# Maternal Exposure to Fine Particulate Matter from a Large Coal Mine Fire is Associated with Gestational Diabetes Mellitus: a Prospective Cohort Study

Shannon M Melody[1*], Jane B Ford[2,3], Karen Wills[1], Alison Venn[1], Fay H Johnston[1]

[1] Menzies Institute for Medical Research, University of Tasmania, 17 Liverpool Street, Hobart, Tasmania, Australia, 7001, [2] Clinical and Population Perinatal Health Research, Kolling Institute, Northern Sydney Local Health District, St Leonards, New South Wales, Australia, 2065, [3] Northern Clinical School, Faculty of Medicine and Health, The University of Sydney, Sydney, Australia, 2065

Corresponding author: Shannon M Melody, c/o Private Bag 23, Menzies Institute for Medical Research, Hobart, Tasmania 7001, +61 36226 7725, shannon.melody@utas.edu.au.

## Abstract

***Background*:** In 2014, the Hazelwood coal mine fire was an unprecedented event that resulted in a six-week period of poor air quality in the Latrobe Valley in regional Australia. We aimed to determine whether maternal exposure to fine particulate matter in coal mine fire smoke was associated with selected obstetric complications, including gestational diabetes mellitus, hypertensive disorders of pregnancy and abnormal placentation. ***Methods***: We defined a complete cohort of pregnant women with births >20 weeks in the Latrobe Valley from 1 March 2012 - 31 Dec 2015 utilising administrative perinatal data. Average and peak fine particulate matter ($PM_{2.5}$) was assigned to residential address at delivery using a chemical transport model. Maternal, meteorological and temporal variables were included in final log-binomial regression models. ***Results***: 3,612 singleton pregnancies were included in the analysis; 766 were exposed to the smoke event. Average maternal $PM_{2.5}$ exposure was 4.4 μg/m$^3$ (SD 7.7; IQR 2.12). Average peak $PM_{2.5}$ exposure was 44.9 μg/m$^3$ (SD 57.1; IQR 35.0). An interquartile range increase in peak $PM_{2.5}$ was associated with a 16% increased likelihood of gestational diabetes mellitus (95%CI 1.09, 1.22; <0.0001). Whereas, an interquartile range increase in average $PM_{2.5}$ was associated with a 7% increased likelihood of gestational diabetes mellitus (95%CI 1.03, 1.10; <0.0001). Second trimester exposure was of critical importance. No association for hypertensive disorders or abnormal placentation was observed. ***Conclusion:*** this is the first study to examine obstetric complications relating to a discrete smoke event. These findings may guide the public health response to future similar events.



**Keywords:** air pollution; pregnancy complications; gestational diabetes; coal mine fire

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**Declaration of conflicts of interest**: no competing interests

***Data sharing:*** the authors do not have permission to share raw data, as we are not the custodians of the data.

**Highlights**

- Exposure to a smoke event was associated with an increased risk of gestational diabetes
- Second trimester exposure was of critical importance to risk of gestational diabetes
- There was no association observed for hypertensive disorders or pregnancy
- There was no association observed for abnormal placentation
- The public health implications may be substantial with a changing climate

## 1. Introduction

There is increasing evidence of an association between maternal exposure to poor ambient air quality and adverse birth outcomes, but less is understood concerning maternal morbidity. Epidemiological studies have demonstrated an association between ambient outdoor air pollution and hypertensive disorders of pregnancy, such as pregnancy-induced hypertension and preeclampsia, as well as impaired glucose tolerance, gestational diabetes mellitus and placental abruption [1,2]. Proposed aetiological mechanisms are underpinned by the pro-inflammatory effects of air pollutants [3]. Obstetric morbidity carries short-term and long-term health sequelae for the fetal-mother dyad. For example, one-third of women with gestational diabetes mellitus are likely to develop type 2 diabetes and experience cardiovascular disease later in life [4]. Infants born to women with gestational diabetes mellitus are more likely to be macrosomic, suffer complications such as shoulder dystocia, require special care nursery admission for neonatal hypoglycaemia and are at an increased risk of cardiometabolic disease as an adult, due to programming of the fetal pancreas [5,6].

No studies to date have explored the impact of time-limited periods of poor outdoor air quality on pregnancy complications, such as that resulting from landscape fires such as forest, peat or coal mine fires. One such time-limited, abrupt air pollution event was the Hazelwood coal mine fire, which occurred in 2014 in regional Victoria, Australia. The mine fire was ignited by nearby wildfire embers and resulted in a six-week period of unprecedented poor air quality in the surrounding region, affecting a population of approximately 75, 000 individuals. 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 ($PM_{2.5}$) were 731 μg/m$^3$ and air quality standards were exceeded for 23 days during the smoke event [7,8].

Time-limited smoke events are becoming more frequent and severe, due to a changing climate [9]. The need to understand the potential impact of maternal exposure to severe smoke events is particularly important given the consequences of maternal and fetal morbidity and mortality. This study aimed to characterise the relationship between maternal exposure to fine particulate matter in coal mine fire smoke and selected obstetric outcomes chosen *a priori*, including gestational diabetes mellitus, hypertensive disorders of pregnancy and conditions characterised by abnormal placentation.

## 2. Methods

Ethics approval for this study was obtained from the Tasmania Health and Medical Human Research Ethics Committee (ref H0015033).

