The Latrobe Early Life Follow-up (ELF) Cohort Study Volume 4

An extended analysis of possible associations between mine fire emissions and perinatal outcomes

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Table of Contents

List of Tables

Abbreviations

95% CI	95 percent confidence interval
CSIRO	Commonwealth Scientific and Industrial Research Organisation
IQR	Interquartile range
Latrobe ELF Study	Latrobe Early Life Follow-Up Study: The child health and development stream of the Hazelwood Health Study
LGA	Large for Gestational Age
$PM_{2.5}$	Particulate matter with an aerodynamic diameter less than 2.5 micrometres
PTB	Preterm birth
RR	Relative Risk
SGA	Small for Gestational Age
tLBW	Low Birth Weight at Term

Executive Summary

The Hazelwood coal mine fire was an unprecedented event that produced moderate to severe episodes of ambient air pollution in Victoria, Australia in 2014. The public health and emergency response was hindered by the lack of evidence concerning the health impacts of air pollution episodes spanning weeks to months, including harms to the pregnant woman and the developing fetus. This analysis is part of the Latrobe Early Life (ELF) Study, which forms the child health and development stream of the Hazelwood Health Study. It aims to understand whether maternal exposure to the coal mine fire emissions were associated with fetal growth and maturity outcomes. Primary outcomes of interest were birthweight, small for gestational age (SGA), large for gestational age (LGA), term low birthweight (tLBW), gestational maturity and preterm birth (PTB).

Children born between 1 March 2012 and 31 December 2015, whose primary residential address was in the Latrobe City local government area were eligible to enrol in the study. Individual 24-hour average and peak fine particulate matter ($PM_{2.5}$) concentrations during the fire were estimated using chemical transport modelling and detailed time-activity diaries of the pregnant mothers. Outcome and covariate data were collected from a comprehensive baseline survey completed by parents and/or guardians at study enrolment. Birth data from a statutory collection of all births in the state, the Victorian Perinatal Data Collection (VPDC), was available for a subgroup of the cohort. Multivariable linear and log-binomial regression was performed.

Technical report volume 1 was released in January 2018 and presented preliminary findings exploring possible associations between maternal exposure to coal mine fire smoke and parent-reported birth outcomes. This report presents updated findings using more refined exposure estimates, a comparison of data from medical records with parent reports, and more comprehensive statistical modelling.

What is different in this report?

1. **Exposure assignment:** exposure to fine particulate matter ($PM_{2.5}$) from the coal mine fire in technical report volume 1 was based on the mother's fixed address in pregnancy, which did not account for mobility during the fire event. Since the release of technical report 1 in early 2018, revised exposure estimates have been calculated by the Latrobe ELF Study team, which account for mobility during the coal mine fire. This report presents the revised analyses using these time-activity exposure estimates.
2. **Comparison of parent reported outcomes with records of the Victorian Perinatal Data Collection:** The Victorian Perinatal Data Collection (VPDC) is a statutory collection of all births in Victoria held by the Consultative Council on Obstetric and Paediatric Mortality and Morbidity. VPDC data is used in this report to compare administrative data on birth outcomes such as birthweight and gestational age, with parent-reported outcomes.
3. **Complete cohort:** at the time that the technical report volume 1 was prepared, data for 23 participants were unavailable and they were not included in the analysis. This revised report presents analyses using the complete Latrobe ELF cohort (n = 571).
4. **Background air pollution:** we included high resolution modelled estimates of ambient Nitrogen Dioxide (NO_2) exposure during pregnancy in the statistical models, to account for the possible effects of background air pollution on the birth outcomes of interest. NO_2 is a strong marker of traffic and industry-derived pollutants as well as an important component of ambient air pollution.

5. **Additional temporal, seasonal and meteorological covariates:** have been included in the statistical models, including year of birth, season of conception and average daily ambient temperature during each trimester. The inclusion of these covariates reduces the likelihood that these factors influenced the reported results.
6. **Improved modelling of missing data:** The number of imputed datasets to account for missing data was expanded from five to twenty, to strengthen the robustness of findings.

A total of 571 children were enrolled; 198 were in utero at the time of the fire. The average maternal $PM_{2.5}$ exposure during the coal mine fire was 6.0 μg/m^3 (median 2.6; IQR 1.2, 7.0 μg/m^3). There was a relatively high proportion of discordance between birthweight and gestational age as reported by parents in the survey compared with VPDC data. We found no association between maternal $PM_{2.5}$ exposure and birthweight, term low birthweight, large for gestational age, gestational maturity and preterm birth. Using parent-reported survey data, we observed that greater maternal $PM_{2.5}$ exposure was associated with a reduced likelihood of an infant being born SGA (Average $PM_{2.5}$ (per 1 μg/m^3) RR 0.85; 95%CI 0.74, 0.99; p-value = 0.04; Peak $PM_{2.5}$ (per 10 μg/m^3) RR 0.92; 95%CI 0.86, 0.99; p-value = 0.02). However, using administrative data in the subgroup who consented to VPDC data extraction (n = 303; 53.1%), we found no association between maternal $PM_{2.5}$ exposure and SGA. Detailed comparison of a subset of records with both parent-reported and administrative records suggest that this finding relating to SGA may have occurred due to outcome misclassification and highlights the challenges in obtaining accurate information in studies of this type and the potential for error in parental recall. Overall, our extended analysis builds upon the findings presented in technical report volume 1 and supports earlier findings that maternal exposure to fine particulate matter from the coal mine fire did not appear to adversely affect fetal growth or maturity at birth in the Latrobe ELF Study cohort.

