



Fetal growth, stillbirth, infant mortality and other birth outcomes near UK municipal waste incinerators; retrospective population based cohort and case-control study



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ABSTRACT

Background: Some studies have reported associations between municipal waste incinerator (MWI) exposures and adverse birth outcomes but there are few studies of modern MWIs operating to current European Union (EU) Industrial Emissions Directive standards.

Methods: Associations between modelled ground-level particulate matter $\leq 10 \mu\text{m}$ in diameter (PM_{10}) from MWI emissions (as a proxy for MWI emissions) within 10 km of each MWI, and selected birth and infant mortality outcomes were examined for all 22 MWIs operating in Great Britain 2003–10. We also investigated associations with proximity of residence to a MWI. Outcomes used were term birth weight, small for gestational age (SGA) at term, stillbirth, neonatal, post-neonatal and infant mortality, multiple births, sex ratio and preterm delivery sourced from national registration data from the Office for National Statistics. Analyses were adjusted for relevant confounders including year of birth, sex, season of birth, maternal age, deprivation, ethnicity and area characteristics and random effect terms were included in the models to allow for differences in baseline rates between areas and in incinerator feedstock.

Results: Analyses included 1,025,064 births and 18,694 infant deaths. There was no excess risk in relation to any of the outcomes investigated during pregnancy or early life of either mean modelled MWI PM_{10} or proximity to an MWI.

Conclusions: We found no evidence that exposure to PM_{10} from, or living near to, an MWI operating to current

Abbreviations: MWI, municipal waste incinerator; EU, European Union; PM_{10} , particulate matter $\leq 10 \mu\text{m}$ in diameter; SGA, small for gestational age; SO_2 , sulphur dioxide; NO_x , nitrogen oxides; HCl, hydrogen chloride; CO, carbon monoxide; VOC, volatile organic compound; POPs, persistent organic pollutants; PCDD/Fs, polychlorinated dibenzo-*p*-dioxins/furans; PCBs, polychlorinated biphenyls; PAHs, polycyclic aromatic hydrocarbons; EU-WID, European Union Waste Incineration Directive; COA, Census Output Area; MSA, Middle Layer Super Output Area; GAM, generalised additive model; OR, odds ratio; ONS, Office for National Statistics; EA, Environment Agency; SEPA, Scottish Environment Protection Agency; NRW, Natural Resources Wales; NHS, National Health Service; NHS NN4B, Numbers for Babies; NWS, NHS Wales' Informatics Service; HSW, Health Solutions Wales; NCCHD, National Child Community Health Dataset; ISD, Information Services Division Scotland

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EU standards was associated with harm for any of the outcomes investigated. Results should be generalisable to other MWIs operating to similar standards.

1. Introduction

Incineration of waste by Municipal Waste Incinerators (MWIs) has been increasing in the UK; since 2000 the tonnage of waste incinerated has more than tripled with approximately 35% of all local authority waste in England now being incinerated (Department for Environment, 2016). MWIs burn waste collected by local authorities that is not classified as hazardous or toxic and is generated mainly by households and commercial establishments (Committee on Health Effects of Waste Incineration, 2000). Air-borne emissions from MWIs depend on the composition of the feedstock incinerated but potentially include particulate matter, sulphur dioxide (SO₂), nitrogen oxides (NO_x), hydrogen

chloride (HCl), carbon monoxide (CO), volatile organic compounds (VOCs), persistent organic pollutants (POPs) such as polychlorinated dibenzo-*p*-dioxins/furans (PCDD/Fs), polychlorinated biphenyls (PCBs), polycyclic aromatic hydrocarbons (PAHs), and heavy metals (Douglas et al., 2017).

MWI emission limit values are legislated by the European Union Waste Incineration Directive (EU-WID) (2000/76/EC) (Council E, 2000), which came into operation for new and existing MWIs on 28 December 2002 and 2005, respectively, and was subsequently incorporated within the current Industrial Emissions Directive (IED) (2010/75/EU) (European Union, 2010). Hazardous and medical wastes are handled by other types of incinerators and are not included in this