### 2.1 Data

***2.1.1 Pregnancy and delivery data:*** We analysed data on singleton births to mothers resident in the Latrobe Valley from 1 March 2012 to 31 December 2015 that were recorded in the Victorian Perinatal Data Collection (VPDC). The VPDC is a statutory collection of information on all births occurring in Victoria, Australia. Data on maternal characteristics, pregnancy care, birth and neonatal outcomes are collected for all births of greater or equal to 20 weeks gestation or at least 400 grams if the gestation is unknown, usually by a midwife. Validation against medical records indicates positive predictive values of 92% on reporting for pre-eclampsia and 94% for gestational diabetes mellitus [10].

The outcomes of interest were gestational diabetes mellitus, hypertensive disorders of pregnancy (pregnancy-induced hypertension, pre-eclampsia and eclampsia) and conditions characterised by abnormal placentation (placenta praevia with haemorrhage, morbidly adherent placenta and placental abruption). For all conditions, timing of diagnosis during pregnancy was not known, simply the presence or absence of a condition as recorded at birth. ***Gestational diabetes mellitus:*** In Australia, it is recommended that pregnant women are screened for gestational diabetes mellitus between 24 and 28 weeks gestation with an oral glucose tolerance test. Women who are recognised as high-risk may be screened earlier in pregnancy. Current guidelines recommend a diagnosis of gestational diabetes mellitus if the 2-hour oral glucose tolerance test result is greater than 8.5 mmol/L following a 75 gram oral glucose load [11]. The diagnostic threshold was lowered during the study period to align with the WHO-2013 diagnostic criteria, with recommendation from the Royal

Australian and New Zealand College of Obstetricians and Gynaecologists that the new criteria be adopted by 1 January 2015. Previous diagnostic thresholds included a 2-hour glucose level of greater than or equal to 11.1 mmol/L following a 75 gram oral glucose load, a random plasma glucose of greater than or equal to 11.1 mmol/L or a fasting glucose of greater than or equal to 7.0mmol/L. The lowering of the diagnostic threshold means that the prevalence of gestational diabetes mellitus in the Australian population would have increased during the study period [12]. We have adjusted for this by including year of conception in the statistical models. If a diagnosis of gestational diabetes mellitus did not appear in the VPDC (International Classification of Diseases 10th Revision (ICD-10AM) code O24.4), it was presumed women did not have gestational diabetes mellitus. Pre-existing diabetes mellitus cases were not counted. ***Hypertensive disorders of pregnancy***: Blood pressure measurement and urinalysis are performed routinely at all antenatal visits, and pregnancy-induced hypertension, preeclampsia and eclampsia are diagnosed according to the ICD-10AM codes O13-O15. Pre-existing hypertensive disorders were not counted. ***Conditions characterised by abnormal placentation:*** it is routinely recommended that pregnant women have a morphology ultrasound at 18-20 weeks, at which time morphology and position of the placenta are noted. If the placenta is positioned low (i.e. low lying placenta), further ultrasounds are arranged for surveillance and determination of placenta praevia at a later gestation, once the lower uterine segment has formed (ICD-10 AM codes O44.1). A morbidity adherent placenta, including placenta accreta, increta or percreta may be diagnosed clinically or on ultrasound where there is evidence of abnormal placental invasion of the uterine wall (ICD-10 AM codes O43.2). Placental abruption is typically a clinical diagnosis and is diagnosed according to International Classification of Diseases, 10th Revision (ICD- 10 AM codes O45).

***2.1.2 Exposure data:*** The Hazelwood coal mine fire lasted from the 9 February to 31 March 2014 (51 days). Average daily concentration of $PM_{2.5}$ directly attributable to the mine fire was the primary exposure metric of interest. Peak $PM_{2.5}$ was the secondary exposure metric, which represents the highest 24-hour average $PM_{2.5}$ exposure during the coal mine fire period.

The average and peak daily $PM_{2.5}$ concentrations for the 51-day period were determined using a chemical transport model developed by collaborators at the Commonwealth Scientific and Industrial Research Organisation (CSIRO) Oceans & Atmosphere Flagship. The model is a high resolution exposure model that estimates $PM_{2.5}$ at an hourly time step and a one-by-one kilometre spatial resolution [7]. The full model included background $PM_{2.5}$ from natural sources, vehicular and power station emissions, landscape fires and the mine fire. The difference between the CSIRO model run with and without emissions from the mine fire was used to determine the concentration of $PM_{2.5}$ specific to the mine fire. Although the fire was declared safe on 26 March 2014, small amounts of smoke emissions continued into the following week, so exposure modelling was continued until 31 March 2014.

Exposure was assigned by first identifying women who were pregnant 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 pregnancy exposures due to conception or birth during the fire event were only assigned $PM_{2.5}$ exposure estimates for the days during the fire that they were pregnant (i.e. days not pregnant during the fire were assigned zero values). Women who were not pregnant at all during the coal mine fire, including those who gave birth before the fire started on 9 February 2014 or conceived after the fire ended on 31 March 2014, 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. Exposure was assigned according to maternal residence at delivery at the geographically detailed level of Statistical Area Level 1 (SA1), as per the 2011 Australian Bureau of Statistics Australian Standard Geographical Classification. SA1s are small geographical classifications and contain approximately 400 individuals. SA1s aggregate directly into SA2s, which are medium-sized geographical classifications representing communities that interact socially and economically [13].

***2.1.3 Weather and other covariates:*** 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 adjust for underlying temporal and seasonal trends in outcomes.