Introduction

The Hazelwood coal mine fire was ignited by wildfire embers in the Latrobe Valley, Victoria, Australia in February 2014 and lasted approximately six weeks, impacting a population of approximately 70,000. The fire was an unprecedented event that produced some of the most extreme concentrations of fine particulate matter ($PM_{2.5}$) ever measured in Australia. In the town of Morwell, the closest residential area approximately 500 m from the mine, peak 24-hour concentrations of particulate matter with an aerodynamic diameter less than 2.5 μM ($PM_{2.5}$) was 731 μg/m^3 (1). Air quality standards for $PM_{2.5}$ (<25 μg/m^3 per 24 hour period) were exceeded for 23 days in the town of Morwell during the smoke event (2, 3). The health harms associated with exposure to air pollution resulting from coal mine fires are poorly characterised (4). As outlined by a parliamentary inquiry into the response to the fire, the lack of available evidence regarding short- and long-term health harms associated with coal fire smoke exposure considerably hindered the public health response, especially for vulnerable subgroups within the population (5).

Maternal exposure to ambient air pollution is a well-recognised risk factor for adverse neonatal and obstetric outcomes, including fetal growth restriction, preterm birth, hypertensive disorders of pregnancy and gestational diabetes (6-9). However, there are considerable gaps in the evidence concerning the comparative risks of different durations of exposure. Far less is understood about the impact of maternal exposure to short- to medium-term periods of air pollution (days to months), such as that caused by coal mine fires, on birth outcomes. A small handful of studies have demonstrated that maternal exposure to acute periods of poor ambient air quality, such as those resulting from wildfires, deforestation fires, oil well fires and volcanic eruptions, is associated with an increased risk of preterm birth and fetal growth restriction (10-14) while others show no adverse relationship (10, 15). An increase in frequency and severity of wildfires is projected with a changing climate, exemplifying the need to characterise this relationship (16, 17).

The Latrobe Early Life Follow-up (ELF) Study forms the child health and development stream of the Hazelwood Health Study and aims to understand the potential health impacts of the coal mine fire on pregnant women and young children. This report forms part of the Latrobe ELF Study and aims to characterise the relationship between maternal exposure to fine particulate matter from coal-mine fire smoke ($PM_{2.5}$) and neonatal outcomes, specifically fetal growth and gestational maturity. As outlined in technical report volume 1, we previously found no relationship between maternal exposure to coal mine fire smoke emissions, based upon mother's fixed address in pregnancy, and parent-reported neonatal outcomes. This technical report volume 4 is an extension of the analyses performed in volume 1, utilising refined exposure estimates, complementary data from the VPDC and considering additional important covariates in the analyses.

Method

The study has approval from the Tasmanian Health and Medical Human Research Ethics Committee (reference H14875).

Study design

The Latrobe ELF Study is a cohort study that recruited 571 children born before, during and after the fire event (born 01/03/2012 to 31/12/2015) and resident in the affected region, the Latrobe Valley in Victoria. Recruitment occurred from February to September 2016. Further details outlining the study design and recruitment methods have been described previously (18).

Data collection

Outcome and covariate data

The Latrobe ELF Study Baseline Survey

The Latrobe ELF Study baseline survey was a detailed survey completed by parents and/or guardians of eligible participants upon enrolment in the Latrobe ELF Study. The survey gathered sociodemographic and health details about the study child and their family, as well as the whereabouts of the mother while pregnant during the fire period. Data from the survey used in this analysis included outcomes such as infant birthweight and gestational age, as well as covariates including maternal smoking status, maternal alcohol consumption in pregnancy and highest level of maternal educational attainment.

Victorian Perinatal Data Collection

The Victorian Perinatal Data Collection (VPDC) is a statutory collection of all births in Victoria held by the Consultative Council on Obstetric and Paediatric Mortality and Morbidity. Data on maternal characteristics, pregnancy care, birth and neonatal outcomes are collected for all births of greater than 20 weeks gestation or at least 400 grams if the gestation is unknown, usually by a midwife. Consent for VPDC data extraction was requested from all study families.

The outcomes of interest were fetal growth and maturity, namely birthweight, term low birthweight (tLBW), small for gestational age (SGA), large for gestational age (LGA), gestational maturity (completed weeks) and preterm birth (PTB). Birthweight was measured in grams. Term low birthweight was defined as birthweight less than 2,500 grams at greater than or equal to 37 weeks gestation. SGA was defined as a birthweight $<10^{th}$ centile for sex and gestational age, and LGA was defined as a birthweight $>90^{th}$ centile for sex and gestational age. 'Appropriately' grown infants were defined as those with a birthweight $\geq 10^{th}$ and $\leq 90^{th}$ centile for sex and gestational age. Birthweight percentiles were defined using published Australian percentiles (19). Gestational age was measured as completed weeks of pregnancy. Preterm birth was defined as birth occurring before 37 weeks of gestation. All outcomes were dichotomous, with the exception of birthweight and gestational age, which were continuous outcomes.

Ambient air pollution data

We obtained annual average Nitrogen Dioxide (NO_2) mapped by collaborators at the mesh block level to adjust for maternal exposure to background air pollution. NO_2 is a strong marker of traffic and industry-derived pollutants as well as an important component of ambient air pollution. Collaborators predicted average annual NO_2 concentrations using land use regression modelling, informed by satellite observations of tropospheric NO_2 columns and other important predictors.

Methods relating to the model are described in detail elsewhere (20). Mesh blocks are the smallest geographical unit defined by the Australian Bureau of Statistics (21). We mapped average annual NO_2 based on pregnancy address and year of conception at the mesh block. For mothers that occupied multiple dwellings within a single gestational period, time weighted estimates were determined based on proportion of pregnancy spent at each residence.