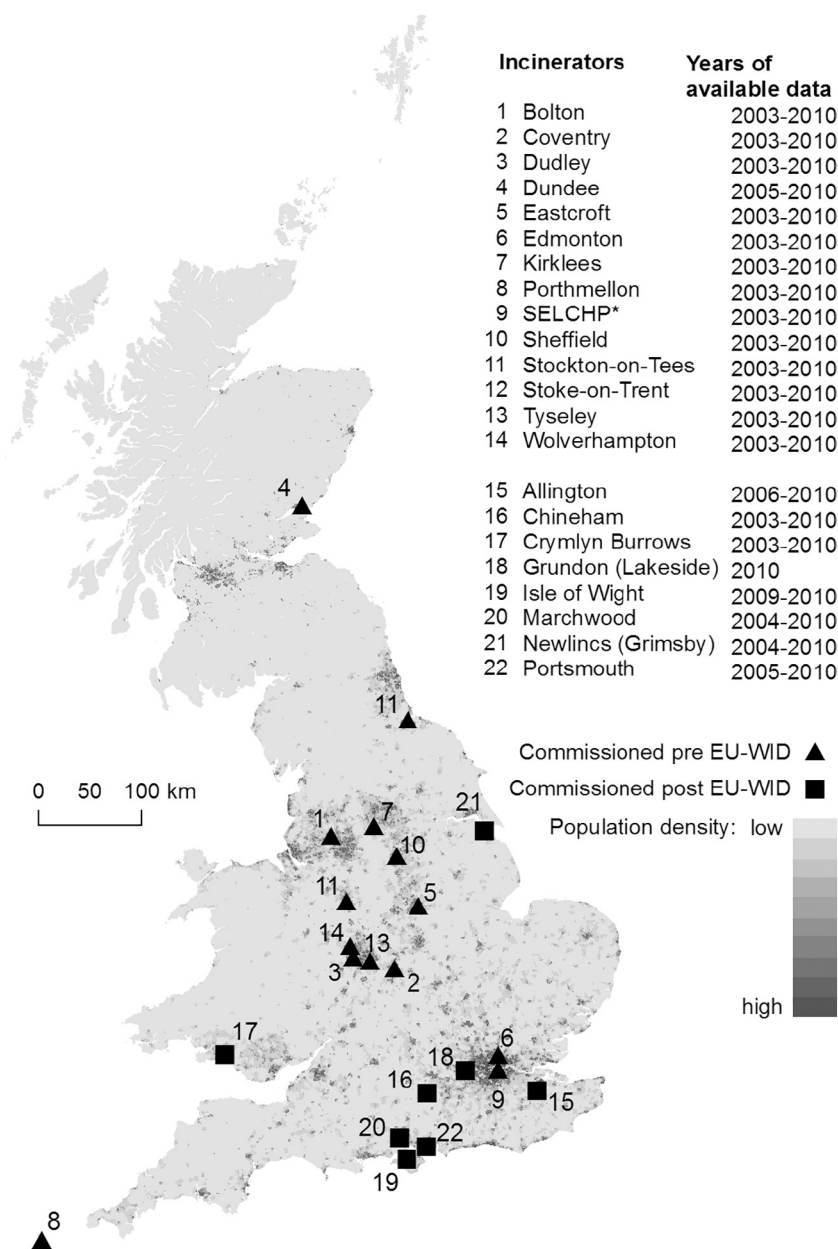


Fig. 1. Location of all municipal waste incinerators (MWIs) operating to the European Union Waste Incineration Directive (EU-WID) in Great Britain 2003–2010. The table denotes the years of data available.

*SELCHP is abbreviated for South East London Combined Heat and Power

study.

Although some studies have reported associations between MWI exposures and increased risks of e.g. preterm delivery (Candela et al., 2013), miscarriages (Candela et al., 2015) and congenital anomalies (Dummer et al., 2003; Cordier et al., 2010), reviews on health effects from MWIs (Health Protection Agency, 2009; Crowley et al., 2003; Maynard et al., 2010; Ashworth et al., 2014) have been inconclusive, and cite the need for improved studies with better exposure assessment. More generally, maternal exposure to ambient PM₁₀, mostly from road traffic sources, during pregnancy has been linked to fetal growth restriction (Dadvand et al., 2013; Pearce et al., 2012). The aim of this study was to investigate at the national scale possible health effects associated with (i) MWI emissions of particulate matter ≤ 10 μm in diameter (PM₁₀) as a proxy for MWI emissions more generally, and (ii) living near a MWI, in relation to fetal growth, stillbirth, infant mortality and other birth outcomes.

2. Methods

2.1. Municipal waste incinerators (MWIs) included

All MWIs in operation between 2003 and 2010 across Great Britain were eligible for inclusion in the study. One MWI in the Isle of Man (Richmond Hill) was excluded due to a lack of health and emissions data, while three other incinerators were excluded as they were not solely MWIs (Fawley, Hampshire; Ellesmere Port, Cheshire; Peak Load Boiler, Shetland) (Douglas et al., 2017). This left 22 MWI for inclusion in the study with the study area defined as a 10 km radius around each MWI. We modelled concentrations of PM₁₀ arising from MWI emissions (Douglas et al., 2017; Ashworth et al., 2013) as a proxy for MWI

emissions more generally (Douglas et al., 2017). Fig. 1 shows the location, name, and years of data availability for each MWI in the study.

