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16. Abstract
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Assessing the impact of aircraft arrival on ambient ultrafine particle number concentrations in near-airport communities in Boston, Massachusetts

Chloe S. Chung [a,1], Kevin J. Lane [a], Flannery Black-Ingersoll [a], Eric Kolaczyk [b,2], Claire Schollaert [a,3], Sijia Li [b], Matthew C. Simon [a,4], Jonathan I. Levy [a,*]

[a] *Department of Environmental Health, School of Public Health, Boston University, Boston, MA, USA*
[b] *Department of Mathematics & Statistics, Boston University, Boston, MA, USA*

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ABSTRACT

Aircraft emissions contribute to overall ambient air pollution, including ultrafine particle (UFP) concentrations. However, accurately ascertaining aviation contributions to UFP is challenging due to high spatiotemporal variability along with intermittent aviation emissions. The objective of this study was to evaluate the impact of arrival aircraft on particle number concentration (PNC), a proxy for UFP, across six study sites 3–17 km from a major arrival aircraft flight path into Boston Logan International Airport by utilizing real-time aircraft activity and meteorological data. Ambient PNC at all monitoring sites was similar at the median but had greater variation at the 95th and 99th percentiles with more than two-fold increases in PNC observed at sites closer to the airport. PNC was elevated during the hours with high aircraft activity with sites closest to the airport exhibiting stronger signals when downwind from the airport. Regression models indicated that the number of arrival aircraft per hour was associated with measured PNC at all six sites, with a maximum contribution of 50% of total PNC at a monitor 3 km from the airport during hours with arrival activity on the flight path of interest (26% across all hours). Our findings suggest strong but intermittent contributions from arrival aircraft to ambient PNC in communities near airports.

1. Introduction

Ultrafine particles (UFP) are defined as airborne particles with an aerodynamic diameter less than 0.1 μm, which can come directly from combustion sources as well as from secondary formation in the air (Keuken et al., 2015; FAA, 2015). Smaller particles are potentially more harmful to human health given their ability to enter the bloodstream, penetrate into lung tissues, and circulate throughout the body (Sioutas et al., 2005; Kumar et al., 2014; Karner et al., 2010). Given its small size and mass, and rapid formation and removal processes, UFP is known to have high temporal and spatial variability (Karner et al., 2010; Padró-Martínez, 2012; Patton, 2014).

In neighborhoods near airports, there are multiple potential sources of UFP, including direct emissions from aviation and vehicle traffic as well as from secondary formation in ambient air (Keuken et al., 2015; FAA, 2015). Disentangling these contributions can be challenging, as emission patterns, composition of particles, particle size, and dispersion characteristics can differ substantially, given the unique plume dynamics of aviation activities (FAA, 2015; Shirmohammadi et al., 2018; Morawska, 2008; Austin et al., 2021; Mueller et al., 2022). For example, given the strong but intermittent nature of aircraft emissions, the in-flight aircraft attribution to highly time-resolved ground-based UFP may have a stronger association in the upper percentiles than at the mean/median.

Monitoring studies near airports have shown aviation activities to be an important source of ambient UFP (Keuken et al., 2015; Austin et al.,

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* Corresponding author. 715 Albany St. T4W, Boston, MA, 02118, USA.
E-mail address: jonlevy@bu.edu (J.I. Levy).

[1] Electric Power Research Institute (EPRI), Palo Alto, CA.

[2] Department of Mathematics & Statistics, McGill University, Montreal, Canada.

[3] University of Washington School of Public Health, Seattle, WA.

[4] Volpe National Transportation Systems Center, U.S. Department of Transportation, Cambridge, MA.

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2021; Mueller et al., 2022; Hudda et al., 2014, 2016), affecting a much broader geographic area compared to emissions from motor vehicles (Austin et al., 2021; Hudda et al., 2016). For example, one study conducted at Boston Logan International Airport (Logan Airport) found 1.33-fold and 2-fold higher average particle number concentration (PNC, a proxy for UFP) at sites 7.3 km and 4 km, respectively, downwind from the airport (Hudda et al., 2016). A study performed at Los Angeles International Airport found large mean PNC increases up to 18 km downwind of the airport (Hudda and Fruin, 2016). A study done in the Netherlands found increased annual mean PNC 7 km downwind of Amsterdam Airport Schiphol (Keuken et al., 2015).

Some of these studies have shown elevated levels of PNC under arrival flight paths (Hudda and Fruin, 2016), with higher concentrations compared with surrounding urban locations with similar road traffic characteristics (Riley, 2016). Emission rates of UFP are much higher during take-offs compared to approaching (Tesseraux, 2004; Hsu et al., 2012), though emissions from arrival aircraft can potentially influence exposures over broader geographic areas due to flying at lower altitudes for longer. However, it is unclear how large or sustained those contributions are, relative to departure aircraft or other emission sources. Most studies to date have ascertained concentration patterns downwind of the airport but have not formally considered flight paths and the intermittent and variable nature of the corresponding emissions. Here, we evaluate in-flight aircraft contributions to ground-based PNC measured at varying distances to the main arrival flight path at Logan Airport, leveraging real-time meteorological and flight activity data to better understand important but highly variable community UFP exposure patterns associated with aircraft arrivals.