Meteorological and temporal data

We obtained minimum and maximum daily temperature data from the Australian Government Bureau of Meteorology for the Morwell station, the single station that serves the Latrobe Valley region (Location 38.23^{0}S, 146.41^{0}E). The 24-hour mean temperatures were calculated. We calculated trimester-specific averages: the first trimester ran from conception to day 84, trimester two ran from day 85 to day 113 and trimester three ran from day 114 to birth. Season of conception and year of conception were also determined to capture underlying temporal and seasonal trends in birth outcomes.

Exposure data

The average and peak daily concentration of particulate matter with an aerodynamic diameter less than 2.5 micrometres ($PM_{2.5}$) directly attributable to the mine fire were the primary exposure metrics used in this study.

The average and peak daily $PM_{2.5}$ concentrations for the 51-day period from 9 February 2014 to 31 March 2014 were determined using a chemical transport model. Collaborators at the Commonwealth Scientific and Industrial Research Organisation (CSIRO) Oceans & Atmosphere Flagship developed a high resolution exposure model to determine exposure estimates of $PM_{2.5}$ at an hourly time step and 1x1 km spatial resolution. Daily whereabouts of pregnant mothers during the fire were gathered through the baseline survey. This time-activity information was used to generate average and peak coal-mine fire $PM_{2.5}$ exposure estimates. If time-activity information was not provided in the survey, exposure based on fixed maternal residual address in pregnancy was used.

Exposure was assigned by first identifying babies that were in utero during the coal mine fire period. The estimated date of conception was calculated by subtracting 266 days from the estimated date of confinement. Those who had partial exposures due to conception or birth during the fire event were assigned a zero for the days they were not in utero. Participants that were not in utero at all during the coal mine fire were assigned a zero average and peak daily $PM_{2.5}$ value. Trimester at the beginning of the coal mine fire, when air quality was the poorest, was also determined to assess for potential sensitive windows of exposure.

Covariate selection

We addressed potential confounding by considering *a priori* several maternal, pregnancy-related, infant, meteorological and temporal characteristics. Maternal characteristics included mother's age (high-risk ($\leq$19 years and $\geq$35 years old) vs. low risk (20 to 34 years old)), the highest level of maternal educational attainment (Post-secondary vs. secondary education) and maternal socioeconomic position (Australian Bureau of Statistics Index of Relative Socioeconomic Disadvantage (IRSD) based on maternal residence at birth at Statistical Area Level 1 (SA1)). Pregnancy-related characteristics included smoking in pregnancy (smoker vs. non-smoker), alcohol consumption in early and late pregnancy (<20 and >20 weeks; any alcohol vs. none) and method of birth (Caesarean section, vaginal delivery). Infant characteristics included infant sex (male, female) and infant Aboriginality (Aboriginal and/or Torres Strait Islander, non-Aboriginal). Meteorological characteristics included the mean daily temperature (^{0}C) for each trimester. Temporal characteristics included season of conception (winter, spring, summer, and autumn) and year of birth. Background maternal air pollution exposure, such as that resulting from traffic and industrial activities, was assessed using average maternal NO_2 exposure while pregnant.

Statistical analysis

We included singleton livebirths in our analysis, as pregnancies complicated by multiple births are systematically different from singleton births. Missing data were handled using multiple imputation by chained equations (MICE package in R) (22). Given the low proportion of missing data, twenty imputed datasets were considered adequate. Regression models were fitted using the imputed data. Participant characteristics were stratified according to coal mine fire exposure (in utero versus not in utero) and summarised as frequency and percentage or median and interquartile range, as appropriate. Linear regression was used to estimate associations between average and peak $PM_{2.5}$ exposure and birthweight and gestational age. Log-binomial regression was used to estimate the associations for dichotomous outcomes SGA, LGA, tLBW and PTB. Covariates were included in the model if there was robust *a priori* evidence for confounding and/or if there was evidence that the covariate was associated with exposure, or associated with the outcome and if adjustment for the covariate altered the coefficient by greater than ten percent. Effect modification was explored for covariates where there was biological plausibility, including smoking in pregnancy, stress in pregnancy, gestational diabetes mellitus, and retained if the interaction term was significant in the model ($p < 0.10$). Bias resulting from non-consent to VPDC data extraction was handled by applying inverse probability weights to the analysis models. The probability of consent was estimated by fitting a logistic regression model using maternal age (continuous), maternal education (dichotomous; post-secondary education yes or no) and maternal smoking in pregnancy (dichotomous; yes or no). Intraclass correlation was calculated to assess agreement between parent-reported and VPDC-derived outcomes. Analyses were conducted using statistical software R (v 3.4.0) (23).

Results

A total of 571 children were included in the analysis; 198 of whom were in utero during the coal mine fire. There were three multiple pregnancies (six twin births) in the cohort. Table 1 presents descriptive statistics relating to infant and maternal characteristics by exposure category. Median birthweight was 3462 grams and median gestational age was 40 weeks. Among term births, 2.8% were low birthweight. The proportion of preterm births among the full cohort was 9.1%. Approximately 70% of the cohort were born by vaginal delivery (n = 393; 68.8%) and 30% by Caesarean Section (n = 172; 30.1%). Some well-recognised risk factors for adverse neonatal outcomes, including smoking in pregnancy and maternal stress in pregnancy, were associated with birth outcomes in our study. For example, smoking in pregnancy were associated with a 79% increased likelihood of an infant being born SGA (95%CI 1.14, 2.80; p = 0.011). Maternal stress in pregnancy was associated with significant reductions in birthweight, gestational maturity and a greater than two-fold increase in the likelihood of PTB. We also observed that gestational length was incrementally shorter year-on-year for the study period (Supplementary Table 1).