2.2. Outcomes

Birth and mortality outcomes in the study area were obtained from routine administrative databases, 2003–10. Outcomes for investigation were selected by consideration of the evidence base and routine data availability e.g. there is no national data collection for spontaneous abortion so we are unable to study this. Congenital anomalies are considered elsewhere. Gestational age information, required for the fetal growth, and preterm birth outcomes, was only available from 2006 as was individual level ethnicity information.

2.2.1. Birth outcomes (2003–2010)

- Multiple births: ≥ 2 births from a single pregnancy.
- Sex ratio (all births): ratio of female births to male births.

2.2.2. Fetal growth and preterm birth (2006–2010)

- Preterm delivery (< 37 weeks gestation) among live singleton births.
- Birth weight among live, singleton term births ≥ 37 weeks to ≤ 44 weeks gestation.
- Small for gestational age (SGA) among live, singleton births, defined as birth weight below the sex and ethnicity specific 10th centile for gestational age for births ≥ 37 weeks gestation. Smoothed birth weight for gestational week centile curves were calculated by sex and ethnicity (Asian, Black, White, Other), using a method for

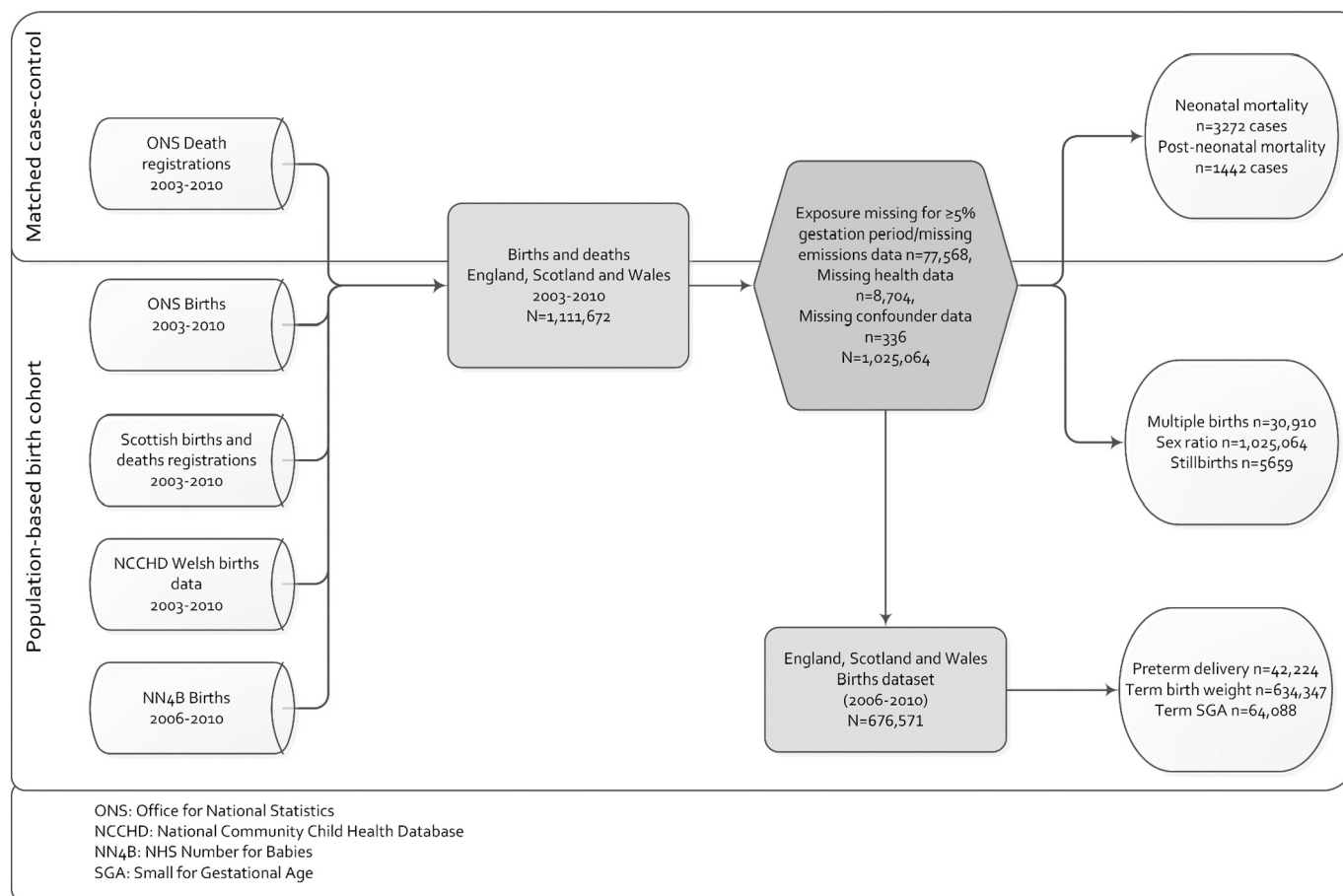


Fig. 2. Datasets and exclusions for each analysis and outcome in the study.

drawing centile curves, consisting of a generalised additive model for location, scale and shape as described by Cole and others (Rigby and Stasinopoulos, 2005; Cole and Green, 1992).