2. Materials and methods

2.1. Study design

The field sampling campaign was conducted from April to September 2017 in the vicinity of Logan Airport. The arrival flight paths to runway 4 L and 4 R were the main focus of this study, 4 R being the primary arrival runway configuration used when the wind is from the northeast, (Massport - How Logan Operates) but also during multiple other meteorological conditions. 4 L is used under similar wind conditions as 4 R, but with a much smaller volume of flights. Six monitoring sites were selected that were at varying distances from the airport and flight paths to runway 4 L/4 R (Fig. 1 and Table 1), and therefore have potentially varying UFP contributions from aircraft arrivals. Based on their distances to the airport as well as based on the average flight altitudes (Table 1), two sites closest to the airport were named N1 and N2 (near sites), two sites that were intermediate distances to the airport as I1 and I2 (intermediate sites), and two farthest away sites as F1 and F2 (far sites) as shown in Fig. 1. Selection criteria for monitoring locations

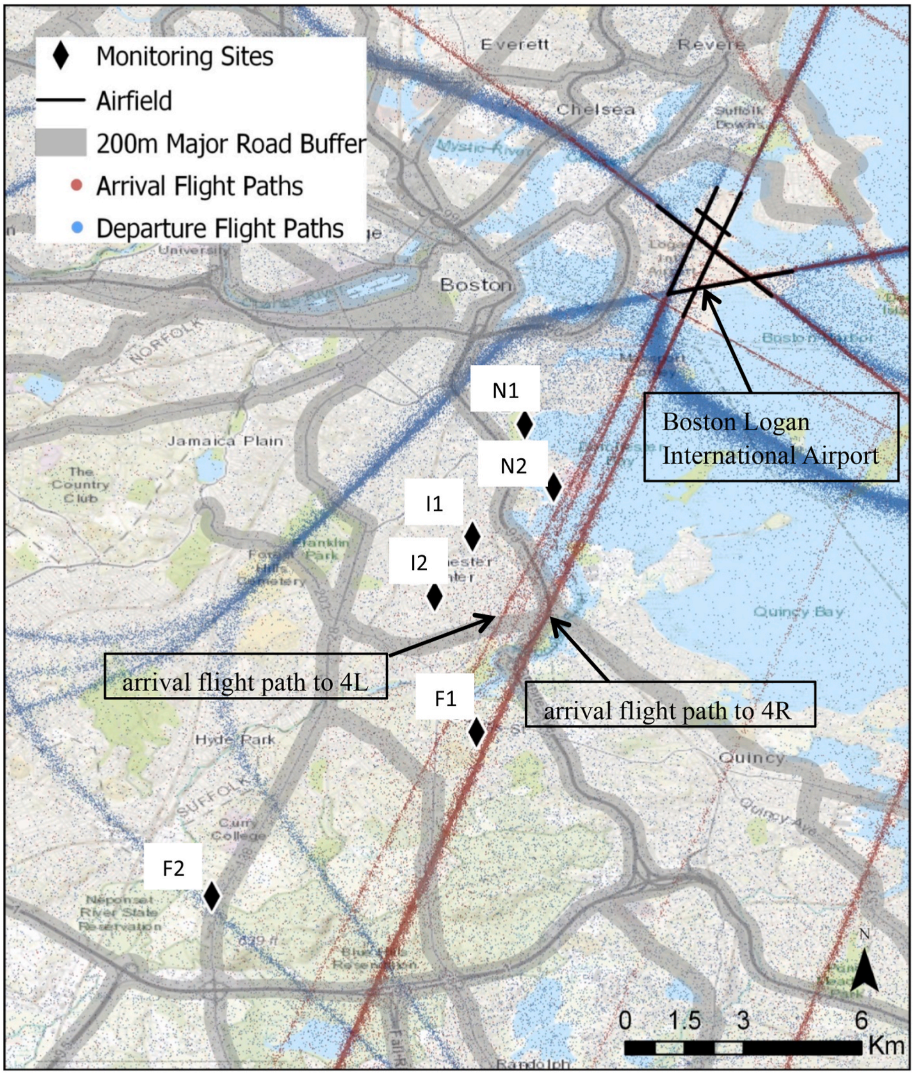


Fig. 1. Map of monitoring sites and flight paths.

Table 1
Characteristics of each monitoring site.

Site	Lateral distance to flight path 4 R (km)	Distance to airport (km)	Average altitudes of arrival aircraft (m)	Monitoring configuration
N1	1	3	210	Indoor[a]: second floor office space facing the bay
N2	<0.5	4	300	Outdoor: open shed on a boat dock
I1	2	7	400	Indoor[a]: first floor restroom facing a small parking area
I2	2	9	460	Outdoor: open shed in the backyard in residential area
F1	<0.5	12	610	Indoor[a]: second floor classroom
F2	4	17	850	Outdoor: greenhouse at a farm

[a] For any indoor deployment, the monitor was placed indoors with tubing running outside to measure ambient concentrations.

prioritized sites to distinguish the aviation contribution to ambient PNC apart from other sources. We did so by creating a 200-m buffer around major roads defined as Class 1 and 2 in the Massachusetts Department of Transportation road layer (Mass GIS) to avoid large motor vehicle traffic contributions to ambient PNC at the study sites based upon previously published distribution patterns of traffic-related UFP (Karner et al., 2010). All potential sites were visited in person and site-by-site determinations were made after considering multiple factors including the surrounding environment (e.g. local traffic volume, restaurants, etc.). One of the six sites (F2) was 160 m from a designated major roadway but was still included as a study site because field observations indicated relatively low traffic volume and preliminary measurements confirmed that PNC levels in the absence of flight activity were similar to other sites.