Table 1. Descriptive statistics by exposure to coal mine fire

	Total cohort N = 571		In utero during coal mine fire N = 198		Not in utero during coal mine fire N = 373	
	n	**%**	**n**	**%**	**n**	**%**
Infant characteristics						
Female sex	277	48.5	100	50.5	177	47.5
Aboriginal and/or Torres Strait Islander	31	5.4	11	5.6	20	5.4
Country of birth Australia	569	99.7	197	99.5	372	99.7
Language other than English spoken at home	39	6.8	12	6.1	27	7.2
Maternal and pregnancy characteristics						
	n	**%**	**n**	**%**	**n**	**%**
Maternal age 'high risk' (19 and under and 35 and older)	102	17.9	26	13.1	76	20.4
Maternal smoking in pregnancy	102	17.9	26	13.1	76	20.4
Alcohol in early pregnancy (<20 weeks)	49	8.6	16	8.1	33	8.9
Alcohol in late pregnancy (>20 weeks)	20	3.5	7	3.5	13	3.5

Stress in pregnancy 'stressed most/nearly all of the time'	97	17.0	32	16.2	65	17.4
Neonatal outcomes						
	Median (IQR)	**Range**	**Median (IQR)**	**Range**	**Median (IQR)**	**Range**
Gestational age (weeks)	40 (38, 41)	30, 43	39.5 (38, 40)	30, 42	40 (38, 41)	32, 43
Birthweight (grams)	3462 (3040, 3802)	1200, 5670	3483 (3143, 3884)	1200, 5330	3459 (3026, 3778)	1417, 5670
	n	%	**n**	%	**n**	%
Caesarean section birth	172	30.1	64	32.3	108	29.1
tLBW	16	2.8	4	2.0	12	3.2
SGA	74	13.0	16	8.1	58	15.6
LGA	68	11.9	27	13.6	41	11.0
PTB	52	9.1	19	9.6	33	8.9
Abbreviations: IQR, interquartile range; LGA, large for gestational age; PTB, preterm birth, SGA, small for gestational age; tLBW, term low birthweight						

The median of the daily average maternal $PM_{2.5}$ exposure during the coal mine fire was 2.6 μg/m^3 (IQR 5.8 μg/m^3). Median peak $PM_{2.5}$ exposure was 71.7 μg/m^3 (IQR 103.1 μg/m^3) (Table 2). Maternal exposure to $PM_{2.5}$ from the mine fire smoke emissions was much greater for Morwell residents than those living in the rest of the Latrobe Valley. Time-activity exposure estimates were missing for six individuals and exposure based on fixed maternal residual address in pregnancy was used for these individuals.

Table 2. Average and peak maternal exposure to coal mine fire smoke $PM_{2.5}$ for participants whose mothers were pregnant during the coal mine fire

	Maternal residence during the coal mine fire		
	Morwell **N = 61**	**Latrobe Valley (rest)** **N = 137**	**All maternal exposures** **N = 198**
Average $PM_{2.5}$ exposure (μg/m^3)			
Mean	13.4	2.7	6.0
Median	9.0	2.0	2.6
Range	0, 46.8	0, 22.9	0, 46.8
Interquartile Range (Q25, Q75)	5.9, 17.1	1.0, 2.9	1.2, 7.0
Peak $PM_{2.5}$ exposure (μg/m^3)			
Mean	217.8	85.0	126.1
Median	167.0	60.8	71.7
Range	0, 844.4	0, 721.0	0, 844.4
Interquartile Range (Q25, Q75)	111.1, 287.2	38.6, 82.2	46.7, 149.8

Greater maternal exposure to average and peak coal mine fire-attributable $PM_{2.5}$ was associated with a reduced likelihood of small for gestational age (Average $PM_{2.5}$ (per 1 µg/m³) RR 0.85; 95%CI 0.74, 0.99; p-value 0.04; Peak $PM_{2.5}$ (per 10 µg/m³) RR 0.92; 95%CI 0.86, 0.99; p-value 0.02) when assessed using parent-reported SGA. There was no evidence that maternal exposure to average or peak $PM_{2.5}$ from the coal mine fire was significantly associated with birthweight, term low birthweight, large for gestational age, gestational maturity or preterm birth (Table 3).

Table 3. Association between maternal exposure to coal mine fire-attributable $PM_{2.5}$ and parent-reported neonatal outcomes in full cohort

Outcome	**Average $PM_{2.5}$ (per 1 µg/m³)**		**Peak $PM_{2.5}$ (per 10 µg/m³)**	
	Unadjusted mean difference (95%CI); p-value	**Adjusted mean difference (95%CI); p-value**	**Unadjusted mean difference (95%CI); p-value**	**Adjusted mean difference (95%CI); p-value**
Birthweight (grams)	8.14 (-0.94, 17.23); 0.08	7.07 (-3.00, 17.13); 0.17	4.31 (-0.63, 9.24); 0.09	3.33 (-2.20, 8.86); 0.24
Gestational age (days)	3.35 (-9.59, 10.70); 0.83	0.79 (-10.67, 10.72); 0.99	1.87 (-7.24, 7.71); 0.90	0.92 (-7.87, 7.98); 0.98
	Unadjusted RR (95%CI); p-value	**Adjusted RR (95%CI); p-value**	**Unadjusted RR (95%CI); p-value**	**Adjusted RR (95%CI); p-value**
tLBW	1.12 (0.96, 1.32); 0.15	1.11 (0.95, 1.29); 0.20	1.06 (0.99, 1.14); 0.11	1.06 (0.98, 1.14); 0.16
SGA	0.91 (0.82, 1.001); 0.05	**0.85 (0.74, 0.99); 0.04**	**0.95 (0.90, 0.99); 0.03**	**0.92 (0.86, 0.99); 0.02**
LGA	0.98 (0.94, 1.01); 0.17	0.99 (0.95, 1.03); 0.50	0.99 (0.97, 1.01); 0.31	0.99 (0.98, 1.02); 0.94
PTB	0.97 (0.91, 1.04); 0.39	0.97 (0.90, 1.05); 0.44	0.99 (0.95, 1.02); 0.44	0.99 (0.95, 1.02); 0.44