2.2.3. Mortality outcomes (2003–2010)

- Stillbirths: Births at ≥ 24 completed weeks gestation showing no signs of life
- Neonatal mortality: deaths among singleton births occurring between birth and ≤ 28 days after birth.
- Post-neonatal mortality: deaths among singleton births occurring between 29 and ≤ 365 days after birth.

2.3. Data

Outcome data were obtained from the Office for National Statistics (ONS) including the National Mortality register for England and Wales, the Births and Stillbirths register for England and Wales and the NHS Number for Babies dataset (NN4B); the National Child Community Health Dataset (NCCHD) from the NHS Wales Informatics Service (NWIS)/Health Solutions Wales (HSW); and from the Information Services Division (ISD) in Scotland. How these datasets were combined for each outcome and analysis is shown in Fig. 2.

Cases were taken from the combined outcome data on all births or deaths in Great Britain between 2003 and 2010 and were included if the postcode centroid (representing on average 12 households) of the mother's usual residence, provided at the time of birth registration, was within 10 km of an open MWI and the estimated date of conception (based on gestation weeks) and outcome were also within the study period (2003–2010).

2.4. MWI PM_{10} exposure assessment

ADMS-Urban (CERC, 2017), extensively validated Gaussian-based atmospheric dispersion model software, was used to estimate daily concentrations of ground-level PM_{10} resulting from MWI emissions as a proxy for MWI emissions more generally (Candela et al., 2013; Cordioli et al., 2013). Methods are as previously described (Ashworth et al., 2013). Input data were obtained from the relevant regulatory agencies in England (Environment Agency; EA), Wales (Natural Resources Wales, NRW) and Scotland (Scottish Environment Protection Agency, SEPA). They comprised within-flue particulate matter/total dust emissions monitored continuously as part of the EU-WID regulations, reported as daily mean concentrations ($\mu\text{g}/\text{m}^3$), and MWI operating characteristics. PM_{10} was estimated rather than total suspended particles as size fraction studies have found that particulate emissions from incinerators have diameters $< 10 \mu\text{m}$ (Buonanno et al., 2009). Results of the modelling for the 22 MWIs are published (Douglas et al., 2017), although since then new flue characteristics data have become available for Sheffield MWI, and thus the Sheffield MWI data have been remodeled as described in Supplement A. A daily estimate of PM_{10} was obtained for each postcode centroid within the study area.

For the birth outcomes and stillbirths the mean concentrations of PM_{10} during pregnancy were estimated (see Supplement B for further details). For neonatal and post-neonatal mortality outcomes, post-birth exposure to MWI emissions was also estimated. For the post-birth mean PM_{10} exposure to be similar for both cases and controls, we used a matched case-control design for these analyses, with controls (four per case) frequency matched by birth date, sex and the postcode of the mother's residence being within 10 km of the same MWI as the cases. Exposure was calculated from the date of birth (considered an exposed day) to date of death of the case.

2.5. Confounders

Potential confounders were selected a priori for each analysis – see

Supplement B - Supplemental Tables B.1–B.3 for details. Individual-level confounders included were sex, maternal age (continuous), season of birth (winter as reference), and, from 2006, gestational age (both linear and quadratic terms) and ethnicity of the baby as reported by the mother (White, Asian, Black or Other). Area-level confounders, derived from the 2011 UK Census, were Carstairs index categorised into fifths (Carstairs and Morris, 1990) as a measure of socio-economic status, calculated for census output areas (COAs); population density (population per square km for each COA); and ethnicity defined as the percentage non-white ethnicity among the female population of reproductive age (15–49 years) in each Middle Layer Super Output Area (MSOA, comprising contiguous COAs with an average population size of 7500). To adjust for other potential PM_{10} sources, models included local road density data from 2014, defined as the continuous total road length within 250 m of each residential postcode; road length within 10 km of each MWI; and industrial emission sources defined as the number of industries in 2003–10 within 10 km of each MWI, based on data included in the Environmental Permitting Regulations – Industrial sites 2010 (Supplemental Table B.3).

Sensitivity analyses additionally adjusted for (i) COA-level tobacco expenditure as a smoking proxy (England and Wales only because of data availability); and (ii) birth registration type (within marriage (reference category), joint-same address, joint-different address, sole registered) as a proxy for individual level socio-economic status (England only) (Graham et al., 2007).