Table 1 summarizes the characteristics of different set-ups at the six monitoring sites. Considering lateral distances, two sites (N2 and F1) were within 0.5 km of the 4 R arrival flight path, while the other four sites (N1, I1, I2, and F2) were at varying distances to the west of the 4 R arrival flight path. Sites also varied by their proximity to the airport, the corresponding altitude of aircraft as they flew by the monitoring sites, and where the monitor was deployed (i.e., indoors or outdoors, at ground level or on the first or second floor). Given the use of identical tubing lengths whether indoors or outdoors and the limited ground-level sources near our monitoring sites, concentrations were unlikely to be affected by variation in monitoring configuration.

2.2. *Instrument and data processing*

The monitoring strategy was to measure at three sites simultaneously for 1 week at a time, rotating among six sites to capture as many different spatial and meteorological combinations as possible. We used three condensation particle counters (CPC, TSI Model 3783, 7–3000 nm; 1-s averaging), enclosed in weatherproof Pelican cases to allow for flexible field deployment and easy transport among the sites. While the CPCs measure particle counts above the ultrafine range, the vast majority of particle number near a combustion source is found below 100 nm, making this an appropriate surrogate of UFP concentrations. Multiple pilot tests were conducted to ensure the portable configurations met the temperature requirements of the instrument.

The instruments were deployed either indoors or outdoors depending on space availability at each site (Table 1). The same instrument configuration was used for both indoor and outdoor sites. For indoor deployment, the CPC remained inside with Tygon tubing, chosen to minimize particle deposition and line loss within the sampling tube, connected to the inlet placed through a window. For outdoor deployment, the CPC was placed under a roof to prevent any weather damage with Tygon tubing connected to the inlet extending to an outdoor area. The same length of tubing was used at all sites for consistency. CPC co-location testing at N2 showed a strong positive correlation between instruments (Pearson correlation coefficient = 0.98; Supplemental Fig. 1).

Observations with automatic error flags by the instrument were reviewed and those observations with errors affecting the data quality were removed (2.7% at N1, 0.27% at N2, 0% at I1, 9.6% at I2, 3.2% at F1, and 9.0% at F2). The majority of these errors related to external vacuum pump malfunctions rather than CPC issues, and did not depend in any way on site characteristics, noting that both CPCs and pumps rotated among sites. Performance Data Analysis and Reporting System (PDARS) data were obtained for the entire study period from the U.S. Federal Aviation Administration (FAA). The data provided real-time three-dimensional location information (latitude, longitude, and altitude) for all arrival flights landing at Logan Airport excluding military aircraft. Meteorological data were acquired from the U.S. National Weather Service station located at Logan Airport (KBOS).

We summarized PNC distributions at the measured resolution (1-s) to develop hypotheses about the influence of aviation and meteorology on concentrations. Specifically, we characterized percentiles from the 0.1st to the 99.9th by study site across the entire study period.

To characterize the influence of aircraft arrival activity on PNC patterns, we used PDARS data to calculate the number of aircraft landing on either 4 L or 4 R runways for each hour across the entire study period. We then constructed a new variable to indicate no ($n = 0$), moderate ($0 < n < 30$) and high ($n \geq 30$) arrival aircraft activity, using the median number of arrival aircraft in an hour as the cut-point (median number of arrival aircraft = 29 among hours with non-zero flight activity). Further, we hypothesized higher PNC associated with aviation activity when the monitoring site was downwind from the airport. We defined a hypothesized aviation impact sector as the wind direction range that positioned monitoring sites downwind of the airport ±15°, which would also capture the impact of aircraft at the end of the 4 L/4 R arrival flight path with aircraft very close to the ground (Hudda et al., 2018).

2.3. *Statistical analyses*

We characterized diurnal PNC patterns using boxplots stratified by the level of arrival aircraft activities (high vs. none, to yield comparisons with maximum contrast), which described the distribution of the data between the 5th and 95th percentiles (5th, 25th, 50th, 75th, 95th) and the mean. Concentration roses were generated to display PNC associations with varying wind speeds and wind directions at the study sites, stratified by arrival aircraft activity (high vs. none) excluding data from 02:00 to 07:00 to remove the impact of early morning time periods when there was limited airport activity, according to the PDARS dataset.

Regression models were developed using a 1-h temporal resolution using three different measures of PNC within those time periods (mean, 95th percentile, and 99th percentile) to understand the contribution of arrival aircraft as well as the impact of meteorological conditions on measured PNC. These regression models were developed for each site to capture potentially varying impact of arrival aircraft as well as meteorology across our study sites. Log-transformed PNC was used as the outcome variable. We examined all variables in our data that were known to be important predictors for PNC based on previously published studies (Münzel et al., 2014; Eriksson et al., 2010; Sørensen et al., 2013) and our summary plots/analyses: wind direction, wind speed, temperature, relative humidity, mixing height, atmospheric pressure, precipitation, and weekday/weekend. In addition, we included terms for aircraft frequency on other runways to ascertain contributions from other non-4L/4 R aircraft operations. Aircraft type information obtained from PDARS were shown to be unable to accurately ascertain varying contributions of different aircraft types to ambient PNC, and therefore were not included in our final models.