Adjusted for infant sex, infant aboriginality, maternal smoking in pregnancy, maternal educational attainment, maternal age (high risk ($\leq$19 and $\geq$35) vs. low risk (20 to 34 years old)), season of conception, year of birth, mean ambient temperature in Trimester 1, 2 and 3, and average maternal NO_2 exposure
Abbreviations: LGA, large for gestational age; PTB, preterm birth, RR, relative risk; SGA, small for gestational age; tLBW, term low birthweight; NO_2, nitrogen dioxide
Twins excluded from the analysis

To determine whether there were any sensitive exposure windows, we examined whether the relationship between maternal coal mine smoke exposure and neonatal outcomes varied by the timing of trimester at the start of the fire. We found no significant relationship between the timing of exposure and the neonatal outcomes of interest (data not shown).

Birthweight and gestational age obtained through the baseline survey was compared with VPDC data to account for possible error in parent-reported outcomes. Approximately half of the parents/guardians of the Latrobe ELF Study cohort consented to VPDC data extraction (n = 303; 53.1%). The parent-reported birthweight matched the birthweight recorded in the VPDC dataset for just 25% of participants. However, for the majority of discordant records, the absolute difference was relatively small, within 50 grams. There was greater concordance between parent-reported and VPDC-reported gestational age. Gestational age in the baseline survey matched the VPDC record for 60% of participants. Intraclass correlation coefficients for birthweight and gestational age were both 0.91 (birthweight ICC 95%CI 0.89, 0.93 and gestational age ICC 95%CI 0.86, 0.94).

Sensitivity analysis:

Analysis using birth data held by the Victorian Perinatal Data Collection

A repeat analysis exploring the relationship between maternal exposure to coal mine fire attributable $PM_{2.5}$ and neonatal outcomes was conducted in the subset of the cohort with VPDC data (n = 303; 53.1%), where the VPDC data was used to define growth and maturity outcomes. Parents/guardians of study participants who consented to VPDC data extraction were systematically different to those who did not consent (Table 4). In the weighted analysis, there was no association between average or peak maternal exposure and any neonatal growth or maturity outcomes of interest. Of particular note, the reduced likelihood of SGA that was observed in association with maternal exposure to coal fire $PM_{2.5}$ in the larger cohort using parent-reported birthweight and gestational age was no longer observed (Table 5). Estimates and inference were similar in the unweighted analyses, and results are presented in Supplementary Table 2. Furthermore, no association between exposure to smoke emissions and any fetal growth or maturity outcomes was observed when the analysis was repeated in this subgroup who consented to VPDC data, using their parent-reported data to define growth and maturity outcomes.

Table 4. Predictors of parental and/or guardian consent to Victorian Perinatal Data Collection extraction	
	RR (95%CI); p value
Maternal age (years old)	**1.06 (1.03, 1.09); <0.001**
Maternal education post-secondary (compared with Year 12 and below)	**1.36 (1.15, 1.61); <0.001**
Maternal smoking in pregnancy (compared with non-smoker)	**0.75 (0.59, 0.95); <0.05**
Maternal coal mine fire-attributable stress increased a lot (compared with increased a little/not affected/reduced)	1.11 (0.095, 1.29); 0.21
Maternal stress in pregnancy (stressed most or nearly all the time compared with sometimes stressed/hardly ever or never stressed)	0.63 (0.27, 1.45); 0.28
Average $PM_{2.5}$ exposure (per 1 μg/m^3)	1.00 (0.99, 1.02): 0.12
Peak $PM_{2.5}$ exposure (per 10 μg/m^3)	1.00 (0.99, 1.01); 0.53

Table 5. Association between maternal exposure to coal mine fire-attributable $PM_{2.5}$ and neonatal outcomes in subcohort with Victorian Perinatal Data Collection data				
Outcome	**Average $PM_{2.5}$ (per 1 μg/m³)**		**Peak $PM_{2.5}$ (per 10 μg/m³)**	
	Unadjusted mean difference (95%CI); p-value	**Adjusted mean difference (95%CI); p-value**	**Unadjusted mean difference (95%CI); p-value**	**Adjusted mean difference (95%CI); p-value**
Birthweight (grams)	-1.55 (-13.04, 9.94); 0.79	-2.67 (-14.90, 9.56); 0.67	0.15 (-5.50, 5.82); 0.96	-1.74 (-7.87, 4.39); 0.58
Gestational age (days)	0.01 (-0.23, 0.24); 0.93	-0.03 (-0.29, 0.23); 0.82	-0.01 (-0.13, 0.11); 0.89	-0.03 (-0.16, 0.10); 0.65
	Unadjusted RR (95%CI); p-value	**Adjusted RR (95%CI); p-value**	**Unadjusted RR (95%CI); p-value**	**Adjusted RR (95%CI); p-value**
tLBW	0.88 (0.75, 1.04); 0.13	0.94 (0.82, 1.08); 0.37	0.96 (0.90, 1.02); 0.17	0.98 (0.93, 1.04); 0.55
SGA	1.02 (0.99, 1.06); 0.14	1.00 (0.95, 1.06); 0.86	1.00 (0.97, 1.02); 0.83	0.97 (0.92, 1.03); 0.30
LGA	1.04 (0.99, 1.09); 0.16	1.01 (0.94, 1.08); 0.78	1.01 (0.99, 1.04); 0.30	0.99 (0.97, 1.03); 0.94
PTB	1.00 (0.99, 1.01); 0.65	1.00 (0.99, 1.01); 0.81	1.00 (0.99, 1.01); 0.99	1.00 (0.99, 1.01); 0.77

