportion of baseline mortality at the current time, this is a significant omission. The Environmental Research Group would be able to investigate these health impact assessment issues further if required but many significant uncertainties would remain.

We have seen that NO_2 concentrations have decreased and in normal circumstances this could also lead to a decrease in health effects, to some extent counteracting the increases in PM concentrations. The exact extent of this counteraction is complicated by the issues discussed above and by the fact that different pollutants have greater or lesser effects on different health outcomes. There is stronger evidence for effects of PM on cardiovascular mortality and changes in long-term exposure to PM often dominate cost-benefit analyses. This might still apply but the pollutants that have stronger links to respiratory rather than cardiovascular effects (NO_2 and O_3) might provide a higher proportion of estimated health effects than usual due to higher baseline rates for respiratory outcomes.

Ozone concentrations were higher in the post-lockdown period due to the episodes mentioned above. Emissions of ozone precursors, NOx and VOCs from the rest of northern Europe will have combined with emissions from the UK to produce the higher ozone concentrations. Short-term exposures to elevated levels of ozone are a cause of adverse health effects.

Even in the absence of the photochemical episodes, the reduction in NO_x emissions in London will have led to an increase in ozone concentrations purely as a result of the simple $NO/NO_2/O_3$ chemistry. These reactions produce no net ozone and the combined pollutant $O_x = O_3 + NO_2$ is conserved. Both ozone and NO_2 contribute to oxidative stress in the lung, ozone more than NO_2 on a unitary basis, reflecting their redox potentials. Both have been shown to be associated with short and long-term health effects in their own right, but the sum of O_x has also been related to mortality in London (Williams et al, 2012) and is therefore worthy of consideration here given the difference in the relative change in the concentrations of O3 and NO2 over the lockdown period. Figure 11 shows a plot of the time series of O_x at selected London sites. These plots show a clear increase in O_x over the lockdown period, but even without the episodes there is an increase in the gaseous oxidative potential of O_x in London. Reductions in O_x will require reductions in NO_2 but also reductions in the tropospheric background of ozone, necessitating reductions of pollutants, chiefly methane, at a global scale.

Figure 11. Time series of O_X (= O_3 + NO_2) weighted by redox potentials of O_3 and NO_2.



10. Changes in personal exposure

ERG's London Hybrid Exposure Model (LHEM) (Smith et al., 2016) has been used to estimate the impacts of the lockdown on personal exposure to $PM_{2.5}$ and NO_2 for several different population subgroups. The LHEM predicts the exposure of people indoors and outdoors, including whilst travelling (train, tube, bus, car, cycling and walking) and includes indoor sources such as cooking. The subgroups included children, professional drivers, hospital workers and tube users. Annual average exposure is estimated, assuming a typical working week and weekend.

For the purpose of this study, outdoor concentrations in the post-lockdown period have been modelled assuming a reduction in road transport (-53%) and aviation-related activity (-73%), with corresponding decreases in emissions relative to a base "before lockdown" case of 2019.

Before lockdown, the differences in exposure to $PM_{2.5}$ reflect the importance of the time spent indoors and the impact of transport-related exposure, with tube users and professional drivers having the highest exposure. This is more pronounced for exposure to NO_2, where the drivers' exposure is considerably higher than for the other subgroups.

After lockdown, owing to changes in both traffic sources of air pollution and people's work activity, average exposures were reduced by 5-24% ($PM_{2.5}$) and 18-27% (NO_2) for the different population subgroups (see Table 1 and Figures 12 and 13 and the Tables in Annex B). Despite these benefits, the drivers' average NO_2 exposure remained substantially higher than other groups.

The sensitivity of changes to indoor activity was tested by increasing time spent at home and, importantly, additional exposure in a kitchen environment where cooking is taking place. The addition of an hour of extra cooking time demonstrates this to be an important source, increasing average $PM_{2.5}$ exposure to above pre-lockdown levels except in the case of the tube user. NO_2 exposure was also increased, although it remained below pre-lockdown levels for all population subgroups.

A more comprehensive analysis for the specific lockdown period, combining changes to European, UK and London emissions as well as a wide range of population subgroups could be undertaken as part of a larger study. This could include different age groups, socioeconomic groups and ethnicities, as well as addressing the LHEM model's uncertainties. More detail on the model assumptions and uncertainties in this study is given in Annex B.

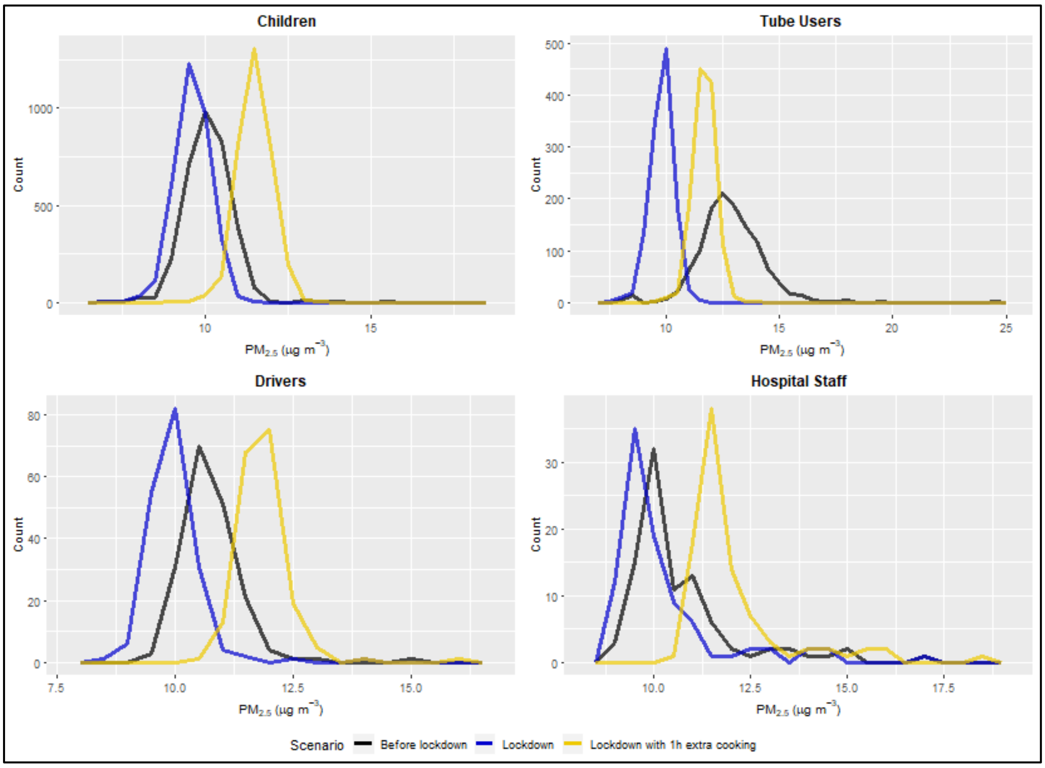


Figure 12. Histograms comparing modelled human exposure to $PM_{2.5}$ before and after the lockdown in different subgroups, with the "1h extra cooking" scenario also included.