We used generalized least squares models and, since we had time-series data, accounted for autocorrelation in the residuals. Forward step-wise regression with an AIC criterion was used to select the variables for the final model using the stepAIC function in the MASS R package. To make the results comparable across different models and sites, we included any variables that were selected for any models. Bonferroni correction was used in determining statistical significance of the predictors to adjust for multiple testing. Exponentiated coefficients from regression models represent the relative magnitude of PNC per one unit increase in 4 L/4 R arrival aircraft, controlling for all other covariates in the final models.

All analyses were conducted using R (version 3.5.2) and Excel; maps were created using ArcMap 10.6.

3. Results and discussion

3.1. PNC site percentile distribution

In total, we collected PNC measurements across 546 sampling days, distributed approximately evenly across the six sites, for a total of >41 million individual 1-s resolution measurements (Table 2). While median PNC was similar across the six study sites, concentration patterns differed at higher percentiles, with elevated PNC above the 95th percentile at sites closer to the airport (N1 and N2). While N1 and N2 had comparable or lower PNC at the median and below as compared with other monitoring sites, they had the highest concentrations above the 95th percentile. Sites F1 and F2, which were farthest from the airport with overhead aircraft at higher elevation, generally had the lowest concentrations across all percentiles. Sites I1 and I2 had the highest concentrations at the median but lower concentrations at the 99th and 99.9th percentile in comparison with sites N1 and N2.

3.2. Aircraft activity and diurnal PNC patterns

The influence of flight activity on concentrations at the six monitoring sites was first examined by characterizing diurnal PNC patterns stratified by level of flight activity (Fig. 2). PNC during hours without arrival aircraft were generally similar at the six study sites, with most hourly PNC averages <25,000 particles/cm^3. We observed only a modest increase in concentrations during the morning rush hour when there was zero flight activity on 4 L/4 R, consistent with our selection of sites with limited local traffic. By comparison, during hours with high arrival aircraft, there were notable increases in PNC at most of our study sites. Mean, 75th, and 95th percentile 1-s PNC were elevated throughout the day when there was high arrival aircraft activity on the 4 L/4 R runways compared to when there was no flight activity. This pattern was more pronounced at sites relatively closer to the airport (N1, N2, I1, and I2). The elevated patterns were similar at N1 and I1. Sites F1 and F2, which were farthest from the airport, had smaller differences in PNC between high and no flight activity and less consistent temporal patterns (Fig. 2).

3.3. Windspeed, wind direction and PNC pollution roses

Our 1-s resolution PNC monitoring data, which had relatively similar median concentrations across monitoring sites, but divergent concentrations at the upper percentiles, suggest strong but intermittent aviation contributions especially at monitoring sites closer to the airport. Stratification by flight activity and meteorology indicated that PNC was higher during hours of high arrival flight activity on 4 L/4 R under wind conditions when the monitoring sites were downwind from the flight path and the airport (Fig. 3). The pattern of aviation contribution to ambient PNC was more difficult to detect at sites farther away. Pollution roses in Fig. 3 reinforced the likelihood that PNC increases were related to arrival aircraft in-flight at lower altitudes rather than ground level activities at the airport. For example, under conditions without flight arrivals on 4 L/4 R but winds from the northeast (airport direction), PNC increased far less. In addition, the highest PNC concentrations were typically at higher wind speeds but only under conditions of high arrival flight activity, consistent with aviation contributions (Hudda et al., 2016).

3.4. PNC flight activity regression modeling

Regression model results for N1, I1, and F1 sites are presented in Table 3 (mean and 95th percentile PNC, using hourly concentrations). The results from modeling 99th percentile data are not presented, as they were similar to the results of 95th percentile PNC. Our results using 10-min concentrations are not presented, since conclusions were similar to the regression models using 1-h concentrations. Hourly concentration results for the other three sites (N2, I2, and F2) can be found in supplemental material (Table S1).