Adjusted for infant sex, infant aboriginality, maternal smoking in pregnancy, maternal educational attainment, maternal age (high risk (≤19 and ≥35) vs. low risk (20 to 34 years old)), season of conception, year of birth, mean ambient temperature in Trimester 1, 2 and 3 and average maternal NO_2 exposure. Inverse probability weighting applied.

Abbreviations: LGA, large for gestational age; PTB, preterm birth, RR, relative risk; SGA, small for gestational age; tLBW, term low birthweight.
Twins excluded from the analysis

Alternative assignment of maternal socioeconomic position

We also repeated the adjusted analyses for the full cohort using an alternative indicator of socioeconomic status. In this sensitivity analysis, socioeconomic position was based on the IRSD for maternal residence at birth, assigned at the geographical level of SA1. Estimates and inference were unchanged from that demonstrated in the main analyses (Supplementary Table 3).

Discussion

Using detailed time-activity patterns, we have characterised the relationship between maternal exposure to fine particulate matter in coal mine fire emissions and a number of fetal growth and maturity outcomes measured at birth. Consistent with what was described in technical report volume 1, we found no evidence that smoke exposure was associated with birthweight, gestational maturity, or the likelihood of tLBW, LGA or PTB. Contrary to our *a priori* expectations, we observed that greater maternal exposure to fine particulate matter from the coal mine fire was associated with a reduced likelihood of an infant being born SGA (according to parent-report). After detailed evaluation we believe that this result is most likely an error due to the minor but systematic errors in parental recall of birth outcomes. SGA is a calculated measure derived from birth weight, and gestational maturity at birth. While it has not been examined specifically in previous studies of maternal exposure to severe smoke events, the limited available evidence suggests that exposure to a severe smoke event is generally associated with decrements in birthweight and an increased risk of preterm birth which together would increase rather than reduce the likelihood of SGA (10-12).

If the result represents a true association, we can only speculate on possible mechanisms. In our previous work exploring these associations in a larger deidentified cohort of children born in the Latrobe Valley during the same timeframe and using VPDC data, we found that coal mine fire smoke exposure was associated with increases in birthweight if the mother had gestational diabetes mellitus (24). This is a more plausible association in this subgroup given the existing evidence of associations between exposure to air pollution and blood glucose control. Another possible explanation is that greater smoke exposure led to protective actions, for example by relocating away from the affected areas. However, as we accounted for maternal mobility during the event by using time-activity diary data, exposure estimates should reflect such actions. However, it is more likely that the observation occurred due to outcome misclassification, resulting from errors or rounding in parent recall of birthweight and gestational maturity. Outcome misclassification is possible, as there was a relatively high rate of mismatch between parent-reported and VPDC data, although the absolute differences were small. The accuracy of the VPDC dataset has been validated elsewhere and is likely to be more accurate overall than parental recall (25). Utilising administrative data to define our outcomes in the subgroup where VPDC data was available, we did not observe any association between fine particulate matter exposure and SGA.

The lack of association between maternal exposure and other outcomes, including birthweight and preterm birth, is at odds with other studies. A small number of studies have explored maternal exposure to severe ambient smoke events, such as wildfires, oil well fires, agricultural fires and volcanic eruptions, on neonatal outcomes. Mixed results are reported, but overall there is some evidence that maternal exposure to acute changes in air quality of short- to medium- term duration increases the risk of fetal growth restriction and preterm birth (26). These findings are consistent with our larger study involving deidentified VPDC data of all births within the Latrobe Valley over the same timeframe, where we found no association between maternal exposure to coal mine fire attributable $PM_{2.5}$ and fetal growth or maturity (unpublished work). We observed several well-recognised risk factors for adverse neonatal outcomes in our cohort, including maternal smoking and psychosocial stress in pregnancy. These findings reinforce the importance of population-level tobacco control strategies, and individual tobacco cessation and psychosocial support prior to and during pregnancy. Gestational length was shorter year-by-year across the study period. This has been described previously and is largely attributed to changes in clinical practice (27).

Strengths of this study include the comprehensive data that were obtained through the baseline survey, allowing us to account for several covariates in the statistical models. The use of time-activity exposure estimates is a particular strength, as they account for maternal mobility during the fire and reduce the likelihood of exposure misclassification. This is particularly important in a study such as this, where the fire caused significant community concern and disruption, and the likelihood that individuals left the region or altered their activities if close to the fire is high. We were also able to adjust for background air pollution, such as that caused by traffic, by adjusting for average maternal NO_2 exposure. Comparing neonatal outcomes collected through two different sources is useful, as it highlights potential limitations in using parent-reported outcomes. Limitations of this study include the inability to adjust for maternal parity, or obstetric complications such as gestational diabetes mellitus. Additionally, we were unable to distinguish iatrogenic versus spontaneous preterm birth.

Conclusion

This extended analysis further supports the findings reported in technical report volume 1. Reassuringly, there was no association between maternal exposure to fine particulate air pollution from the Hazelwood coal mine fire and birthweight, tLBW, LGA, gestational maturity or PTB. At odds to *a priori* expectations, we observed that greater maternal exposure was associated with a reduced likelihood of an infant being born SGA when using parent-reported outcomes. However, detailed comparison of a subset of records with both parent-reported and administrative records suggest that this finding may have occurred due to outcome misclassification and highlights the importance of obtaining accurate outcome data.