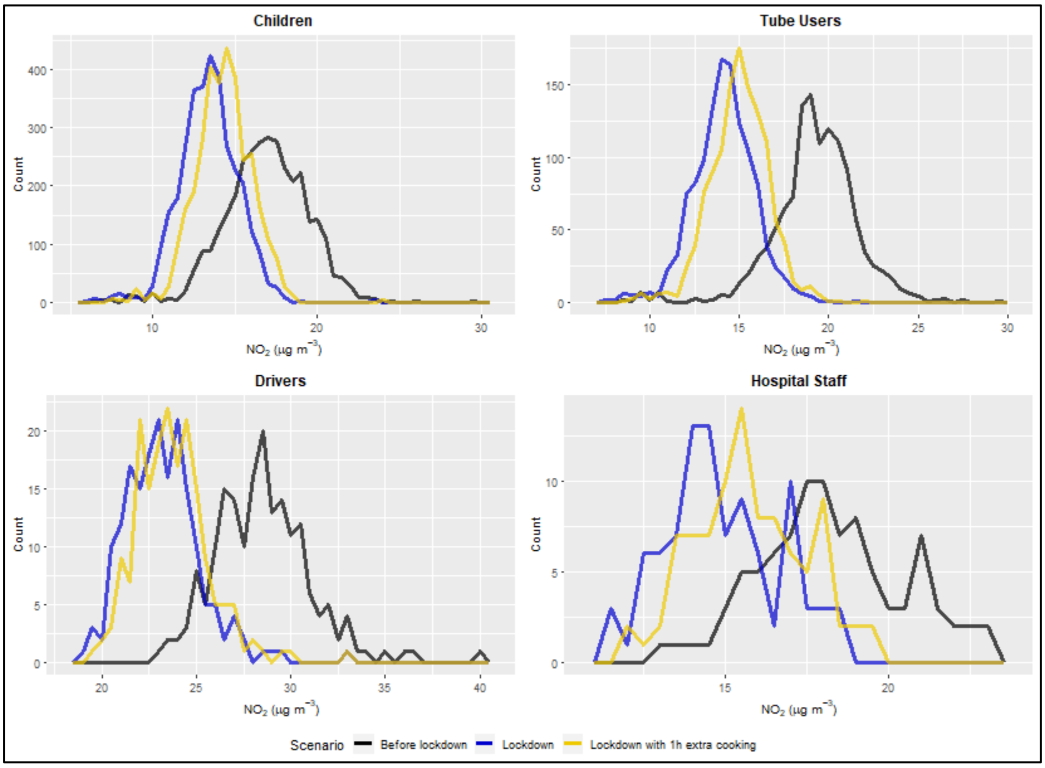


Figure 13. Histograms comparing modelled human exposure to NO_2 before and after the lockdown in different subgroups, with the "1h extra cooking" scenario also included.

References

Sandradewi J, Prévôt A S, Szidat S, Perron N, Alfarra M R, Lanz V A, Weingartner E, and Baltensperger U, Using aerosol light absorption measurements for the quantitative determination of wood burning and traffic emission contributions to particulate matter. Environ Sci Technol. 2008 May 1;42(9):3316-23.

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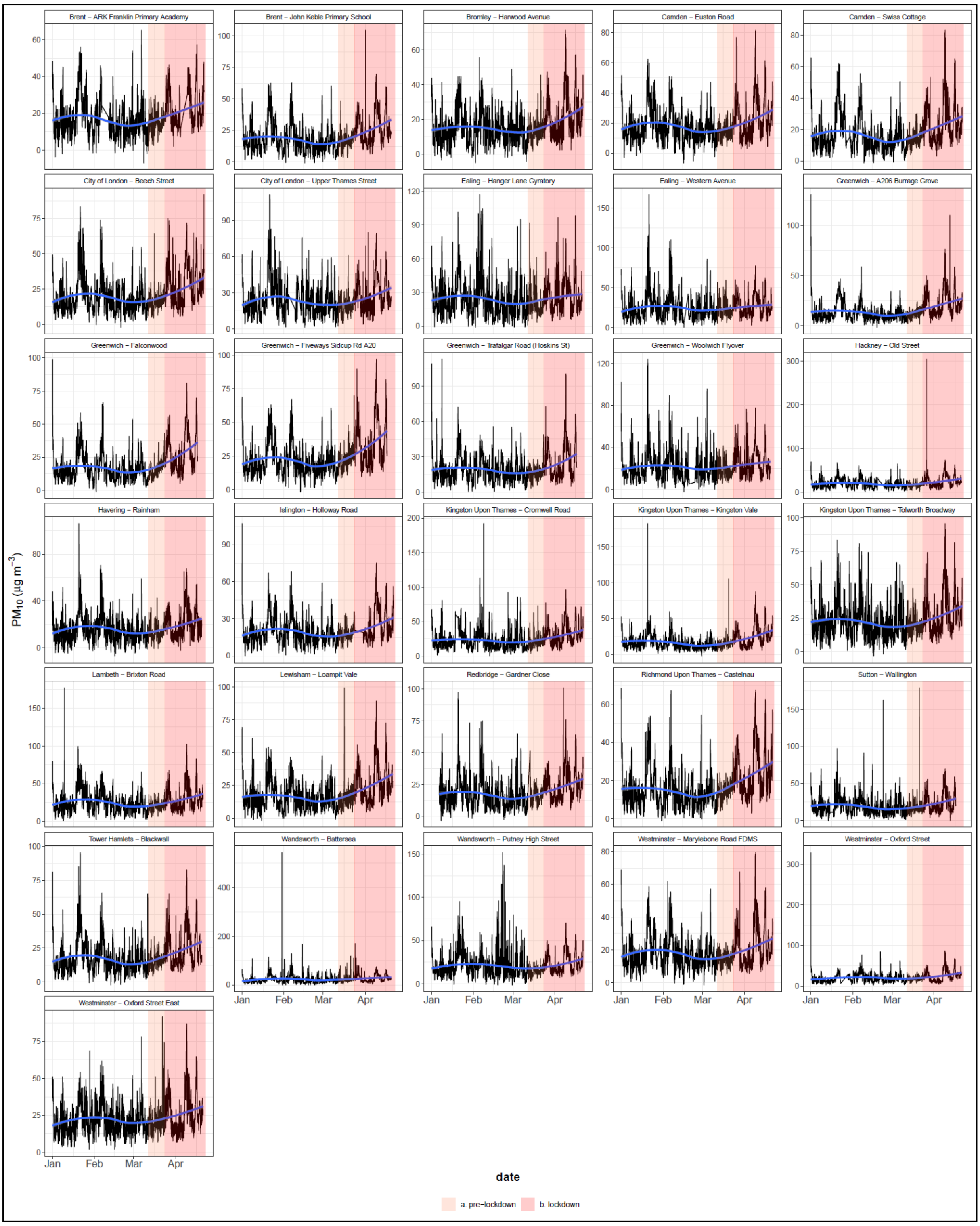
ANNEX A