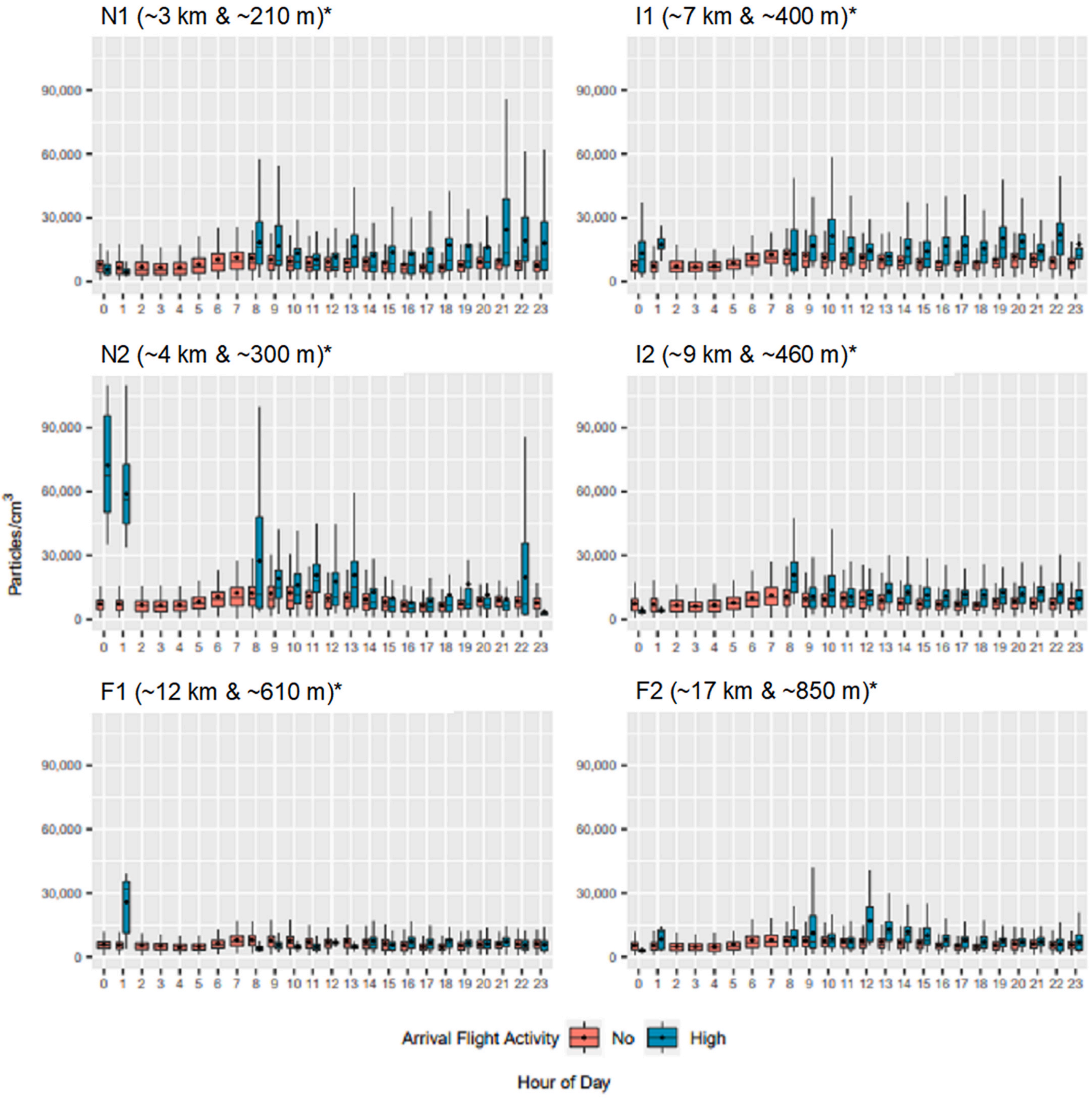
Overall, our regression models indicated a positive association between 4 L/4 R arrival aircraft frequency and PNC. The 95th percentile models had a larger increase in PNC than the mean models. The impact of all other aircraft activity at all sites was similar between the mean and the 95th percentile models. The coefficients for aircraft activity, including both the 4 L/4 R arrival aircraft and all the other aircraft activity, were lowest at the far site (F1) compared to the near and intermediate sites (N1 and I1) (Table 3).

3.5. Arrival aircraft model contributions

We applied the regression models to estimate the contribution of arrival aircraft at all six study sites, comparing predictions with and without arrival flight activity. The aircraft contribution at N1 was the largest compared to all other sites (Fig. 4). For the 27% of hours with arrival aircraft on 4 L/4 R, the estimated arrival aircraft contribution at site N1 had a mean of 11,100 particles/cm^3 (50% of total PNC). The second and third largest aircraft contributions were shown at I1 and N2 with the estimated arrival aircraft contribution of 9200 and 6500

Table 2
Distribution of 1-s PNC (particles/cm^3) across monitoring sites.

	N1	N2	I1	I2	F1	F2
Sample Size (days)	98	94	86	92	84	92
Sample Size (seconds)	7,468,604	7,537,890	6,685,191	6,928,122	6,473,741	7,038,958
0.1st percentile	390	530	1200	850	800	880
1st percentile	930	1300	2100	1300	1200	1200
5th percentile	2000	2400	3500	2500	2000	2000
25th percentile	4600	4800	6300	5100	3900	3900
50th percentile	7400	7500	9200	7900	5700	5800
75th percentile	12,000	11,000	14,000	12,000	7800	8200
95th percentile	29,000	28,000	29,000	22,000	13,000	15,000
99th percentile	59,000	58,000	48,000	34,000	22,000	24,000
99.9th percentile	94,000	110,000	74,000	49,000	39,000	46,000