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Supplementary Table 1. Summary of univariate analysis examining the association between key infant, maternal, labour, temporal and meteorological-related variables and neonatal outcomes

	Outcome					
	Birthweight (grams)	**Gestational age (weeks)**	**tLBW**	**SGA**	**LGA**	**PTB**
	Mean difference (95%CI); p value		**RR (95%CI); p value**			
Infant characteristics						
Sex (male vs. female)	**156.11 (50.13, 262.09); <0.01**	-0.18 (-0.50, 0.14); 0.28	1.26 (0.65, 2.44); 0.49	1.18 (0.78, 1.81); 0.44	0.67 (0.40, 1.11); 0.12	1.10 (0.65, 1.88); 0.73
Aboriginal and/or Torres Strait Islander (yes vs. no)	-28.14 (-262.64, 206.35); 0.81	0.12 (-0.60, 0.83); 0.74	0.96 (0.22, 4.23); 0.96	**2.34 (1.31, 4.18); <0.01**	0.77 (0.25, 2.34); 0.64	1.10 (0.36, 3.32); 0.87
Maternal characteristics						
Maternal age ('high risk' ≤19 years old or ≥35 years old vs. 20 to 34 years old)	7.45 (-148.91, 163.81); 0.93	-0.05 (-0.52, 0.42); 0.83	0.82 (0.35, 2.25); 0.67	1.41 (0.78, 2.31); 0.21	0.69 (0.36, 1.43); 0.30	0.71 (0.25, 1.57); 0.46
Maternal education (secondary vs. post-secondary)	-31.20 (-140.64, 78.24); 0.58	-0.25 (-0.58, 0.08); 0.13	0.64 (0.33, 1.24); 0.19	1.44 (0.95, 2.18); 0.08	0.89 (0.53, 1.48); 0.64	1.55 (0.92, 2.63); 0.10
Smoking in pregnancy (smoker vs. non-smoker)	-117.91 (-255.35, 19.53); 0.09	-0.29 (-0.70, 0.13); 0.18	0.62 (0.29, 1.32); 0.21	**1.79 (1.14, 2.80); 0.01**	0.67 (0.36, 1.24); 0.20	1.11 (0.57, 2.14); 0.77
Alcohol in early pregnancy (<20 weeks) (any alcohol vs. no alcohol)	-54.03 (-242.70, 134.64); 0.57	-0.12 (-0.68, 0.45); 0.68	1.21 (0.36, 4.09); 0.76	0.68 (0.29, 1.61); 0.39	1.88 (0.65, 5.41); 0.24	0.89 (0.33, 2.36); 0.81
Alcohol in late pregnancy (>20 weeks) (any alcohol vs. no alcohol)	-90.53 (-366.31, 185.26)	0.07 (-0.76, 0.90); 0.88	0.44 (0.12, 1.58); 0.21	1.00 (0.34, 2.89); 0.99	1.49 (0.34, 6.58); 0.60	1.02 (0.27, 3.95); 0.97
Maternal stress in pregnancy (stressed most/nearly all of the time vs. not stressed at all/hardly ever stressed))	**-163.19 (-321.29, -5.10); 0.04**	**-0.86 (-1.33, -0.39); <0.001**	0.42 (0.18, 1.40); 0.40	0.97 (0.53, 1.79); 0.93	1.78 (0.81, 3.95); 0.15	**2.89 (1.48, 5.64); <0.01**

Maternal stress response to coal mine fire (increased a lot. vs. reduced/not affected/increased a little)	-108.25 (-288.53, 72.03); 0.24	-0.48 (-1.06, 0.10); 0.10	0.48 (0.13, 1.72); 0.26	0.97 (0.35, 2.65); 0.95	0.97 (0.84, 1.11); 0.63	2.06 (0.90, 4.70); 0.09
Labour characteristics						
Vaginal delivery (Vaginal delivery vs. Caesarean Section)	33.16 (-83.42, 149.73); 0.58	**0.70 (0.35, 1.04); <0.0001**	1.4 (0.80, 1.60); 0.25	0.79 (0.51, 1.24); 0.30	**2.16 (1.29, 3.60); <0.01**	**0.38 (0.22, 0.65); <0.001**
Temporal and meteorological variables						
Year of birth						
2012	Ref	Ref	Ref	Ref	Ref	Ref
2013	-156.57 (-345.15, 32.01); 0.10	**-0.63 (-1.20, -0.07); 0.03**	0.42 (0.32, 1.28); 0.16	1.16 (0.56, 2.37); 0.69	0.91 (0.33, 2.49); 0.86	**4.39 (1.02, 18.89); 0.04**
2014	-43.88 (-212.97, 125.21); 0.61	**-0.68 (-1.19, -0.17); <0.01**	0.27 (0.03, 2.12); 0.21	0.68 (0.33, 1.41); 0.30	0.53 (0.22, 1.24); 0.14	**3.65 (0.88, 15.17); 0.08**
2015	**-194.31 (-370.34, -18.28); 0.03**	**-0.61 (-1.14, -0.08); 0.02**	0.32 (0.22, 1.10); 0.15	1.40 (0.73, 2.69); 0.32	0.82 (0.32, 2.10); 0.68	3.22 (0.75, 13.80); 0.12
Trimester 1 average temperature (°C)	12.44 (-2.36, 27.24); 0.099	0.01 (-0.03, 0.06); 0.65	1.05 (0.96, 1.15); 0.28	1.00 (0.94, 1.05); 0.88	0.96 (0.90, 1.03); 0.28	0.99 (0.92, 1.07); 0.89
Trimester 2 average temperature (°C)	5.82 (-8.89, 20.52); 0.44	0.01 (-0.05, 0.04); 0.81	1.09 (1.00, 1.20); 0.061	**0.94 (0.89, 1.00); 0.05**	0.99 (0.93, 1.06); 0.80	0.99 (0.92, 1.08); 0.89
Trimester 3 average - temperature (°C)	-8.50 (-22.04, 5.04); 0.22	-0.01 (-0.05, 0.03); 0.62	0.97 (0.90, 1.06); 0.52	0.99 (0.94, 1.05); 0.85	1.02 (0.96, 1.09); 0.52	1.01 (0.94, 1.08); 0.82
Average maternal NO_2 exposure over pregnancy (ppb)	3.54 (-32.81, 38.89); 0.85	**0.012 (0.01, 0.23); 0.03**	0.97 (0.79, 1.20); 0.82	1.05 (0.94, 1.18); 0.37	1.05 (0.87, 1.27); 0.61	0.87 (0.68, 1.12); 0.29