2.6. Data and statistical analysis

There were a total of 1,111,672 births from 2003 to 2010; 77,568 (7%) were excluded due to missing emissions data or where $\geq 5\%$ of the exposure period had invalid values or the dispersion model was unable to estimate a concentration (Douglas et al., 2017; Ashworth et al., 2013). A further 8704 (0.78%) records were excluded due to missing health data (e.g. birth weight, gestational age, ethnicity) and 336 (0.03%) due to missing area-level confounder data (Fig. 2). This left a total of 1,025,064 births available for analysis from 2003 to 2010, including 30,910 (3.02%) multiple births, 5659 (0.55%) stillbirths, 3260 neonatal and 1442 post-neonatal deaths. For the period 2006 to 2010, there were 676,571 live singleton births with gestational age information. For 2006 to 2010 there were 634,347 (93.76%) term births and 42,224 (6.24%) pre-term births, of the term births 64,088 (10.01%) were SGA (Supplemental Tables B.4 and B.5). For the population-based cohort analysis (2003–2010), overall 51% of births were males, 25% of the areas had over 50% non-white ethnicity and 50% of all births were in the most deprived areas by Carstairs quintile. For the matched case-control analysis a slightly higher proportion were male (53%), 28% of the areas had over 50% non-white ethnicity and 54% of all births were in the most deprived Carstairs quintile.

As the mean PM_{10} exposures distributions were highly skewed, they were log transformed for analysis. Proximity to the nearest MWI was calculated as a continuous measure of linear distance (km) based on postcode centroid of maternal residence at birth. For the population based cohort analyses we also conducted sensitivity analyses with exposures analysed as quintiles.

Associations between mean ground-level PM_{10} concentrations and each outcome, adjusted for relevant potential confounders, were examined using multiple logistic regression (multiple births, sex ratio, preterm deliveries, term SGA and stillbirths) and multiple linear regression (birth weight). These regression models included a random intercept for each MWI to allow for differences in baseline rates between areas, and a random slope to account for unobserved heterogeneity. Conditional logistic regression was used for neonatal and post-neonatal mortality analyses. Since PM concentrations may vary seasonally (due to seasonal patterns in weather and wind direction), we checked for seasonal patterns using a generalised additive model (GAM), which did not show any evidence of seasonal effects (not

shown). All analyses were conducted in Stata version 13.

3. Results

3.1. Birth and fetal growth outcomes

The mean modelled PM₁₀ concentrations during pregnancy for all live births were 2.51 × 10⁻³ µg/m [IQR 0.47–2.86] (Supplemental Table B.6). For the birth, fetal growth and preterm birth outcomes we found no associations in the adjusted models between term birth weight (co-efficient 0.12 g [95%CI - 1.51, 1.75]), term SGA (Odds Ratio 0.99 [0.98, 1.00]), sex ratio (OR 1.00 [1.00–1.00]), multiple births (OR 0.99 [0.99, 1.00]) or preterm delivery (OR 0.99 [0.97, 1.01]) per doubling of PM₁₀ from MWIs during pregnancy (Table 1).

There were no associations between the same outcomes and proximity to an incinerator, in adjusted models; the coefficient for term birth weight was -0.56 g/km [95% CI -1.80, 0.68].

3.2. Mortality outcomes

For the mortality outcomes we found no associations in the adjusted models, for stillbirths (OR 0.98 [0.97, 1.00]), neonatal (OR 1.00 [0.96, 1.02]) and post-neonatal mortality (OR 1.02 [0.96, 1.07]) per doubling of PM₁₀ from MWIs (Table 2). Findings were similar when analyses were restricted to 2006–10, years when gestational age information was available (Supplement Table B.11). There was also no association between post-neonatal mortality and exposure after birth, in the adjusted models. Proximity to nearest MWI was not associated with mortality.

Sensitivity analyses by quintiles of PM₁₀ concentrations (Supplemental Tables B.12 and B.13) or with additional adjustment for tobacco sales and birth registration (Supplement Tables B.14 and B.15) did not alter the findings.

4. Discussion

This is, to our knowledge, the largest study to date to examine potential impacts of modern MWIs operating to current EU regulations on a range of fetal outcomes, preterm delivery and infant mortality.

Table 1

Risk of mortality outcomes associated with a doubling in ground-level PM₁₀ concentrations and proximity from residential address to an incinerator^a.