We addressed potential confounding by considering *a priori* several maternal, pregnancy-related, meteorological and temporal characteristics. Maternal characteristics included mother's age (continuous outcome and dichotomous outcome: <35 years old and $\geq$35 years old) and area-level maternal socioeconomic position (Australian Bureau of Statistics Index of Relative Socioeconomic Disadvantage (IRSD) quintile assigned to the maternal residence at the level of SA1). IRSD is a composite measure that summarises information about economic and social circumstances of people and households within an area. Pregnancy-related characteristics included: parity (nulliparous, 1-2, 3 and above); smoking in early pregnancy (first 20 weeks; yes/no) and smoking in late pregnancy (last 20 weeks; yes/no). Meteorological characteristics included the mean daily temperature ($^{0}$C) for each trimester. Temporal characteristics included season of conception (winter, spring, summer and autumn) and year of conception.

We included singleton births in our analysis, as pregnancies complicated by multiple births are systematically different from singleton births. We were not able to distinguish multiple pregnancies within the study period to the same mother; therefore, eligible births may include more than one pregnancy to the same woman.

***2.1.4 Missing data:*** Missing data were handled using multiple imputation by chained equations (MICE package in R). Given the low proportion of missing data, twenty imputed datasets were considered adequate [14]. Covariates included in the multivariable regression models were used as imputer variables. Regression models were fitted using the imputed data.

### 2.2 Statistical analysis

Statistical analysis was conducted using R (v 3.4.0) [15]. The association between maternal exposure to coal-mine fire attributable $PM_{2.5}$ and dichotomous outcomes, including gestational diabetes mellitus, hypertensive disorders of pregnancy and conditions of abnormal placentation, were estimated using multivariable log-link binomial generalised linear models. Covariates that were included in the model were chosen if there was robust *a priori* evidence or if there was evidence that the covariate was associated with exposure, associated with the outcome and adjustment for the covariate altered the coefficient by greater than ten percent. Effect modification was explored for covariates where there was biological plausibility and the interaction term was significant in the model. The effect of timing of exposure in pregnancy was explored by including an interaction term for average and peak exposure and trimester at fire start, and marginal effects were explored using the R package 'ggeffects' [16]. We set the statistical significance level (α) at 0.05. Sensitivity analyses were conducted to examine the robustness of the main results, which included a subset analysis by gestation to exclude prevalent cases of gestational diabetes mellitus at the commencement of the fire. Where a significant association was observed, the attributable number was calculated to determine the number of additional cases that were directly attributable to the exposure.

The funding body had no role in data collection, analysis or interpretation of the findings; in writing the manuscript; and was not involved in the decision to publish.

## 3. Results

A total of 3,612 singleton pregnancies were included in the analysis; 766 (21.2%) of women were pregnant during the coal mine fire. Table 1 outlines the descriptive maternal, pregnancy and infant characteristics by exposure group. Median maternal age was 28 years (Interquartile range (IQR) 8 years) and approximately 40% of pregnant women were nulliparous (n = 1,428; 39.5%). Approximately six percent of women had a diagnosis of gestational diabetes mellitus (n = 224; 6.2%) and just under five percent of women had a diagnosis of a pregnancy-related hypertensive disorder (n = 164; 4.5%). Less than 1% had a condition related to abnormal placentation (n = 30; 0.8%). Just under half of labours were of spontaneous onset (n = 1,641; 45.4%) and method of birth was via Caesarean section for just over a quarter of births (n = 968; 26.8%). The median of the daily average maternal $PM_{2.5}$ exposure over the coal mine fire period was 1.9 μg/m$^3$ (IQR 2.1 μg/m$^3$) and median peak $PM_{2.5}$ exposure was 30.2 μg/m$^3$ (IQR 35.0) (Figure 1). There was minimal missing data; variables with the highest proportion of missing data were those relating to maternal smoking in early and late pregnancy; missing for 4.4% and 1.4% of the cohort respectively.

We did not find an association between maternal $PM_{2.5}$ exposure and hypertensive disorders of pregnancy or conditions of abnormal placentation. However, mean and peak maternal $PM_{2.5}$ exposure was strongly associated with gestational diabetes mellitus. An interquartile range increase in average $PM_{2.5}$ was associated with a 6% increased likelihood of gestational diabetes mellitus (RR 1.06; 95%CI 1.03, 1.10; $p < 0.001$) and an interquartile range increase in peak $PM_{2.5}$ was associated with a 15% increased likelihood of gestational diabetes mellitus (RR 1.15; 95%CI 1.08, 1.22; $p < 0.0001$) (Table 2). There were 16 additional cases of gestational diabetes mellitus directly attributable to fire smoke exposure. Examining the relationship by timing of exposure in pregnancy demonstrated that exposure in trimester two appeared to be of most importance, whereas exposure in trimester one or three was less important (Figure 2). The precision of estimates when examining trimester-specific effects were large, owing to the reduced sample size in these subsets.

While we do not have data regarding severity of gestational diabetes, we did compare outcomes known to be associated with glycemic control between gestational diabetic cases exposed to the fire and those not exposed to the fire. Using log-link binomial regression, there was no significant difference in likelihood of induction of labour, Caesarean section birth, preterm birth, macrosomia or requirement for neonatal admission to special care nursery or neonatal intensive care unit when comparing women with gestational diabetes who were exposed to the fire, compared to those who were not (Table 3.0).