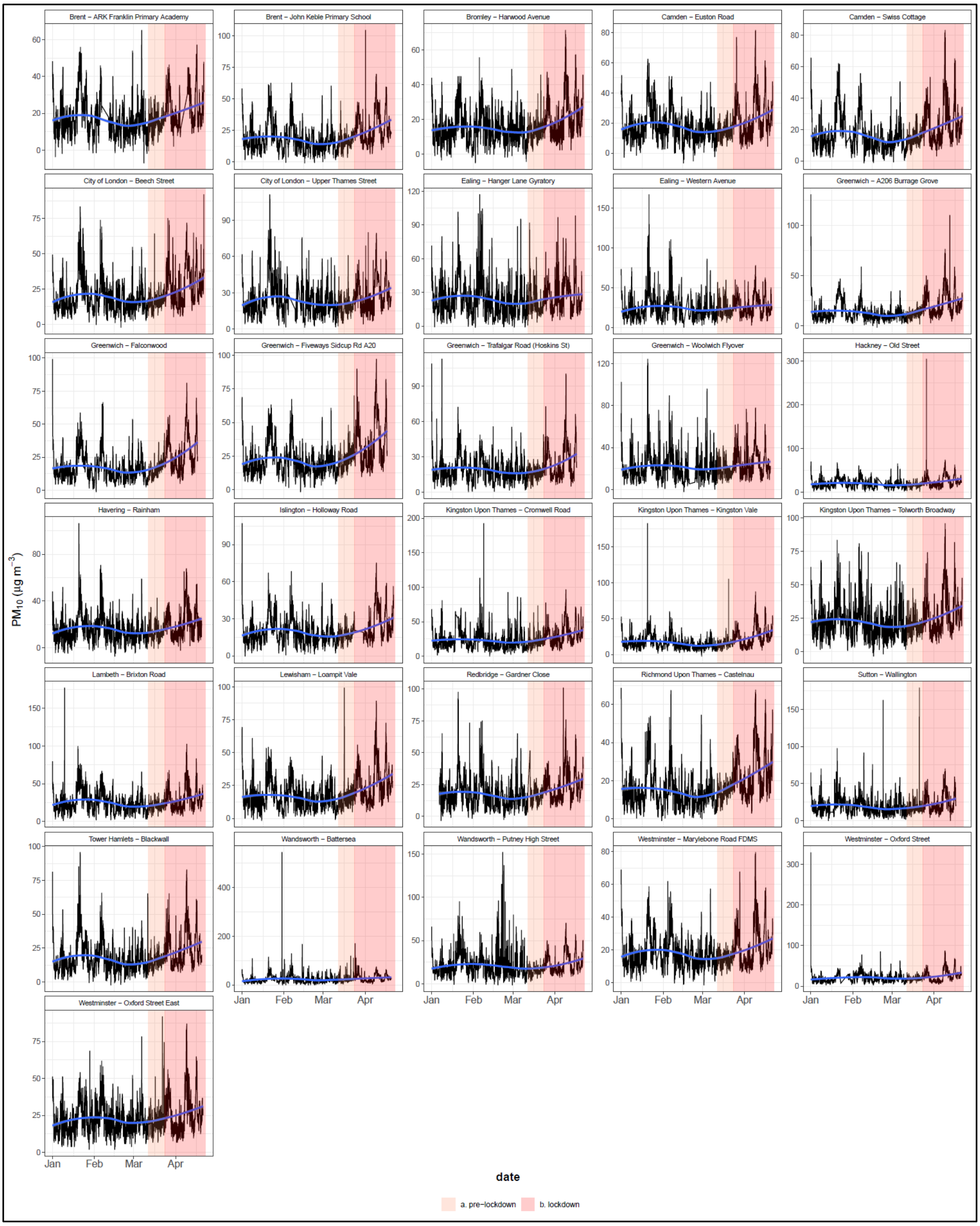
Hourly time series for **all roadside** locations across the **London Air Quality Network**.

Nitrogen oxides ($NO_X = NO + NO_2$)

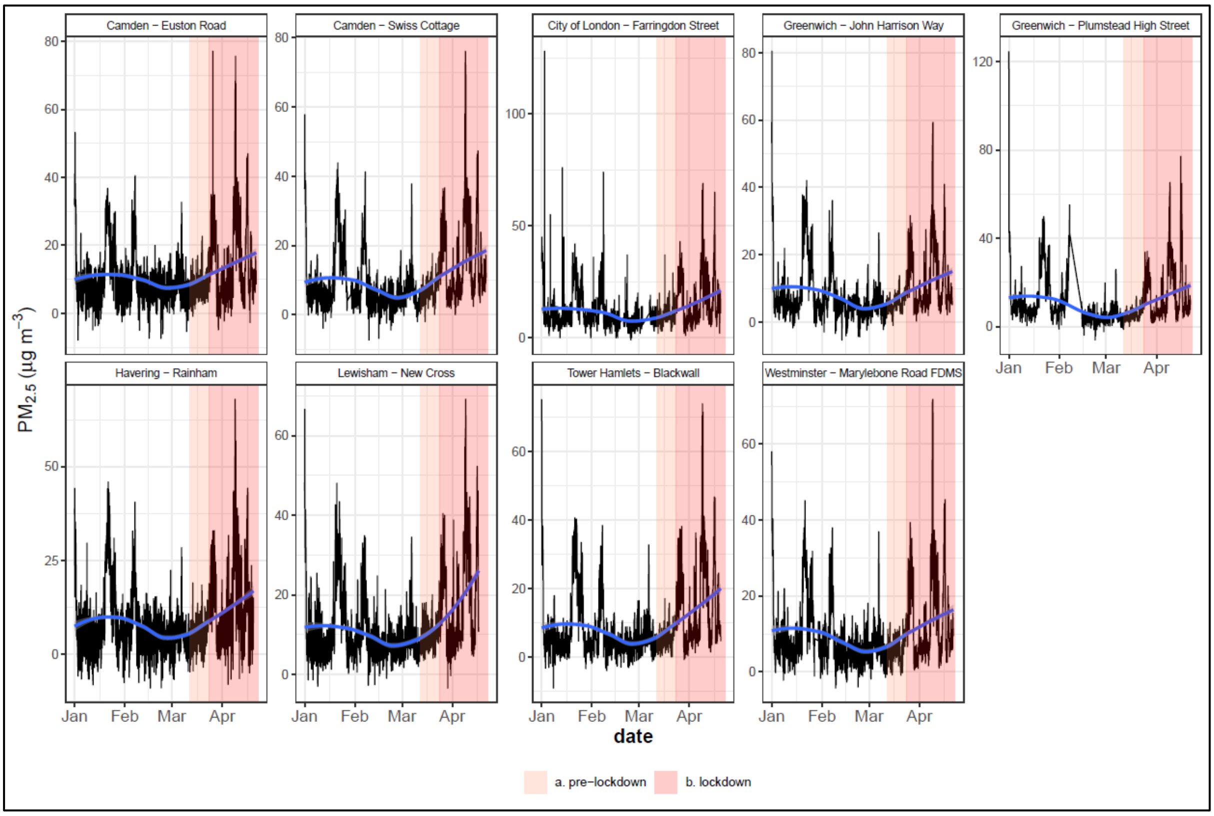
Nitrogen dioxide (NO_2)