Abbreviations: LGA, large for gestational age; PTB, preterm birth, RR, relative risk; SGA, small for gestational age; tLBW, term low birthweight; NO_2, nitrogen dioxide; ppb, parts per billion
Twins excluded from analysis

Supplementary Table 2. Association between maternal exposure to coal mine fire-attributable $PM_{2.5}$ and neonatal outcomes in subcohort with Victorian Perinatal Data Collection data (unweighted data)

Outcome	**Average $PM_{2.5}$ (per 1 μg/m³)**		**Peak $PM_{2.5}$ (per 10 μg/m³)**	
	Unadjusted mean difference (95%CI); p-value	**Adjusted mean difference (95%CI); p-value**	**Unadjusted mean difference (95%CI); p-value**	**Adjusted mean difference (95%CI); p-value**
Birthweight (grams)	-0.47 (-11.81, 10.88); 0.94	-1.84 (-13.98, 10.30); 0.77	0.39 (-5.04, 5.83); 0.89	-1.50 (-7.41, 4.42); 0.62
Gestational age (days)	0.02 (-0.21, 0.25); 0.87	-0.02 (-0.28, 0.23); 0.87	0.00 (-0.12, 0.11); 0.95	-0.02 (-0.15, 0.11); 0.95
	Unadjusted RR (95%CI); p-value	**Adjusted RR (95%CI); p-value**	**Unadjusted RR (95%CI); p-value**	**Adjusted RR (95%CI); p-value**
tLBW	0.87 (0.67, 1.12); 0.28	0.93 (0.75, 1.15); 0.49	0.95 (0.86, 1.05); 0.31	0.98 (0.90, 1.06); 0.60
SGA	1.01 (0.96, 1.10); 0.64	0.98 (0.91, 1.07); 0.70	0.99 (0.95, 1.03); 0.61	0.97 (0.91, 1.03); 0.30
LGA	1.03 (0.96, 1.10); 0.39	1.01 (0.93, 1.11); 0.76	1.01 (0.98, 1.04); 0.55	0.99 (0.96, 1.04); 0.98
PTB	1.00 (0.99, 1.01); 0.67	1.00 (0.99, 1.01); 0.59	1.00 (0.99, 1.01); 0.85	1.00 (0.99, 1.01); 0.74

Adjusted for infant sex, infant aboriginality, maternal smoking in pregnancy, maternal educational attainment, maternal age (high risk ($\leq$19 and $\geq$35) vs. low risk (20 to 34 years old)), season of conception, year of birth, mean ambient temperature in Trimester 1, 2 and 3 and average maternal NO_2 exposure
Abbreviations: LGA, large for gestational age; PTB, preterm birth, RR, relative risk; SGA, small for gestational age; tLBW, term low birthweight.
Twins excluded from the analysis

Supplementary Table 3. Association between maternal exposure to coal mine fire-attributable $PM_{2.5}$ and parent-reported neonatal outcomes in full cohort with statistical adjustment using an alternative assignment of maternal socioeconomic position

Outcome	**Average $PM_{2.5}$ (per 1 µg/m³)**	**Peak $PM_{2.5}$ (per 10 µg/m³)**
	Mean difference (95%CI); p-value	**Mean difference (95%CI); p-value**
Birthweight (grams)	6.07 (-3.95, 16.10); 0.24	3.23 (-2.40, 8.86); 0.26
Gestational age (days)	-0.026 (-0.24, 0.19); 0.81	-0.01 (-0.13, 0.11); 0.90
	RR (95%CI); p-value	**RR (95%CI); p-value**
tLBW	1.01 (1.00, 1.02); 0.09	1.00 (0.99, 1.01), 0.08
SGA	**0.89 (0.79, 0.95); <0.05**	**0.93 (0.89, 0.97); <0.001**
LGA	1.00 (0.99, 1.00); 0.28	1.00 (0.99, 1.00); 0.72
PTB	0.97 (0.93, 1.02); 0.28	0.99 (0.96, 1.01); 0.29

Adjusted for infant sex, infant aboriginality, maternal smoking in pregnancy, maternal IRSD score, maternal age (high risk ($\leq$19 and $\geq$35) vs. low risk (20 to 34 years old)), season of conception, year of birth, mean ambient temperature in Trimester 1, 2 and 3 and average maternal NO_2 exposure

Abbreviations: LGA, large for gestational age; PTB, preterm birth, RR, relative risk; SGA, small for gestational age; tLBW, term low birthweight.

Twins excluded from the analysis