**3.1 Sensitivity analysis**

We were not able to exclude prevalent cases of gestational diabetes mellitus because the timing of a diagnosis in pregnancy was not known. To address this, we conducted a subset analysis restricted to those in the first 24 weeks of pregnancy at the start of fire, as the majority of women are screened for gestational diabetes mellitus from 24 to 28 weeks gestation. The association was preserved in this subset analysis, whereby average and peak $PM_{2.5}$ were associated with an 8% and 23% increased likelihood of gestational diabetes mellitus per IQR increase, respectively (Average $PM_{2.5}$ 95%CI 1.01, 1.16; p = 0.018; Peak $PM_{2.5}$ 95%CI 1.06, 1.43; p <0.01 per 1QR increase). The prevalence of gestational diabetes mellitus was 7.8% (Table 4).

## 4. Discussion

We observed a strong association between maternal exposure to particulate matter from the coal mine fire and gestational diabetes mellitus, with the highest risk associated with exposure in the second trimester. Significant increases in risk were associated with both average exposure over the duration of the fire and peak exposure, although the magnitude of association was greatest for peak exposure. The association was preserved in the sensitivity analyses. To our knowledge, this is the first study to explore the relationship between maternal exposure to air pollution from a severe smoke event and gestational diabetes mellitus. While there is substantial evidence concerning ambient air pollution and type 2 diabetes in the non-pregnant adult population, the association between ambient air pollution and gestational diabetes mellitus is less well characterised [17]. In the few studies concerning gestational diabetes mellitus, findings suggest an association but are mixed regarding the relative importance of different pollutants, timing of exposure and susceptible subpopulations. A handful of studies have demonstrated an association between first or second trimester exposure to nitrogen oxides, fine particulate matter and ozone ($O_3$) exposure and gestational diabetes mellitus [1,18,19]. Alternatively, others have reported an association with impaired glucose tolerance, rather than occult gestational diabetes mellitus, or a relationship that is restricted to young mothers under the age of 20 years [2,20].

We found no evidence for increased risk of hypertensive disorders in pregnancy or conditions characterised by abnormal placentation in association with maternal exposure to fine particulate matter in emissions from the coal mine fire. This is at odds with an increasing number of studies that have demonstrated an association between ambient air pollution and hypertensive disorders of pregnancy [21-24]. On the other hand, there are limited studies exploring the relationship for conditions characterised by abnormal placentation. A Japanese study found an association between nitrogen dioxide ($NO_2$) exposure and placental abruption, but no association was observed for sulfur dioxide ($SO_2$), PM or $O_3$ [25]. Similarly, $NO_2$ and $SO_2$ have been associated with an increased risk of placenta praevia and suspended particulate matter with placenta accreta [26]. However, our study was limited by the relatively small study population, with just 164 (4.6%) cases of hypertensive disorders of pregnancy and 30 (0.8%) cases of abnormal placentation. The limited number of the latter also introduces the risk of potential sparse data bias. These low numbers precluded further analysis of these outcomes by timing of trimester at the start of the fire.

From a mechanistic point of view, it has been proposed that systemic inflammation, oxidative stress, ischemia, infarction and abnormal vascularisation associated with air pollution may underpin the obstetric complications of interest [27-29]. Trimester two exposure was associated with the greatest risk of gestational diabetes mellitus, which is biologically plausible as gestational diabetes represents a pathologic increase in the physiological insulin resistance that occurs in the second trimester [30]. Our findings could guide responses to smoke events in the future, by highlighting pregnant women as a particularly vulnerable subgroup of the population that requires targeted advice and heightened surveillance to avoid the health harms that we have described. Such targeted advice may include the recommendation of evidence-based interventions, such as portable air filter use within the home, avoidance of the most smoke-affected areas and possibly relocation, if safe and feasible to do so [31]. Additionally, clinicians caring for women exposed to a severe smoke event in early pregnancy could be alerted to the increased risk of gestational diabetes mellitus and associated complications, and ensure glucose tolerance testing and appropriate maternal and fetal surveillance is conducted.

The implications of these findings are of clinical and public health significance. Clinically, gestational diabetes mellitus confers increased morbidity to the mother, fetus and eventually the child in later life. Severe smoke events, such as that resulting from wildfires or coal mine fires, are likely to increase with a changing climate [9,32]. We observed an additional 16 cases of gestational diabetes mellitus in a relatively small exposed cohort. As such, smoke events affecting larger populations, for example in urban centres, may be associated with a much greater burden of gestational diabetes mellitus than observed in our regional population. Additionally, the implications of these findings are likely to extend beyond abrupt, time-limited smoke events. The particulate matter pollution that was observed during the coal mine fire is comparable, or lower, than ambient air pollution experienced in many cities in the world. For example, the annual average $PM_{2.5}$ in Beijing for 2018 was 73 μg/m$^3$, well above the average exposure of this study cohort (and the World Health Organisation guideline of 10 μg/m$^3$) [33]. However, it is unclear whether the change in exposure from background is important, that is, whether the physiological insult and response differs for a pregnant woman breathing air with low background levels of $PM_{2.5}$ who is suddenly exposed to a smoke event, compared to a woman breathing polluted air with an equivalent stepwise increase in fine particulate matter pollution. Further epidemiological studies examining both ambient air pollution and abrupt smoke events are required to support our findings, including further elucidation of underpinning biological mechanisms.