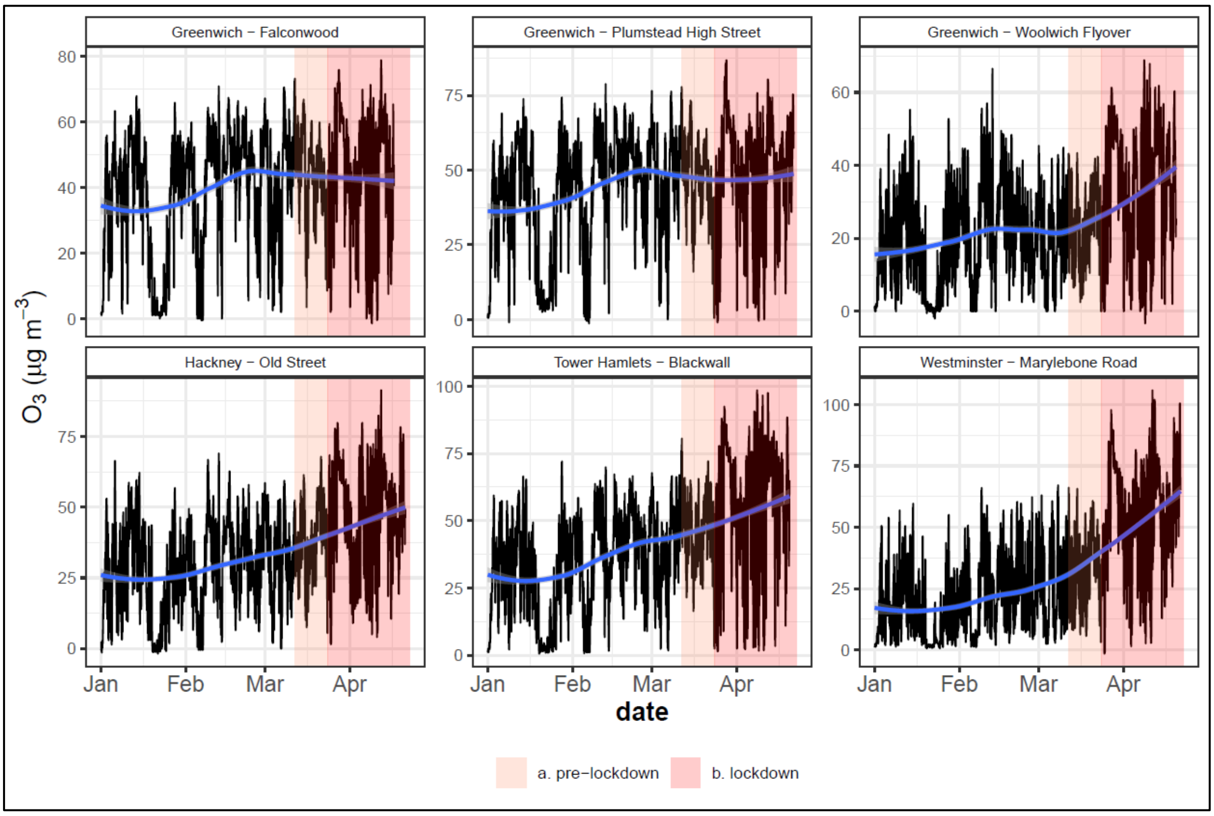
Particulate Matter 10 µm (PM_{10})



Particulate Matter 2.5 µm ($PM_{2.5}$)

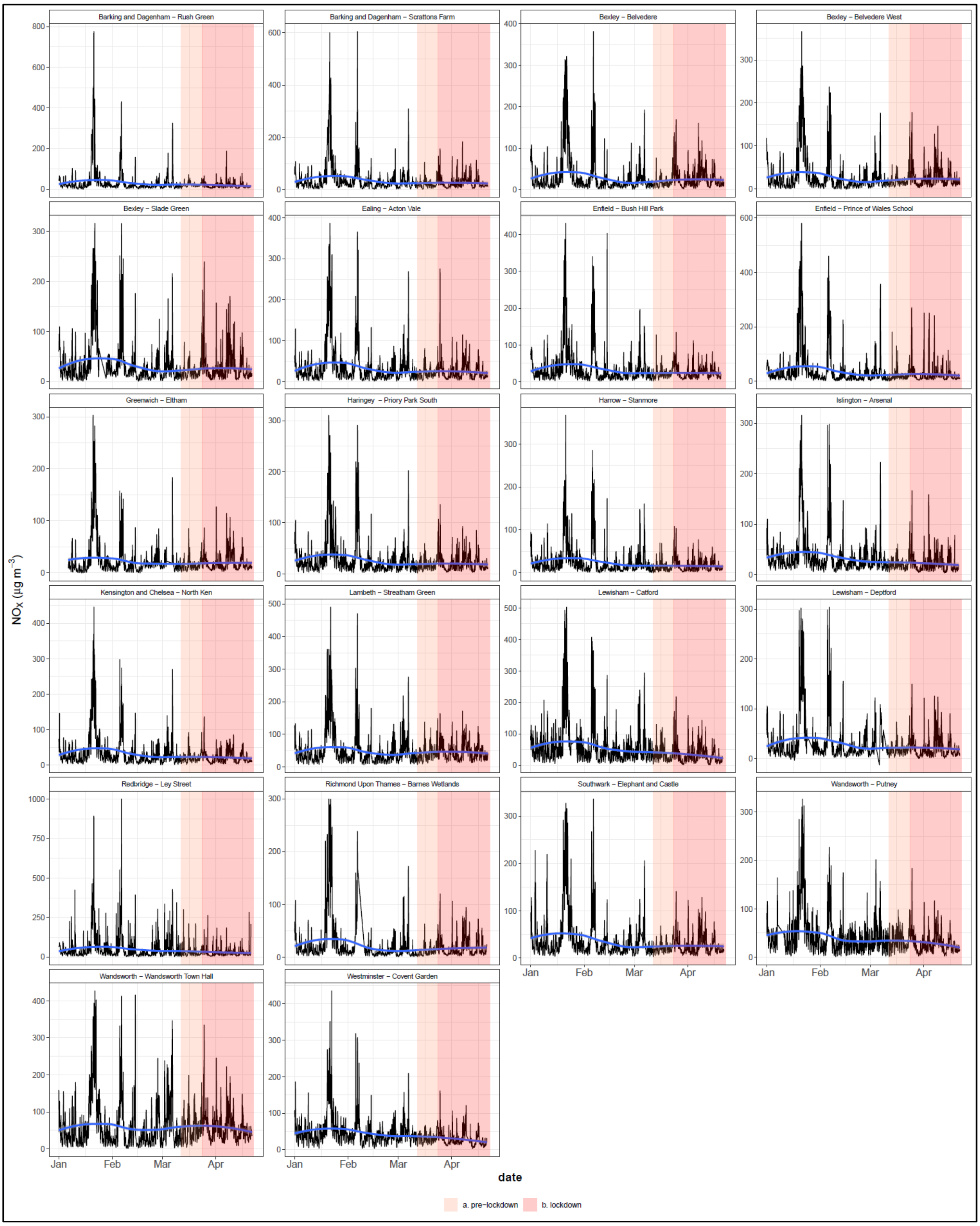


Ozone (O_3)