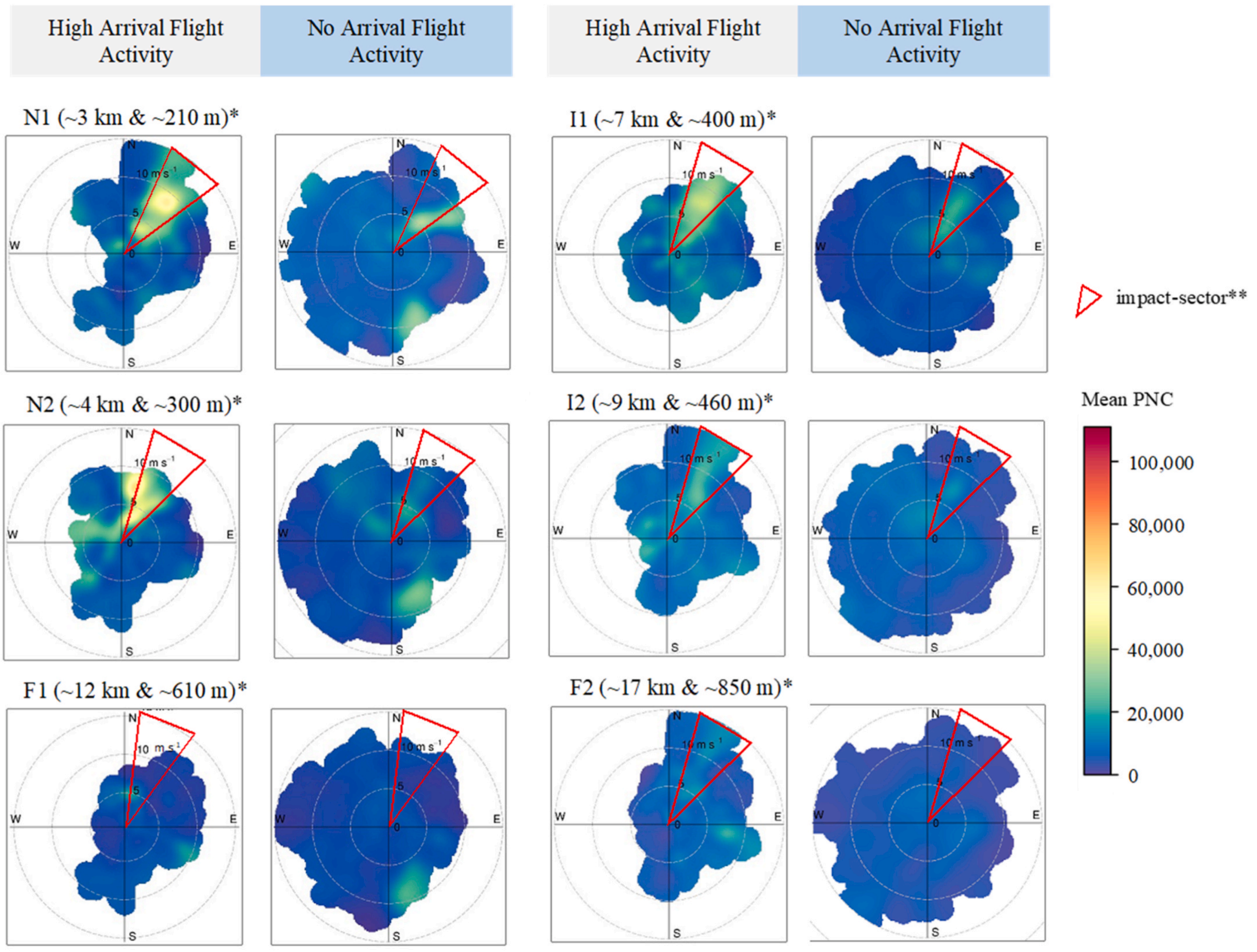
* distance to the airport and average altitudes of arrival aircraft over the site

Fig. 2. Diurnal pattern of PNC under different arrival aircraft activity conditions.

particles/cm^3, respectively, during the hours with arrival aircraft activity. Both the background level PNC and aircraft contribution at I2, F1, and F2 were lowest compared to other sites, with aircraft contributions ranging from 2300 to 5000 particles/cm^3 (Table S1). Across all hours (not restricting the data to hours with 4 L/4 R arrival aircraft activity), the mean predicted arrival aircraft contributions ranged from 7% to 26% with the highest observed at N1 and lowest at F1. Our models also identified generally greater associations with impact sector winds at near-airport sites than sites farthest from the airport, with more pronounced patterns for 95th percentile concentrations (Table 3).

3.6. *Strengths and limitations*

One limitation of this study was the varying surrounding environments at the monitoring sites. Even though we selected sites at appreciable distances from major roads and other identifiable combustion sources, the level of non-aviation UFP contributions was non-zero and varied across sites, including construction projects at N2. However, based on our descriptive analyses, the non-aviation UFP contributions did not preclude us from observing intermittent concentration increases consistent with aviation contributions. In general, one of the strengths of this study was our selection of monitoring sites specifically intended for



* distance to the airport and average altitudes of arrival aircraft over the site

** wind sector that positions monitoring sites downwind of the airport and the arrival flight paths to 4L/4R runways

Fig. 3. Pollution roses displaying the association between wind speed and wind direction and PNC under different arrival aircraft activity conditions on runway 4 L/4 R.

aviation arrival source attribution, as opposed to some prior studies in which post hoc analyses were conducted at sites intended for other purposes. Sites were placed at varying distances from the airport and from the arrival pathway and not proximate to major roadways, as opposed to multiple prior studies with sites very close to airports or directly at the end of runways. While our study aimed to quantify surface and in-flight aviation contributions to community UFP, other studies have addressed total traffic and aviation exposure. A study in communities near Seattle-Tacoma International Airport (Sea-Tac) examined both traffic and aviation contributions to community UFP exposures (Austin et al., 2021). This study at Sea-Tac examined size distributions of PNC to delineate between aviation and traffic UFP contributions and found PNC in the range of 10–20 nm to be more strongly associated with aircraft activity (Austin et al., 2021). A limitation of our study is that we only investigated total PNC and not particle size distributions, given evidence that aircraft UFP emissions have a different size distribution than motor vehicle UFP emissions. Future studies should consider, when possible, the inclusion of particle size distributions to differentiate between aircraft and traffic source contributions.