Major strengths of this study included the use of deidentified administrative data that enabled us to study a complete cohort of pregnant women with births after 20 weeks gestation who were resident in the affected region before, during, and after the fire. Further, by combining information from monitoring and atmospheric transport models we were able to assign exposure at high geographical resolution. However, by assigning exposure to maternal residence at delivery, we were unable to capture potential residential mobility during the fire, which may have introduced exposure misclassification bias. The direction of such bias is unclear. Additionally, we did not have data on the timing of complication relative to exposure during pregnancy. As such, we cannot demonstrate temporality. However, we tested this in a sensitivity analysis, by restricting the analysis to women in early pregnancy (and therefore less likely to have prevalent gestational diabetes mellitus).

The prevalence of gestational diabetes mellitus in our cohort was 6.2%, which is comparable to the Victorian rate of 7.5% in 2011. The lower prevalence may be explained by the younger age profile of our pregnant cohort of whom 13.2% are aged 35 years or older compared to 25.0% in the wider Victorian pregnant population [34]. The diagnostic threshold for gestational diabetes mellitus was lowered during the study period, which would have increased the prevalence in the Australian population during the study period. Although formal implementation was recommended by 1 January 2015, implementation was phased in at various times during the study period, varying by practitioner and laboratory. We accounted for this change in diagnostic criteria by including year of conception in our statistical models. The preservation of the finding following adjustment for year of conception is reassuring and indicates the results were not driven by an artificial increase in the prevalence of gestational diabetes mellitus over the study period. Additionally, a small proportion of prevalent gestational diabetes mellitus cases are likely to reflect undiagnosed type 2 diabetes mellitus and we were unable to discern this from the data. Finally, we did not have data on the severity of gestational diabetes and were only able to comment on possible markers of clinical severity.

## 5. Conclusion

Maternal exposure to fine particulate matter resulting from a coal mine fire in the second trimester was significantly associated with gestational diabetes mellitus. No association was observed for the less common outcomes, including hypertensive disorders of pregnancy and conditions such as placental praevia and abruption. Given the immediate, short- and long-term morbidity associated with gestational diabetes mellitus, these findings are of potential public health significance and may guide the public health response to future similar events. Further research examining both ambient air pollution and abrupt, time-limited air pollution events, is required to support our findings and guide emergency and public health responses to similar events in the future.

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***Authorship contributions:*** SM was involved in study conceptualisation, data curation, methodology, formal analysis, visualisation, funding acquisition, writing the original draft and incorporation of feedback to inform the final manuscript. JF was involved in study conceptualisation, methodology, formal analysis, supervision, validation and review and editing of the final manuscript. KW was involved in study conceptualisation, methodology, formal analysis, supervision, validation and review and editing of the final manuscript. AV was involved in study conceptualisation, methodology, project administration, funding acquisition, supervision, validation and review and editing of the final manuscript. FJ was involved in study conceptualisation, data curation, methodology, formal analysis, project administration, funding acquisition, supervision, validation and review and editing of the final manuscript.

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**Table 1.** Descriptive maternal, pregnancy, labour and neonatal statistics for all singleton births in the Latrobe Valley, Victoria during the study period

| | Total cohort<br><br>N = 3612 | Pregnant during the coal mine fire<br><br>N = 766 | Not pregnant during the coal mine fire<br><br>N = 2846 |
|---|---|---|---|
| **Maternal and pregnancy characteristics** | **N (%)** | **N (%)** | **N (%)** |
| Age 'high-risk' (≤19 or ≥35 years old) | 697 (19.3) | 140 (18.3) | 557 (19.6) |
| Aboriginal and/or Torres Strait Islander | 119 (3.3) | 24 (3.1) | 95 (3.3) |
| Country of birth Australia | 3257 (90.2) | 694 (90.6) | 2563 (90.1) |
| Nulliparous | 1428 (39.5) | 307 (40.1) | 1121 (39.4) |
| Diagnosis of gestational diabetes mellitus | 224 (6.2) | 60 (7.8) | 164 (5.8) |
| Diagnosis of hypertensive disorder of pregnancy* | 164 (4.6) | 26 (3.4) | 138 (4.9) |
| Diagnosis of abnormal placentation** | 30 (0.8) | 7 (0.9) | 23 (0.8) |
| **Labour and birth characteristics** | **N (%)** | **N (%)** | **N (%)** |
| Spontaneous onset of labour | 1641 (45.4) | 328 (42.8) | 1313 (46.1) |
| Caesarean section birth | 968 (26.8) | 224 (29.2) | 744 (26.1) |
| Preterm birth (<37 weeks gestation) | 308 (8.5) | 68 (8.9) | 240 (8.4) |
| Low birth weight at term (<2, 500 grams at >37 weeks gestation) | 71 (2.0) | 10 (1.3) | 61 (2.1) |

| | | | |
|---|---|---|---|
| Small for gestational age (<10th centile birth weight for gestational age) | 318 (8.8) | 59 (7.7) | 259 (9.1) |
| Large for gestational age (>90th centile birth weight for gestational age) | 434 (12.0) | 95 (12.4) | 339 (11.9) |
| **Infant characteristics** | **N (%)** | **N (%)** | **N (%)** |
| Female gender | 1782 (49.3) | 373 (48.7) | 1409 (49.5) |
| Aboriginal and/or Torres Strait Islander | 157 (4.4) | 34 (4.4) | 123 (4.3) |
| Congenital anomaly identified | 267 (7.4) | 45 (5.9) | 222 (7.8) |
| Admitted to Special Care Nurse or Intensive Care Unit | 835 (23.1) | 184 (24.0) | 651 (22.9) |
| | **Median (IQR)** | **Median (IQR)** | **Median (IQR)** |
| Gestational age | 39 (38, 40) | 39 (38, 40) | 39 (38, 40) |
| Birthweight (grams) | 3460 (3074, 3805) | 3462 (3086, 3810) | 3460 (3070, 3800) |