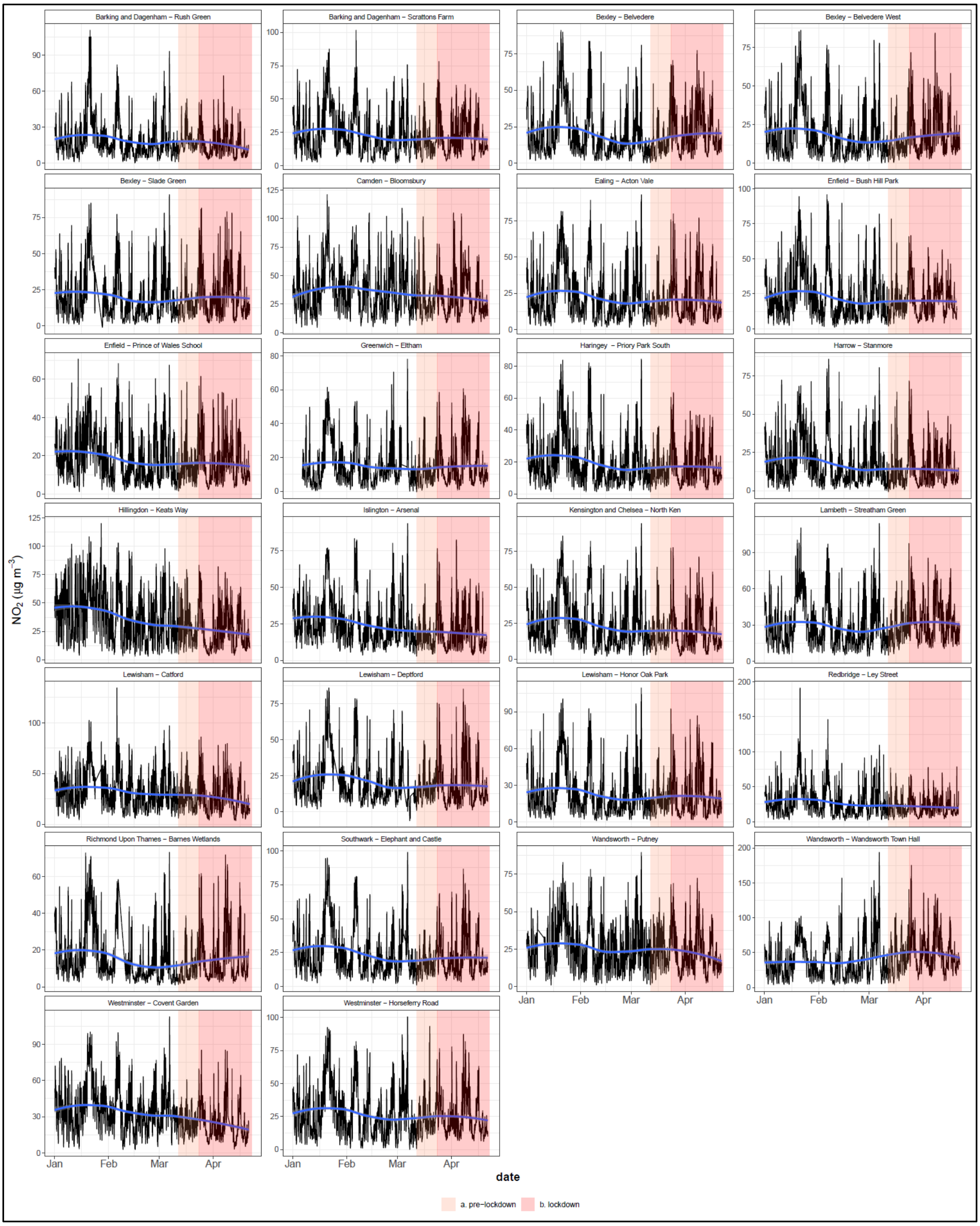


Hourly time series for **all background and suburban** locations across the **London Air Quality Network**.

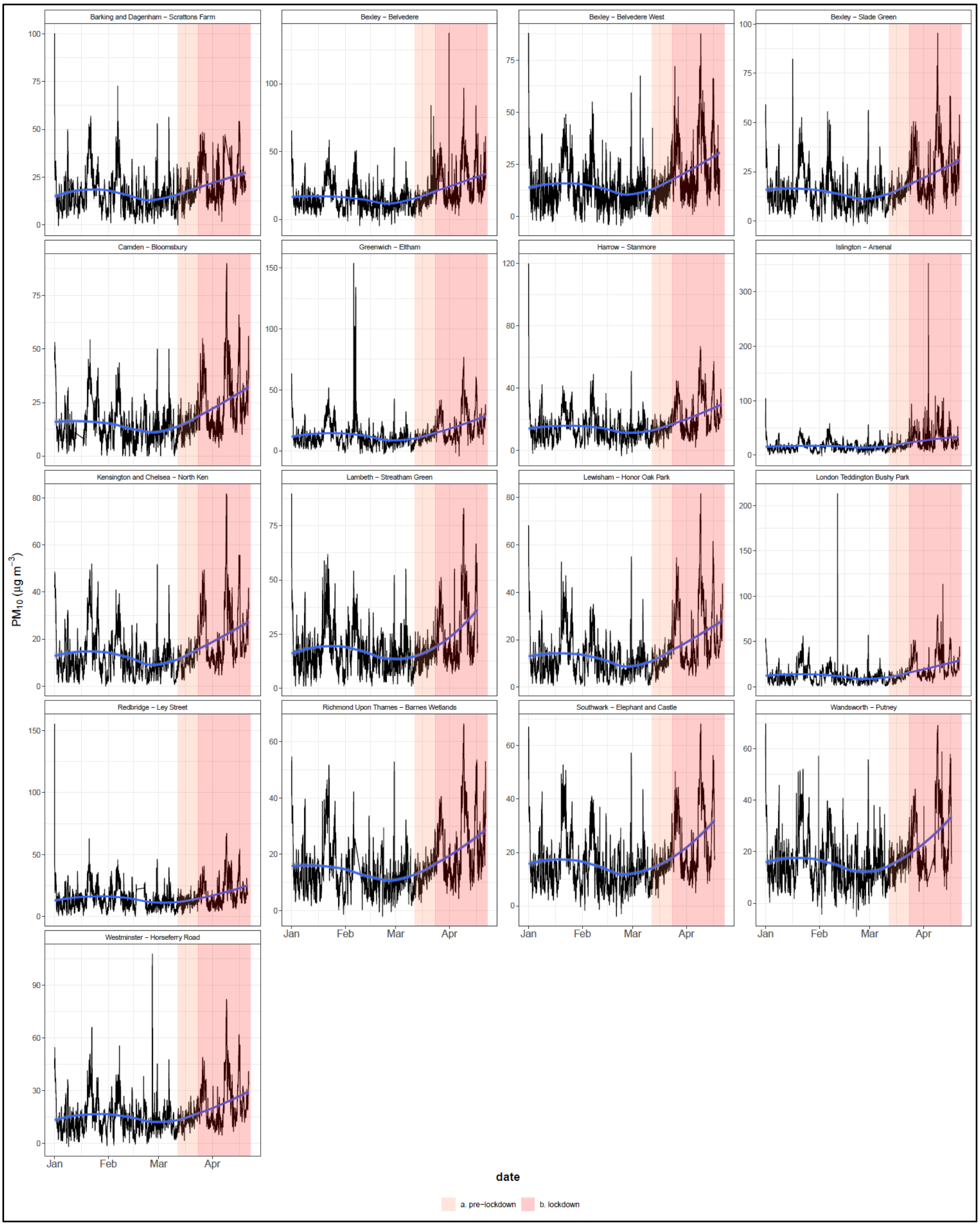
Nitrogen oxides ($NO_X = NO + NO_2$)