In addition, given that PNC is strongly associated with wind speed and direction as well as temperature and other meteorological factors, it is more challenging to discern source contributions in a location like Boston where meteorology varies substantially across days. That said, in comparison to airports where wind speed and direction are very consistent across days, our study provides more refined insight regarding the impacts of varying meteorological conditions on arrival aircraft PNC patterns. Lastly, the portable instrument configuration allowed for easy semi-long-term data collection at different sites under various site combinations, which provided insight over a wider geographic area than would have been available with a more limited number of sites.

3.7. Significance of the results

Studies collecting measurements downwind of major airports have often found the airport to be the dominant contributor to UFP, especially when there is a strong prevailing wind (Keuken et al., 2015; Hudda et al., 2014). At monitoring sites along an arrival flight path that is often upwind of the airport, our findings were in agreement with other studies that have shown that other sources including traffic contribute more to ambient UFP in urban areas (Riley, 2016; Hsu et al., 2014). However, our stratified analyses suggest that the additional exposure to UFP from

Table 3
Multivariable regression model results of hourly mean and 95th percentile PNC at multiple monitoring sites, accounting for autocorrelation.

	Mean		95th percentile	
	Exponentiated Regression Coefficients	95% CI	Exponentiated Regression Coefficients	95% CI
		N1		
Intercept	15,100	(9,800, 23,100)	18,300	(12,200, 27,600)
4L4R runway arrival aircraft frequency	1.016	(1.013, 1.020)	1.025	(1.021, 1.029)
All other aircraft activity frequency	1.007	(1.006, 1.009)	1.008	(1.006, 1.01)
Temperature (Celsius)	0.982	(0.969, 0.994)	0.969	(0.958, 0.981)
Relative humidity (%)	0.993	(0.990, 0.997)	0.997	(0.994, 1.000)
Wind speed (m/s)	0.934	(0.910, 0.959)	0.955	(0.929, 0.983)
Mixing height (m)	1.000	(1.000, 1.000)	1.000	(1.000, 1.000)
Atmospheric pressure (millibar)	0.986	(0.976, 0.997)	1.006	(0.995, 1.016)
Precipitation (mm/hour)	0.966	(0.934, 1.000)	0.971	(0.934, 1.009)
Weekday vs. weekend	1.062	(0.889, 1.267)	1.054	(0.903, 1.230)
Impact sector (yes)	1.119	(0.855, 1.466)	1.356	(1.003, 1.835)
Wind speed (m/s) *Impact sector (yes)	1.114	(1.056, 1.176)	1.081	(1.018, 1.148)
		I1		
Intercept	24,900	(17,600, 35,300)	30,900	(21,600, 44,100)
4L4R runway arrival aircraft frequency	1.015	(1.012, 1.018)	1.020	(1.016, 1.023)
All other aircraft activity frequency	1.010	(1.009, 1.012)	1.012	(1.011, 1.014)
Temperature (Celsius)	0.964	(0.954, 0.974)	0.954	(0.945, 0.964)
Relative humidity (%)	0.995	(0.993, 0.998)	0.997	(0.995, 1.000)
Wind speed (m/s)	0.913	(0.893, 0.933)	0.919	(0.897, 0.941)
Mixing height (m)	1.000	(1.000, 1.000)	1.000	(1.000, 1.000)
Atmospheric pressure (millibar)	1.003	(0.994, 1.012)	1.006	(0.997, 1.015)
Precipitation (mm/hour)	0.991	(0.963, 1.02)	0.995	(0.963, 1.029)
Weekday vs. weekend	0.904	(0.796, 1.025)	0.906	(0.804, 1.020)
Impact sector (yes)	1.244	(1.021, 1.516)	1.213	(0.970, 1.519)
Wind speed (m/s) *Impact sector (yes)	1.038	(0.997, 1.079)	1.064	(1.018, 1.112)
		F1		
Intercept	20,100	(13,100, 30,800)	24,500	(15,200, 39,400)
4L4R runway arrival aircraft frequency	1.010	(1.007, 1.013)	1.012	(1.008, 1.016)
All other aircraft activity frequency	1.004	(1.003, 1.005)	1.006	(1.004, 1.007)
Temperature (Celsius)	0.982	(0.970, 0.994)	0.976	(0.963, 0.989)
Relative humidity (%)	0.990	(0.987, 0.993)	0.990	(0.987, 0.993)
Wind speed (m/s)	0.904	(0.884, 0.925)	0.913	(0.888, 0.939)
Mixing height (m)	1.000	(1.000, 1.000)	1.000	(1.000, 1.000)
Atmospheric pressure (millibar)	0.997	(0.986, 1.007)	0.999	(0.988, 1.011)
Precipitation (mm/hour)	1.024	(0.979, 1.071)	1.022	(0.965, 1.081)
Weekday vs. weekend	1.094	(0.946, 1.266)	1.177	(1.019, 1.36)
Impact sector (yes)	1.079	(0.861, 1.354)	0.986	(0.741, 1.312)
Wind speed (m/s) *Impact sector (yes)	1.023	(0.964, 1.086)	1.072	(0.996, 1.155)

aviation is still notable, especially in communities that are close to aviation sources. Given that we quantified source contributions even at monitors 17 km from the airport, the number of individuals exposed to arrival aircraft UFP could be substantial in urban areas surrounding major airports. Our study also clearly indicated the impact of aircraft arrivals on ambient PNC, while a number of other studies only displayed a noticeable impact from take-offs but not arrivals, in part because of their site selection (Zhu et al., 2011; Hsu et al., 2013).