**Footnotes:**

*Hypertensive disorders of pregnancy include pregnancy-induced hypertension, preeclampsia and eclampsia

**Abnormal placentation conditions include morbidly adherent placenta (placenta accrete and percreta), placenta praevia with haemorrhage and placental abruption

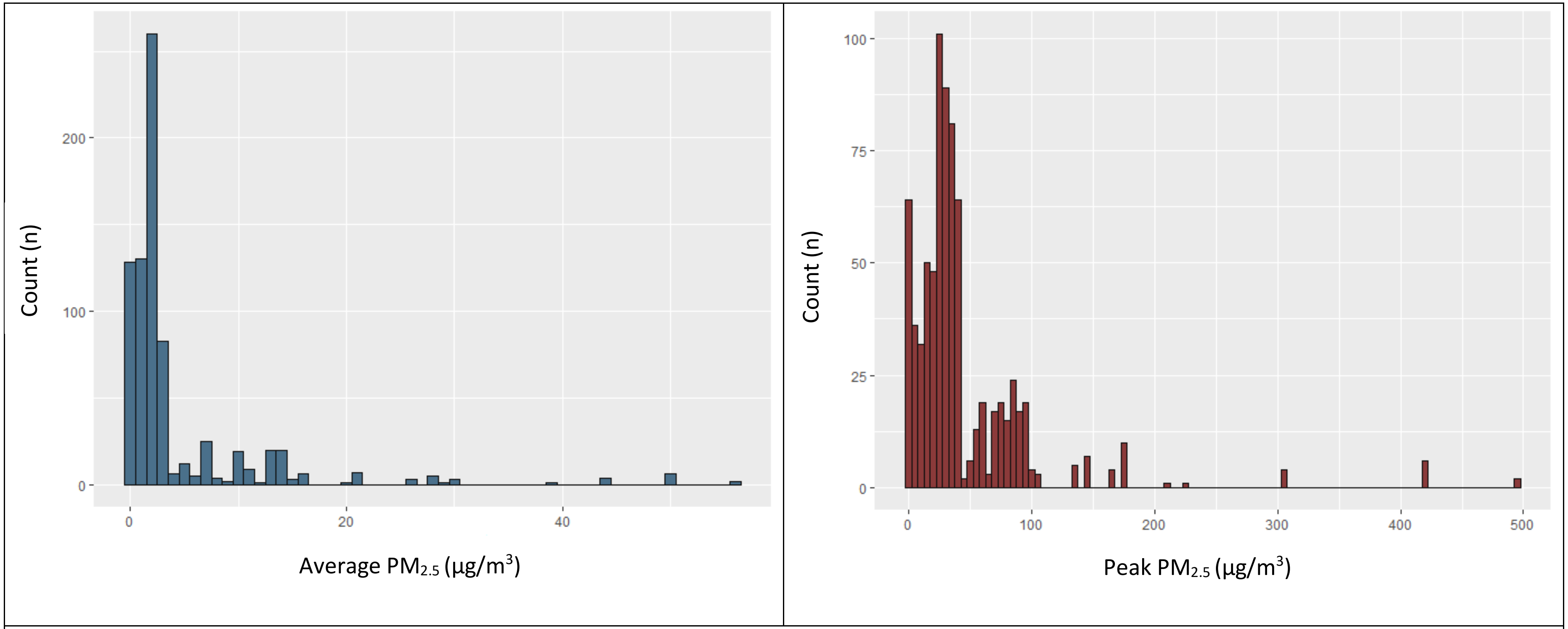



**Figure 1.** Average and peak $PM_{2.5}$ (µg/m$^3$) exposure during the coal mine fire period among pregnant women

**Table 2.** Association between maternal average and peak $PM_{2.5}$ exposure attributable to the coal mine fire and obstetric outcomes

| **Exposure** | **Gestational diabetes mellitus** | | **Hypertensive disorder of pregnancy*** | | **Abnormal placentation**** | |
|---|---|---|---|---|---|---|
| | **Unadjusted** | **Adjusted[a]** | **Unadjusted** | **Adjusted[b]** | **Unadjusted** | **Adjusted[c]** |
| | **RR (95%CI); p value** | **RR (95%CI); p value** | **RR (95%CI); p value** | **RR (95%CI); p value** | **RR (95%CI); p value** | **RR (95%CI); p value** |
| **Average $PM_{2.5}$ (per IQR increase)** | **1.08 (1.05, 1.11); <0.0001** | **1.06 (1.03, 1.10): <0.001** | 0.99 (0.90, 1.08); 0.75 | 0.95 (0.78, 1.15); 0.59 | 1.04 (0.90, 1.19): 0.62 | 1.02 (0.88, 1.17); 0.81 |
| **Peak $PM_{2.5}$ (per IQR increase)** | **1.19 (1.13, 1.25); <0.0001** | **1.15 (1.08, 1.22); <0.0001** | 1.00 (0.92, 1.09); 0.99 | 0.98 (0.81, 1.19); 0.86 | 1.03 (0.89, 1.18); 0.71 | 1.00 (0.71, 1.40); 0.98 |