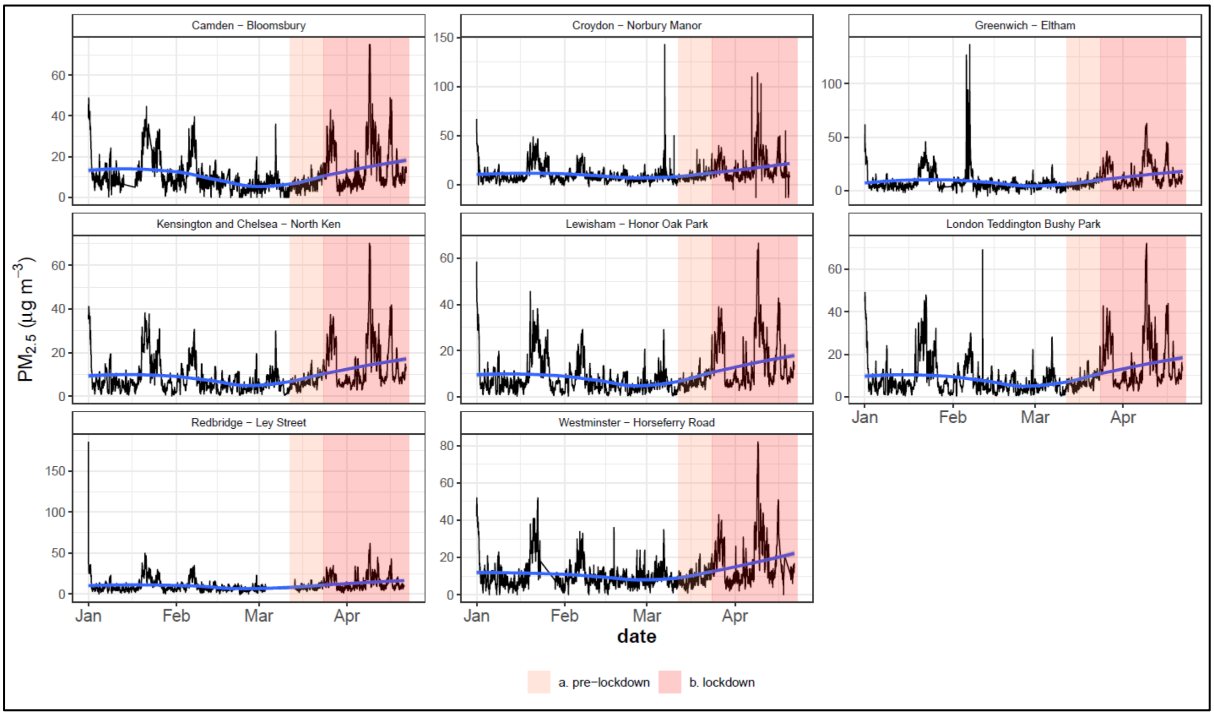
Nitrogen dioxide (NO_2)



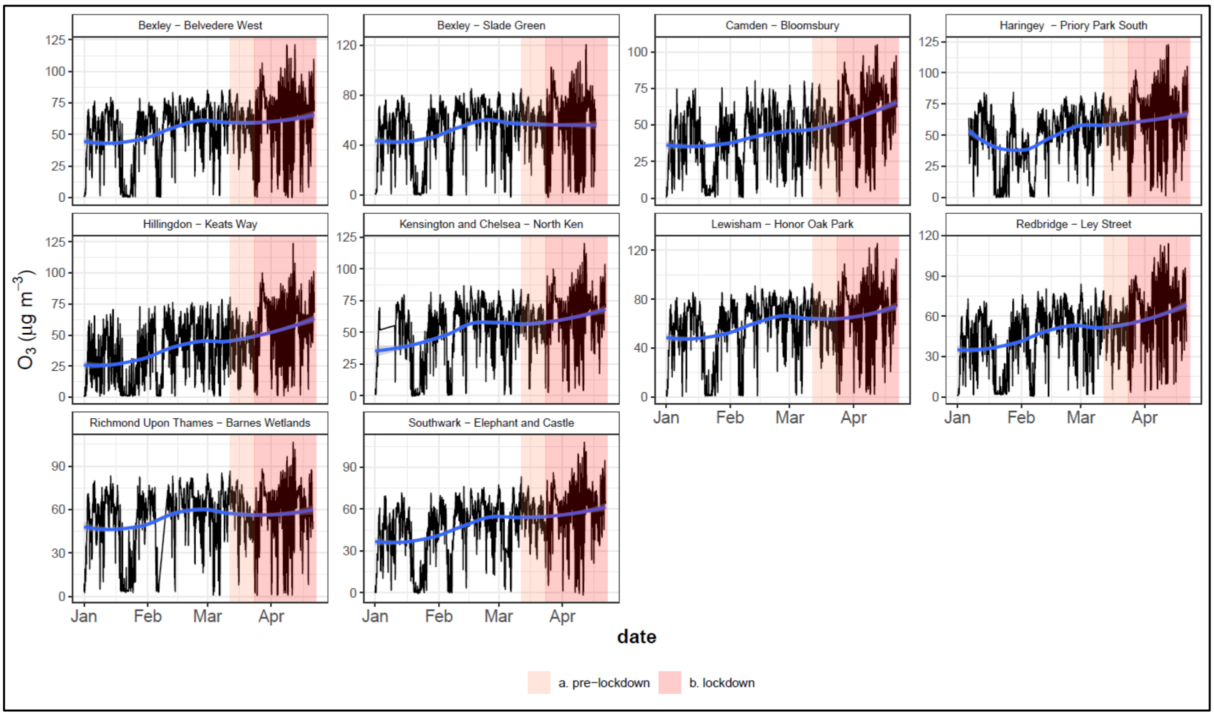
Particulate Matter 10 µm (PM_{10})



Particulate Matter 2.5 µm ($PM_{2.5}$)



Ozone (O_3)



ANNEX B

The Impact of Covid-19 on human exposure indoors and outdoors

Key Messages (see Table 1):