| | n cases/N total | Risk per doubling of PM ₁₀ ^b | | Proximity to MWI (continuous) per km | |
|--|--------------------------|--|--------------|--------------------------------------|--------------|
| | | OR | 95%CI | OR | 95%CI |
| Multiple births | | | | | |
| Unadjusted | 30,910/1,025,064 | 1.00 | 1.00, 1.00 | 0.98 | 0.97, 0.98 |
| Adjusted | | 0.99 | 0.99, 1.00 | 1.00 | 0.99, 1.00 |
| Sex ratio | | | | | |
| Unadjusted | 525,272(males)/1,025,064 | 1.00 | 1.00, 1.00 | 1.00 | 1.00, 1.00 |
| Adjusted | | 1.00 | 1.00, 1.00 | 1.00 | 1.00, 1.00 |
| Preterm delivery | | | | | |
| Unadjusted | 42,224/676,571 | 1.00 | 0.99, 1.00 | 1.01 | 1.00, 1.01 |
| Adjusted | | 0.99 | 0.97, 1.01 | 1.00 | 0.99, 1.00 |
| Term SGA | | | | | |
| Unadjusted | 64,088/634,347 | 1.00 | 0.99, 1.00 | 1.01 | 1.01, 1.02 |
| Adjusted | | 0.99 | 0.98, 1.00 | 1.00 | 0.99, 1.01 |
| Term birth weight | | | | | |
| Mean difference in term birth weight (g) | | Coefficient | 95%CI | Coefficient | 95%CI |
| Unadjusted | 634,347 | -5.43 | -5.83, -5.04 | -5.52 | -6.01, -5.04 |
| Adjusted | | 0.12 | -1.51, 1.75 | -0.56 | -1.80, 0.68 |

^a All analyses adjusted for year of birth, maternal age, area-level deprivation, population density, road density, incinerator road density, other potential sources of emissions, and included a random effect for incinerator area and random slope for the exposure. Analyses additionally adjusted for one or more of sex, season of birth, ethnicity (area or individual level), gestational age depending on outcome as detailed in Supplement Table B.1.

^b The odds ratios from a log transformed exposure do not represent a risk per increase in PM₁₀ unit (µg/m³) on a linear scale so to aid interpretation we present the risk associated with a doubling of the ground-level PM₁₀ concentrations, for example an odds ratio of 1.05 would indicate a 5% higher risk of an outcome each time the PM₁₀ is doubled.

Table 2

Risk of mortality outcomes associated with a doubling in ground-level PM₁₀ concentrations and proximity from residential address to an incinerator^a.

| | n cases/N total | Risk per doubling of PM ₁₀ ^b | | Proximity to MWI (continuous) per km | |
|--|-----------------|--|------------|--------------------------------------|------------|
| | | OR | 95%CI | OR | 95%CI |
| Stillbirths | | | | | |
| 2003–2010 | | | | | |
| Unadjusted | 5659/ | 1.01 | 1.00, 1.02 | 1.02 | 1.01, 1.03 |
| Adjusted | 1,025,064 | 0.99 | 0.97, 1.00 | 1.00 | 0.99, 1.02 |
| Neonatal mortality (pregnancy exposure)^c | | | | | |
| 2003–2010 | | | | | |
| Unadjusted | 3260/12,944 | 1.03 | 1.00, 1.06 | 1.03 | 1.02, 1.05 |
| Adjusted | | 0.99 | 0.96, 1.02 | 1.01 | 1.00, 1.03 |
| Post-neonatal mortality (pregnancy exposure) | | | | | |
| 2003–2010 | | | | | |
| Unadjusted | 1442/5750 | 1.10 | 1.04, 1.16 | 1.03 | 1.01–1.05 |
| Adjusted | | 1.02 | 0.96, 1.07 | 0.99 | 0.97, 1.02 |
| Post-neonatal mortality (birth to death of case exposure) | | | | | |
| 2003–2010 | | | | | |
| Unadjusted | 1442/5750 | 1.04 | 1.01, 1.08 | - | - |
| Adjusted | | 1.01 | 0.98, 1.04 | - | - |

^a Stillbirth analyses are adjusted for year of birth, sex, season of birth, maternal age, area-level deprivation, area-level ethnicity, population density, road density, incinerator road density, other potential sources of emissions, random effect for incinerator area and random slope for the exposure. Infant mortality outcome analyses are case-control analyses adjusted for sex, maternal age, area-level deprivation, area-level ethnicity, population density, road density.

^b The odds ratios from a log transformed exposure do not represent a risk per increase in PM₁₀ unit (µg/m³) on a linear scale so to aid interpretation we present the risk associated with a doubling of the ground-level PM₁₀ concentrations, for example an odds ratio of 1.05 would indicate a 5% higher risk of an outcome each time the PM₁₀ is doubled.

^c Pregnancy exposure only is presented as babies are likely very sick and considered unlikely to leave hospital before death, therefore only the pregnancy window is relevant as an exposure.

Estimated ground-level PM₁₀ concentrations from MWI emissions, as a proxy for MWI emissions more generally (Douglas et al., 2017), were not associated with increased risk of adverse birth, fetal growth or mortality outcomes. Living near an incinerator was also not associated with increased risks to infant health.