Footnotes:

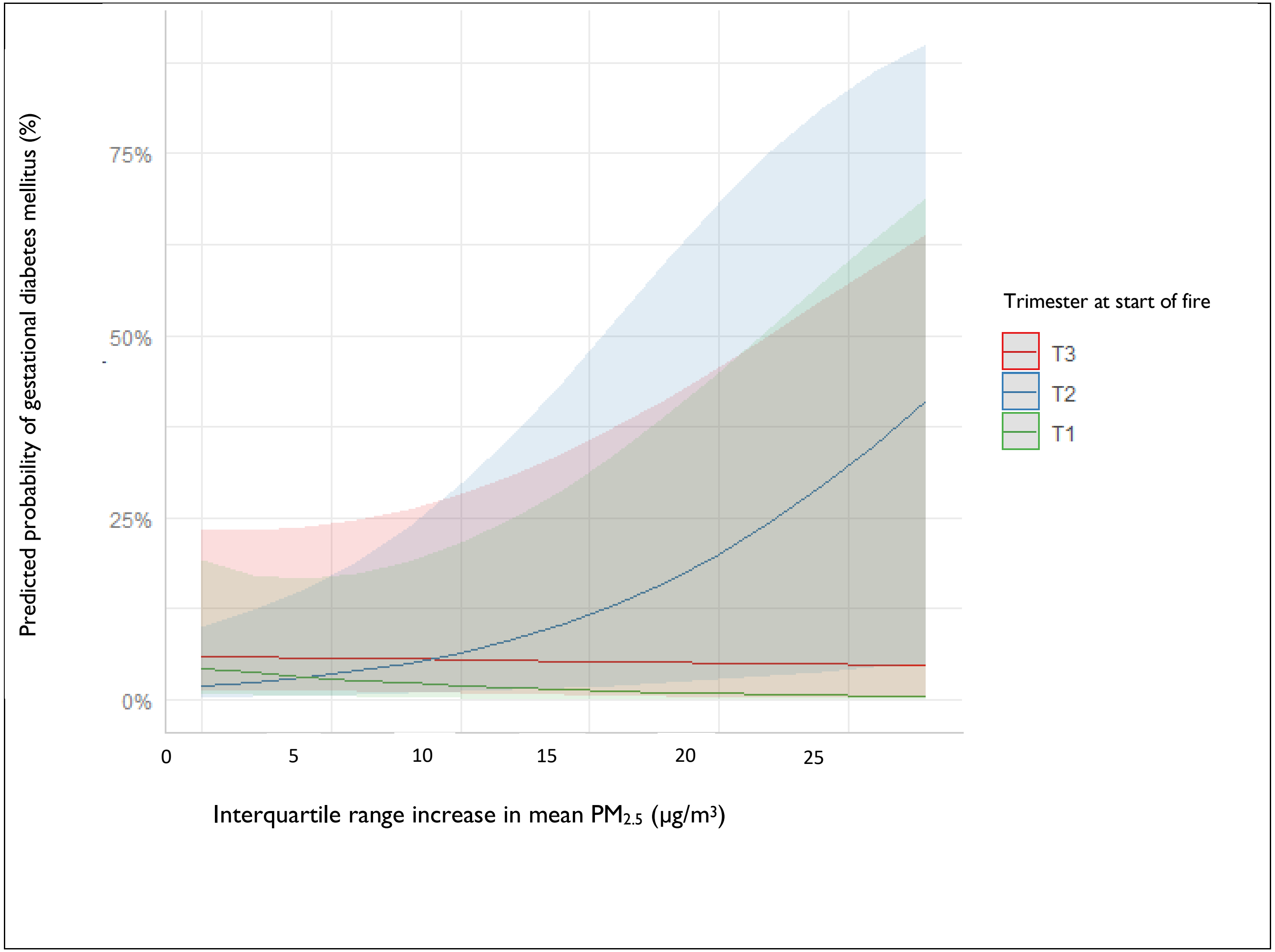
*Hypertensive disorders of pregnancy include pregnancy-induced hypertension, preeclampsia and eclampsia

**Abnormal placentation conditions include morbidly adherent placenta (placenta accrete and percreta), placenta praevia with haemorrhage and placental abruption

a Adjusted for smoking in early pregnancy, smoking in late pregnancy, maternal age ≥35 years old, maternal socioeconomic status (IRSD), season of conception and year of conception

b Adjusted for smoking in early pregnancy, smoking in late pregnancy, mother's age (continuous), parity, gestational diabetes mellitus, maternal socioeconomic status (IRSD) and year of conception

c Adjusted for smoking in early pregnancy, smoking in late pregnancy, maternal age ≥35 years old, parity and maternal socioeconomic status (IRSD)



Predicted probability of gestational diabetes mellitus (%)
75%
50%
25%
0%
0
5
10
15
20
25
Interquartile range increase in mean PM2.5 (μg/m3)
Trimester at start of fire
T3
T2
T1