- We have estimated the exposure to $PM_{2.5}$ and NO_2 of several population subgroups in London, indoors and outdoors, whilst travelling to work and working. The subgroups included children, professional drivers, hospital workers and tube users. It was assumed that hospital workers and professional drivers continued to work as normal, while tube users and children stayed at home. The exposure represents an annual average, assuming a typical working week and weekend.
- Before lockdown, the differences in exposure to $PM_{2.5}$ reflect the importance of the time spent indoors and the impact of transport-related exposure, with tube users and professional drivers having the highest exposure. This is more pronounced for exposure to NO_2, where the drivers' exposure is considerably higher than for the other subgroups.
- After lockdown, and due to changes in traffic sources of air pollution and people's work activity, average subgroup exposures were reduced by 5-24% ($PM_{2.5}$) and 18-27% (NO_2). Despite these benefits the driver remained the most exposed.
- The sensitivity of changes to indoor activity was tested by increasing time spent at home and, importantly, additional exposure in a kitchen environment where cooking is taking place. The addition of an hour of extra cooking time demonstrates this to be an important source, increasing $PM_{2.5}$ exposure to above pre lockdown levels except in the case of the tube user. In kitchen exposure also increases NO_2 although it remains below pre lockdown levels for all population subgroups.
- The addition of 2 hours cooking is further evidence of the kitchen as an exposure environment and is meant as a possible maximum exposure or reflective of modern kitchen diner design.
- A more comprehensive analysis for the specific lockdown period, combining changes to European, UK and London emissions as well as a wide range of population subgroups could be undertaken as part of a larger study. This could include different age groups, socioeconomic groups and ethnicities, as well as addressing the LHEM model's uncertainties.

Table 1. Mean (min-max) exposure to $PM_{2.5}$ and NO_2 in different scenarios.

Scenarios	Children (n = 3319)	Tube users (n = 1218)	Drivers (n = 183)	Hospital staff (n = 92)
	$PM_{2.5}$ ($\mu g\ m^{-3}$)			
Before lockdown	10.1 (7.1-18.1)	12.9 (7.8-24.6)	10.8 (9.3-14.9)	10.5 (9.1-14.9)
After lockdown	9.6 (9.3-9.9)	9.8 (7.6-12.4)	10.0 (8.6-14.2)	10.0 (8.8-14.6)
Add 1-h cooking	11.5 (9.1-13.3)	11. 7 (9.6-14.2)	11.8 (10.6-15.9)	11.9 (10.7-16.3)
Add 2-h cooking	13.4 (11.1-15.1)	13.4 (11.5-16.0)		
	NO_2 ($\mu g\ m^{-3}$)			
Before lockdown	16.9 (6.7-29.9)	19.2 (8.4-29.6)	28.5 (23.0-40.2)	18.2 (13.2-23.1)
After lockdown	13.4 (6.2-23.6)	14.1 (7.5-21.4)	23.2 (21.8-32.9)	14.9 (11.3-18.7)
Add 1-h cooking	14.3 (7.4-24.1)	15.0 (8.6-21.9)	23.7 (19.6-32.9)	15.7 (12.2-19.4)
Add 2-h cooking	15.2 (8.6-24.6)	15.8 (9.8-22.5)		

Background

We have used the London Hybrid Exposure Model (LHEM) (Smith et al., 2016), to assess the change in exposure of London's population as a consequence of the Covid-19 lockdown. The LHEM model predicts the exposure of people indoors and outdoors, including whilst travelling (train, tube, bus, car, cycle and walk) and includes indoor sources such as cooking. The model can predict the exposure of the entire London population and, in this analysis, we assumed that the 'before lockdown' exposures reflected typical activity during 2019. In contrast the 'after lockdown' exposures reflect a 53% reduction in road traffic, 73% reduction in aviation, changes to people's daily work activities, increased time spent at home and changes to indoor cooking activities. Specifically, we have added to the 'after lockdown' case an additional 1 hour of cooking activity per day to reflect increased levels of home cooking replacing alternatives such as restaurants and home delivery. In this case cooking activity means an hour longer spent in the kitchen environment. We have not added other changes to important indoor sources such as wood burning. We have selected specific population subgroups for this analysis: children and tube users, whose response to the lockdown is assumed to be to spend all of their time at home[1], and professional drivers and hospital staff, who are assumed to continue to work as normal[2].

[1] Owing to the lack of data on exercise patterns, it has been assumed that the children and tube user subgroups now spend all their time indoors at their home address. Tube users have been defined as anyone spending 20 minutes or more on the London underground on the day for which they completed the LTDS. Children have been defined as anyone under the age of 16

[2] For the purpose of this study, the driver category reflects the daily activity of bus, taxi and delivery drivers. These occupations were identified by answers given in the LTDS. The hospital staff category reflects the people who spent more than 7 hours at one of 43 London Hospitals on the day for which they completed the LTDS.

Model evaluation and assumptions

Estimating human exposure using the London Hybrid Exposure Model indoors, outdoors and in transit requires a detailed combination of outdoor and indoor air pollution concentrations, combined with a detailed knowledge of where, when and how people travel and where they live and work.

Home, work and travel information were taken from the London Travel Demand Survey (LTDS), an anonymised, comprehensive survey undertaken by Transport for London at ~8000 households each year and representative of the entire London population. The people selected for this analysis were all surveyed in the spring months of March-May.

Outdoor air pollution estimates ($PM_{2.5}$ and NO_2) were taken from King's London Air Quality Toolkit Model as average hourly concentrations every 20m across London. The model was evaluated against ~100 air pollution stations from kerbside to suburban background, giving r and normalised bias estimates of 0.7-0.8 and 7% and 0%, respectively.

Indoor air pollution estimates were calculated for kitchen and living rooms using indoor/outdoor measurements of 78 ($PM_{2.5}$) and 89 (NO_2) London households and incorporated into the LHEM mass balance model. Exposure concentrations to cooking emissions are estimated by averaged concentrations in kitchens during cooking hours (7-8 pm) from measurements of 16 London households.

Indoor travel concentrations were predicted using a mass balance approach, combining outdoor concentrations with vehicle air exchange rates, loss rates, area/volume estimates and occupancy, from the wider literature. Estimates of PM exposure on the tube were based around average measurements on the underground, described by Smith et al., 2020.

Model uncertainties

Whilst we have been careful to evaluate many of the LHEM model components, and to use robust indoor measurements where possible, there are still uncertainties surrounding our exposure estimates. Examples include uncertainty in transport exposure, where evaluation is limited to comparisons with the wider literature. Furthermore, due to the limited time available, the estimate of 1 hour of additional cooking is a working assumption to demonstrate the importance of indoor sources. Additional sources of $PM_{2.5}$/NO_2 in offices, hospitals and schools have also not been accounted for in the model.

Current LHEM model developments

- Tube line specific exposure measurements are currently being implemented in LHEM.
- Further assessment of in-vehicle exposure to black carbon is underway as part of the DeMIST project at KCL.
- A more comprehensive evaluation of indoor exposure is being developed, combining modelled indoor/outdoor ratios and the aforementioned household measurements. Further analysis of changes in domestic cooking activity would also be beneficial.
- Estimates of children's exposure in London and the effect on their cognitive development is being undertaken as part of the MRC CLUE project.
- Estimates of changes to exposure brought about by the ULEZ in London and Birmingham is also being undertaken as part of the APEX project.