We assumed that the predominant pathway of exposure to incinerator emissions would be through air. We used estimated mean ground-level concentrations of PM₁₀ as our main exposure measure. Ambient PM₁₀ concentrations have previously been reported to be associated with adverse birth outcomes (Dadvand et al., 2013; Lamichhane et al., 2015), but ambient concentrations of PM₁₀ are approximately 3–5 orders of magnitude greater than our estimates for the contribution from MWIs (Douglas et al., 2017), so the results are not directly comparable. We also examined distance from incinerator as has been done in several other studies (Obi-Osius et al., 2004; Tango et al., 2004; Lloyd et al., 1979; Williams et al., 1992). Although distance is a relatively crude (but readily obtained) measure, it may capture exposures not reflected in the emissions modelling (e.g. transport of waste to the MWI) as well as non-airborne exposure pathways.

Some studies have, like ours, used modelled PM₁₀ (Candela et al., 2013; Candela et al., 2015; Santoro et al., 2016) or modelled dioxin concentrations (Vinceti et al., 2008; Lin et al., 2006). The most comparable recent studies to ours were a multi-site (Candela et al., 2013; Candela et al., 2015) and a single site MWI study (Santoro et al., 2016), both from Italy, which used modelled PM₁₀ in relation to MWIs operating to the EU-WID. The Candela et al. (2013, 2015) study, where the outcomes chosen and the exposure modelling methods (ADMS-Urban) were comparable to this study, was generally consistent with our findings of a lack of any associations with sex ratio, multiple births, and SGA. Where this study was not consistent with ours was for preterm births – Candela et al. (2013), covering eight Italian incinerators, found an increased odds ratio of 1.30 (95% confidence interval [1.08–1.57]) comparing highest vs. lowest fifth of PM₁₀ concentrations. They also found an increased risk of spontaneous abortions (Candela et al., 2015) but that measure of fetal mortality was not directly comparable with our mortality outcomes. Candela et al. used a smaller buffer around each incinerator than our study, 4 km vs 10 km, which may have led to fewer outcomes with a lower estimated exposure being included in their study as compared to ours. However, overall they estimated a mean per-person exposure level of 0.57 ng/m³ which was lower but still of the same order of magnitude as our mean finding per pregnancy for the birth outcomes of 2.51 ng/m³. The Santoro et al. (2016) study also found an increased risk of preterm births however this was a study of only one incinerator in a highly industrialized area and included data from the incinerator from before the introduction of the EU-WID regulations. The lack of an association in our study of incinerator emissions or proximity with sex ratio (Tango et al., 2004; Lloyd et al., 1979; Lin et al., 2006; Rydhstroem, 1998), birth weight (Candela et al., 2013; Tango et al., 2004; Santoro et al., 2016; Lin et al., 2006), SGA (Candela et al., 2013; Santoro et al., 2016), stillbirths, neonatal and post-neonatal mortality (Dummer et al., 2003; Tango et al., 2004; Vinceti et al., 2008) is consistent with other studies.

Evidence on multiple births has been inconsistent: while two studies, Lloyd et al. (1979) in Scotland and Obi-Osius et al. (2004) in Germany, found increased risks of twinning, the Rydhstroem (1998) study in Sweden found decreased risks of multiple births. However these studies were of pre-EU-WID incinerators and used either distance from the incinerator as a proxy for exposure (Obi-Osius et al., 2004; Lloyd et al., 1979) or compared twinning rates for the periods before/after an incinerator opening (Rydhstroem, 1998), which may have been confounded by temporal trends in twinning rates. The more recent Candela et al. (2013) with comparable exposure modelling to ours also found no association between MWI emissions and multiple births.

4.1. Strengths and limitations

This is a large study, using comprehensive national birth and death registration data and included all MWIs nationally, avoiding selection bias. Over one million births were included in the analyses providing sufficient statistical power to be able to detect small associations. We used two methods to assess potential exposure to incinerator emissions: modelled PM₁₀ concentrations and distance from incinerator. We made the assumption that modelled PM₁₀ dispersion is a reasonable proxy of spatial exposure patterns to other components of MWI emissions (Douglas et al., 2017). This assumption was investigated in the following ways.

- For NO₂ and SO₂: We conducted dispersion modelling for NO₂ and SO₂ using in-stack measurements for a representative incinerator (details in Supplement C). Modelled NO₂ and SO₂ correlated well with modelled concentrations of PM₁₀ with Spearman's correlation values of $r = 0.88$ – 0.99 (Supplemental Table C.3).
- For heavy metals: We previously examined ratios in air pollutant metal concentrations measured at ambient monitoring stations near six incinerators (Font et al., 2015). We found no evidence that MWI emissions contributed to ambient air pollution metal concentrations near four MWIs and minimal contributions from the remaining two. (Dispersion modelling could not be used for heavy metals - or for PCDD/Fs, PAHs or PCBs emissions - as these are monitored for regulatory purposes using intermittent spot measurements, unlike particulates for which continuous measurements are taken.)