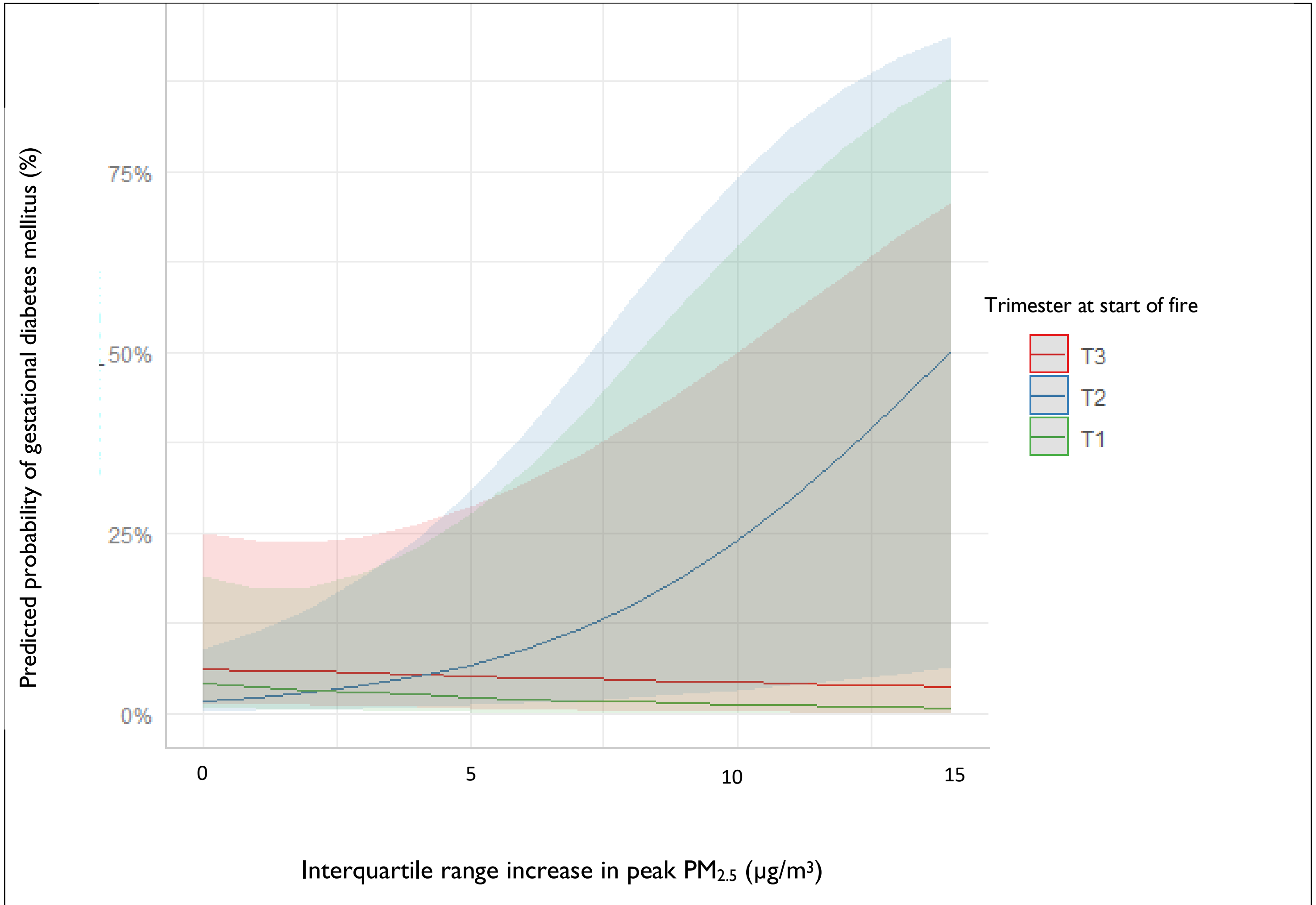



**Figure 2.** Relationship between average and peak $PM_{2.5}$ exposure and likelihood of gestational diabetes mellitus by trimester at the start of the coal mine fire

**Table 3.0** Likelihood of fetal growth, fetal maturity, labour and postnatal outcomes in cases of gestational diabetes mellitus exposed to the coal mine fire compared to unexposed cases of gestational diabetes mellitus

| Fetal growth, fetal maturity, labour and postnatal characteristic | RR (95%CI); p value |
|---|---|
| Small for gestational age | 0.68 (0.20, 2.34); 0.54 |
| Macrosomia (>4, 000 g at any gestation) | 1.07 (0.52, 2.18); 0.85 |
| Preterm birth | 0.51 (0.15, 1.70); 0.27 |
| Required induction of labour (compared with spontaneous onset) | 1.16 (0.95, 1.42); 0.14 |
| Caesarean section birth | 0.89 (0.62, 1.30); 0.56 |
| Required Special Care Nursery or Neonatal Intensive Care Unit admission | 0.99 (0.95, 1.02); 0.48 |

**Table 4.0** Sensitivity analyses exploring the association between maternal average and peak $PM_{2.5}$ exposure and gestational diabetes mellitus in a subset of the study population

| Study population | Average $PM_{2.5}$ * Per IQR increase RR (95%CI); p value | Peak $PM_{2.5}$ * Per IQR increase RR (95%CI); p value |
|---|---|---|
| Pregnant and gestation equal to or less than 24 weeks at the start of the fire (N = 511) | **1.08 (1.01, 1.16); 0.018** | **1.23 (1.06, 1.43); <0.01** |

*Adjusted for smoking in early pregnancy, smoking in late pregnancy, maternal age ≥35 years old, maternal socioeconomic status (IRSD), season of conception, year of conception