In addition, our study reinforces that using mean or median PNC over a longer averaging time, as is common in the literature (Keuken et al., 2015; Hudda et al., 2016a), may not capture the large but intermittent contributions from aircraft. To our knowledge, our study is the first to focus explicitly on the sensitivity of aircraft source attribution results to choices about distributional characterization (mean vs. 95th percentile) of PNC data. There are a limited number of studies that included peaks or upper percentile measurements in their analyses; however, for those that did, it was either using a more descriptive approach or not the main focus of the study (Zhu et al., 2011; Hsu et al., 2012; Lammers et al., 2020). Whether large but intermittent contributions to ambient PNC with a more modest contribution to long-term average concentrations is a potential public health concern is beyond the scope of this study, although there is evidence that short-term exposures to UFP can influence heart rate variability (Zhang et al., 2022) as well as respiratory outcomes (Li et al., 2019). Our findings can be useful especially when examining the combined UFP exposures from multiple sources. UFP composition varies by source, which may be associated with specific health outcomes (Hime et al., 2018). Broadly, our work reinforces that aviation source attribution studies are strengthened by considering higher-resolution monitoring data and upper percentile contributions.

Author statement

Chloe Chung: Methodology, Software, Investigation, Formal Analysis, Data Curation, Validation, Visualization, Writing – Original Draft. **Kevin Lane**: Writing – Review and Editing, Supervision, Project Administration, Funding Acquisition. **Flannery Black-Ingersoll**:

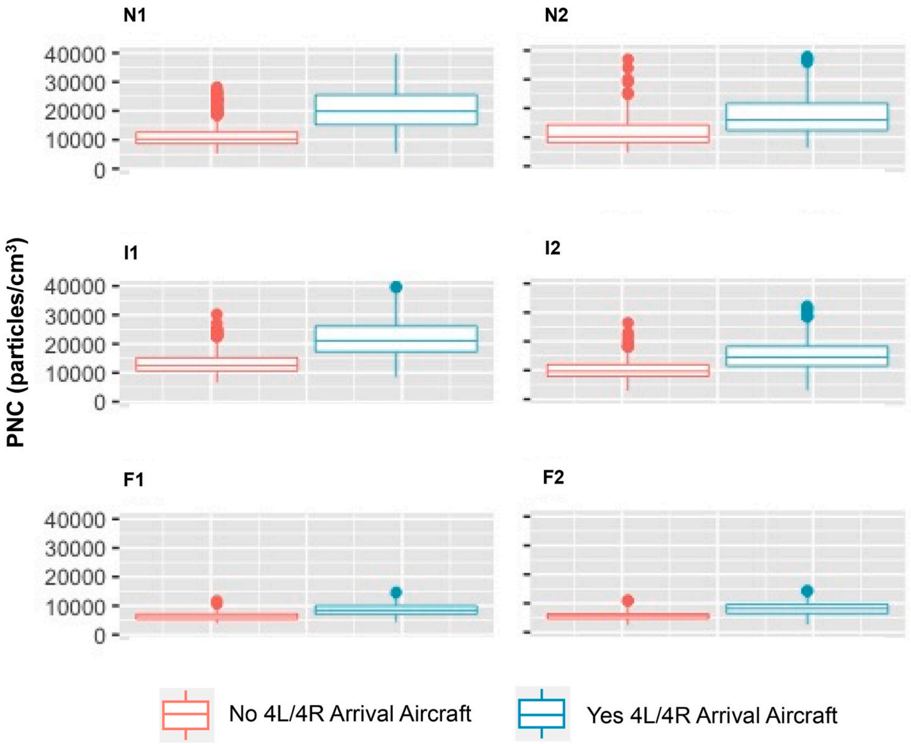


Fig. 4. Boxplots displaying 4 L/4 R arrival aircraft contributions to estimated ambient PNC (95th percentile, 1-h average) using multivariable regression model predictions with actual arrival activity and assuming no arrival aircraft restricting to time-periods with non-zero 4 L/4 R arrival aircraft activity.

Investigation, Writing – Review and Editing. **Eric Kolaczyk**: Methodology, Supervision, Writing – Review and Editing. **Claire Schollaert**: Investigation, Data Curation, Validation, Writing – Review and Editing. **Sijia Li**: Software, Formal Analysis. **Matthew Simon**: Software, Formal Analysis, Writing – Review and Editing. **Jonathan Levy:** Conceptualization, Writing, Supervision, Project Administration, Funding Acquisition.

Declaration of competing interest

The authors declare no potential competing interests, provided that is consistent with other articles in the journal with extramural grant support. The authors can modify this form in the system if necessary.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envres.2023.115584.

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