We only had information on residential address at time of birth. We did not have information on change in residence during the pregnancy, estimated at around 16% in the UK (Tunstall et al., 2010). Maternal mobility is more likely in younger mothers living in more deprived areas (Hodgson et al., 2009) which may have introduced some differential exposure misclassification. Gestational age at birth, a major risk factor in mortality outcomes, was not adjusted for in the mortality analysis as gestational age information was only available for 5 of the 8 years of the analysis. The assumption that all births prior to 2006, with no gestational age information, were term births is a potential source of exposure misclassification, particularly for outcomes likely not to go to full term e.g. stillbirths. However, sensitivity analyses for stillbirths and infant mortality restricted to 2006–10, the years when gestational age was available, were consistent with those for the whole study period. There was no evidence that emissions levels changed systematically between the earlier study years and following the implementation of the EU-WID at the end of 2005 (Douglas et al., 2017), but we did not have information on changes in feedstock for each MWI over that time period.

We controlled for major confounders including age, ethnicity and deprivation. We did not have individual-level information on maternal smoking and deprivation, but adjustments at the small-area level for tobacco sales and at individual-level for birth registration type (a proxy for socio-economic status as it is related to qualifications and housing tenure (Graham et al., 2007)) did not materially change the results.

The majority of exclusions were due to gaps in the emissions data. This did result in a study population that included more areas with higher percentage of ethnic minorities and that were more deprived (Supplement Table B.18). To explore the impact of this, we relaxed the criteria for missing emissions data from 5% to 15%, and reran the analyses (Supplement Tables B.16 and B.17) but results were similar to those reported here.

MWIs are not randomly located across the country and are often built in heavily industrialized areas with other sources of pollution (Font et al., 2015). The model adjusted for a count of relevant industries and for road density, which has been shown to perform well as a representation of spatial variation in road traffic air pollution (Rose et al., 2009). To account for remaining spatial variability not explained by the

covariates, we included a random effect for incinerator MWI area in the statistical models. We also included a random slope term in the statistical models to allow for heterogeneity in the exposure-response relationship, which should allow for differences in composition of waste incinerated at each MWI for which information is not available. Despite these efforts, we cannot exclude the possibility of residual confounding that may have affected our estimates.

5. Conclusions

This large national study found no evidence for increased risk of a range of birth outcomes, including birth weight, preterm delivery and infant mortality, in relation to either MWI emissions or living near an MWI operating to the current EU waste incinerator regulations in Great Britain. The study should be generalisable to other MWIs operating to similar regulations and with similar waste streams.

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Data

Births and deaths data were from the Office for National Statistics (ONS) National Mortality, Births and Stillbirth registers for England and Wales and the National Health Service (NHS) Numbers for Babies (NN4B). Welsh births data were from the National Child Community Health Dataset (NCCHD) from the NHS Wales' Informatics Service (NWIS)/ Health Solutions Wales (HSW). Scottish births and deaths were from the Information Services Division (ISD) Scotland.

Incinerator emissions data came from the Environment Agency (EA), Scottish Environment Protection Agency (SEPA), and Natural Resources Wales (NRW).

Data on industrial sites came from the Environment Agency Environmental Permitting Regulations – Industrial sites (England), Natural Resources Wales - Environmental Permitting Regulations – Industrial sites and the Scottish Pollutant Release Inventory.

2011 Census aggregate data came from the Office for National Statistics (for England and Wales) and the National Records of Scotland (2016): UK Data Service (Edition: June 2016).

Road length data came from Meridian 2014 road lengths. Ordnance Survey data © Crown copyright and database right 2014.

CACI tobacco expenditure data is © Copyright 1996-2014 CACI Limited. We attest that we have obtained appropriate permissions and paid any required fees for use of copyright protected materials.

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Declaration of interests

None. Anna Hansell declares a Greenpeace membership but has not received any money from the organisation nor been involved in campaigns; nor other relationships or activities that could appear to have influenced the submitted work. Brandon Parkes declares a Friends of the Earth membership but has not been involved in campaigns; nor other relationships or activities that could appear to have influenced the submitted work. The authors have no other relationships or activities that could appear to have influenced the submitted work.

The views expressed are those of the author(s) and not necessarily those of the NIHR, the Department of Health or Public Health England.

Ethical approval

The study uses SAHSU data, supplied from the Office for National Statistics; data use and link between UK National Births and Stillbirth register data and NHS Numbers for Babies (NN4B) was covered by approval from the National Research Ethics Service 17/L0/0846 and by the Health Research Authority Confidentiality Advisory Group (HRA-CAG) for Section 251 support (HRA – 14/CAG/1039). Approval for Scottish data was covered by SAHSU existing ethics and from the NHS National Services Scotland Privacy Advisory Committee (PAC) reference - PAC 17/14.

Data sharing

Health data are available from the data providers on application with appropriate ethics and governance permissions, but we do not hold data provider, ethics, or governance permissions to share these datasets with third parties.

Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.envint.2018.10.060>.

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