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Appendix 1. Histograms of human exposure before and after lockdown

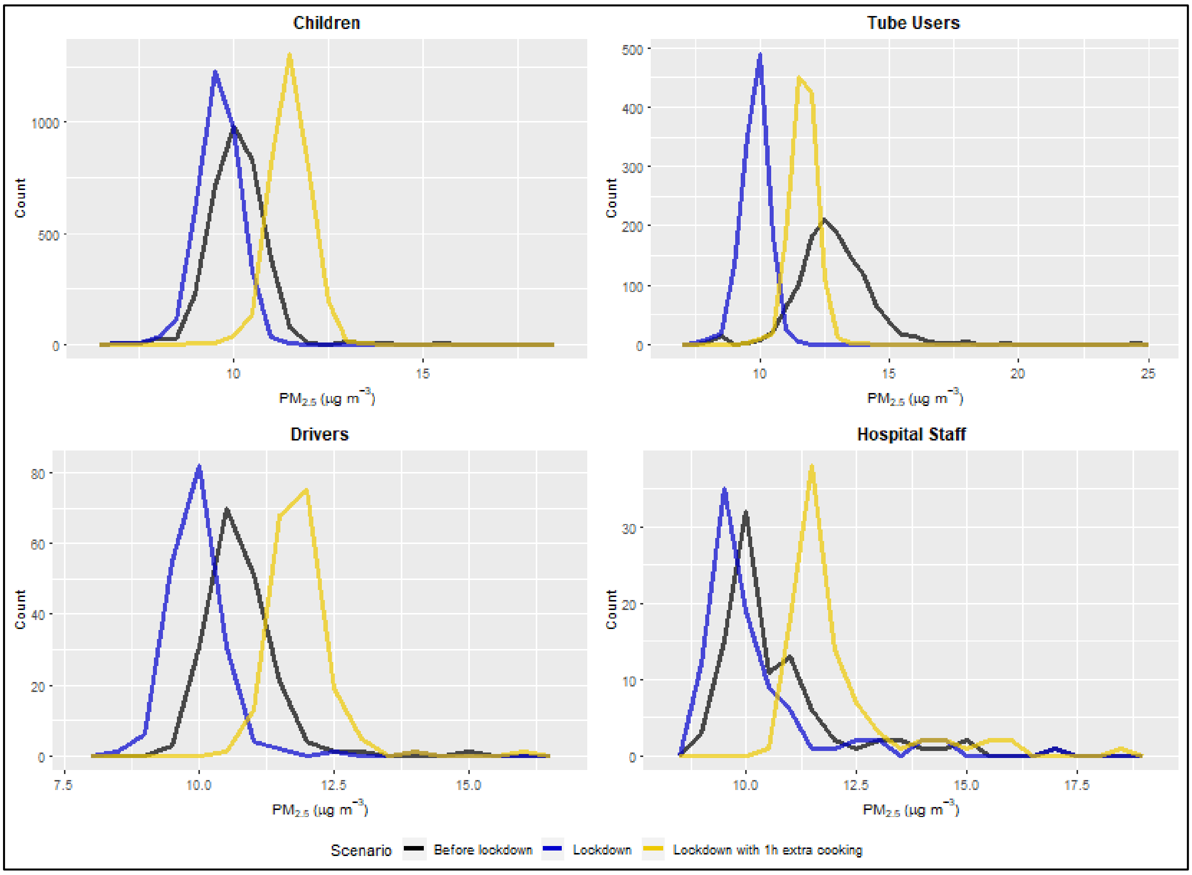

Fig.1. Histograms comparing modelled human exposure to $PM_{2.5}$ before and after the lockdown in different subgroups, with the "1h extra cooking" scenario also included.

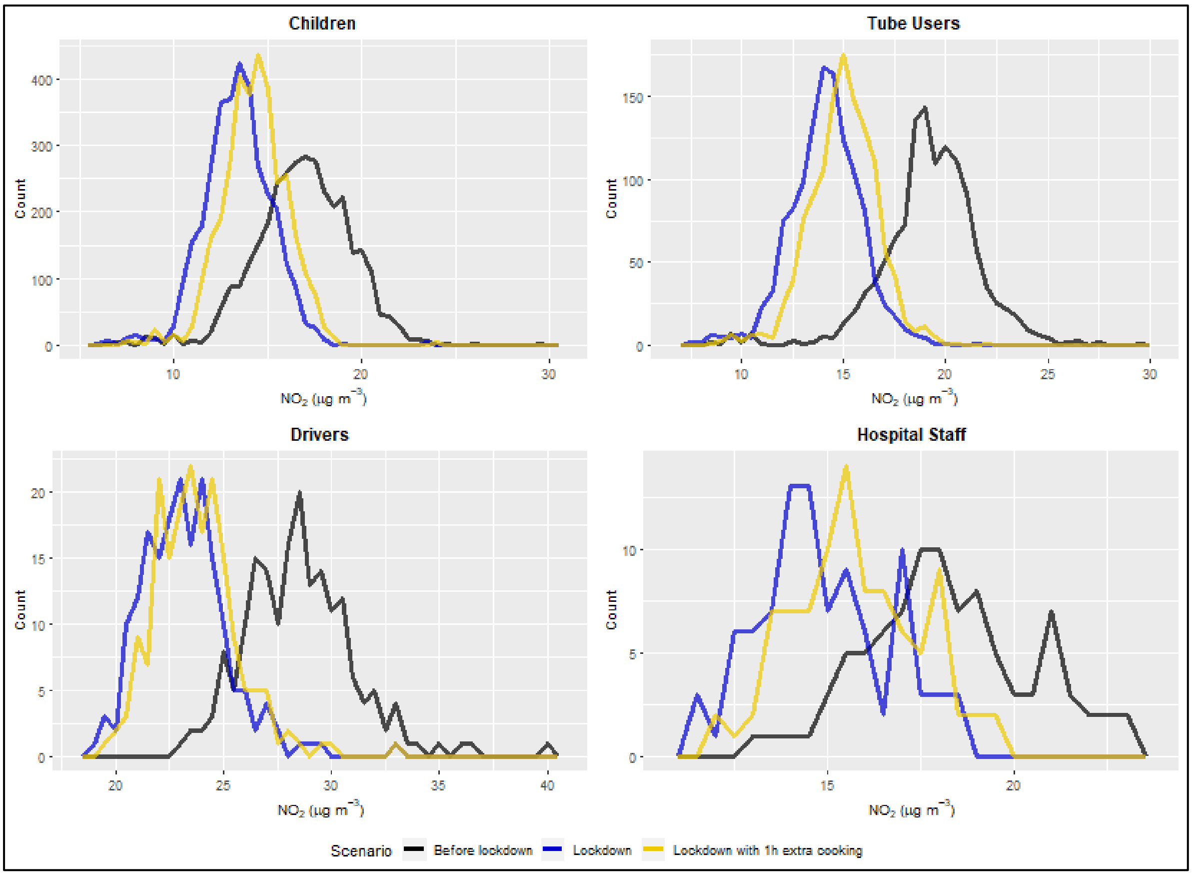

Fig.2. Histograms comparing modelled human exposure to NO_2 before and after the lockdown in different subgroups, with the “1h extra cooking” scenario also included.