**Birth outcomes, health and healthcare needs of childbearing women following wildfire disasters: An integrative, state of the science review.**

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**Abstract**

**Background**: The frequency and severity of extreme weather events such as wildfires are expected to increase in response to climate change. Childbearing women, that is, women who are pregnant, soon to be pregnant or have recently given birth, may be particularly vulnerable to the effect of wildfire exposure.

**Objectives**: This review sought to systematically assess what is known about birth outcomes, health and healthcare needs of childbearing women during and after exposure to wildfires.

**Methods**: An integrative review methodology was utilised to enable article selection, data extraction and synthesis across qualitative and quantitative studies. Comprehensive searches of SCOPUS (including Medline and Embase), CINAHL, PubMed and Google Scholar identified studies for inclusion with no date restriction. Included studies were independently appraised by two reviewers using the Crowe Critical Appraisal Tool. The findings are summarised and illustrated in tables.

**Results**: Database searches identified 480 records. Following title, abstract and full text screening, sixteen studies published between 2012-2022 were identified for this review.

Eleven studies considered an association between *in utero* exposure to wildfire and impacts on birthweight and length of gestation. One study reported increased rates of maternal gestational diabetes mellitus and gestational hypertension following exposure; while one study reported differences in the secondary sex ratio. Two studies reported higher incidence of birth defects following in utero exposure to wildfire smoke. Three studies reported increased mental health morbidity, while one study associated a reduction in breastfeeding among women who evacuated from a wildfire disaster.

**Discussion:** Evidence indicates that wildfire exposure may be associated with changes to birth outcomes and increased morbidity for childbearing women and their babies. These effects may be profound and have long-term and wide-ranging public health implications. This research can inform the development of effective clinical and public health strategies to address the needs of childbearing women exposed to wildfire disaster.

**Keywords:** wildfire, bushfire, climate change, birth outcomes, birthweight, birth defect, gestational diabetes mellitus, mental health, pregnancy, preterm birth, midwifery.

1. **Introduction**

While fire, both naturally occurring and anthropogenic in nature, has shaped the landscape and influenced the natural biome for millions of years, wildland fires that are catastrophic to the ecosystem or human society, have been rare throughout history.1 Climate change and an increase in populations living close to the wildland-urban interface have contributed to increased frequency and intensity of wildfires.2

The United Nations identifies climate change as ‘the defining issue of our time… global in scope and unprecedented in scale’.3 The World Health Organization (WHO) cites climate change and related natural disasters as having a major negative effect on the social and environmental determinants of health and estimates more than 250,000 climate-related deaths per year by 2030.4

The impetus for this work arose in response to the extreme Australian 2019-20 bushfire season (the Black Summer). Throughout the spring and summer of 2019-20, the changing global climate contributed to an extreme bushfire season across the Australian continent resulting in devastating loss of life, property, wildlife, and environmental destruction.5

There are numerous studies and reviews available on natural disasters and the effects of exposure to disaster events on the health of childbearing women and their babies, with outcomes related to decreased fetal growth, increased maternal mental health morbidity, as well as adverse outcomes relating to the sexual and reproductive health of women, and their increased economic vulnerability both during and after disaster.6 Exposure to disaster has also been reported to influence the secondary sex ratio.7-9

The smoke from wildfires is a source of fine particulate matter (PM2.5) and presents a risk to human health.10,11 Maternal exposure to PM2.5 is well studied and exposure is associated with a reduction in birthweight,12,13 increased incidence of preterm birth,14 increased incidence of cleft palate,15 as well as development of gestational diabetes mellitus (GDM).16-18

The effect of wildfire exposure on birth, health outcomes, and healthcare needs of childbearing women, that is, women who are pregnant, soon to be pregnant or have recently given birth, and their babies, is the focus of this review. In this context, wildfire is defined as an unplanned, uncontrolled fire in areas of vegetation and includes fires that would be described using the Australian English term ‘bushfire’. Given that climate change will continue and natural disasters including wildfires are anticipated to increase in frequency and severity, understanding how wildfires impact on birth outcomes and gathering evidence to support the health and healthcare needs of childbearing women during and after wildfire events is important. To our knowledge, this is the first integrative review to consolidate the evidence on the impact of this exposure on birth outcomes and childbearing women’s health and healthcare needs.

1. **Methodology**

An integrative review methodology based on the framework proposed by Whittemore and Knafl,19 was chosen to enable article selection, data extraction and synthesis across qualitative and quantitative studies in order to gain a holistic understanding of the topic and to present comprehensive perspectives to answer the research question ‘What do we know about birth outcomes and health and healthcare needs of childbearing women during and after exposure to wildfire smoke or a wildfire disaster?’

A protocol for this review was registered in the International Prospective Register of Systematic Reviews database (PROSPERO # 42020214499) on 15 November 2020.

* 1. **Search Strategy**

A comprehensive, reproducible search strategy was developed to identify relevant qualitative and quantitative studies. Thematic, systematic searches were performed by JE and replicated by DD using the search string described in Table 1. Final searches were performed on 19 May 2022. SCOPUS (including Medline and Embase), PubMed and CINAHL searches used identical terms, the Google Scholar search used a simpler syntax in an effort to conveniently return relevant grey literature. To maintain manageable scope - only the first 50 Google Scholar matches were considered. To further scope, reference lists of studies for full text review were hand searched to identify additional studies (JE).

* 1. **Inclusion and exclusion criteria**

Titles and abstracts were double screened independently (JE, DD) to assess eligibility by applying inclusion and exclusion criteria. They were first screened by title and abstract and further after full text review. In order to be included in the review, studies had to be original wildfire specific research with outcomes relevant to the research question. Case studies and reviews were excluded. Any pregnancy or birth outcome was considered, and healthcare and social needs of childbearing women were included. No date limitation was applied to the search. Non-wildfire studies were excluded, for example fires associated with other disasters, fires associated with specific industries, or prescribed burns or fires which were agricultural in nature, for example to clear land for farming, or to prepare a crop for harvest. Non-English language articles were excluded, as were non-human studies.

* 1. **Quality assessment**

Critical appraisal of the sixteen full text articles was undertaken by two reviewers independently (JE & DD) and scored using the Crowe Critical Appraisal Tool v1.4 (CCAT).20 The CCAT is particularly suited to assess quality of evidence in this review as it is a tool that can be used to compare and appraise evidence quality in a standardised way across a range of research designs including quantitative and qualitative studies.21 Following the CCAT framework, appraisal of each study focused on eight domains - Preliminaries, Introduction, Design, Sampling, Data collection, Ethical matters, Results, and Discussion. A checklist of items is provided for each domain to guide appraisal, some of which will not apply to certain study designs. For example, the domain “design” includes assessment of the justification for design, the suitability of the design, justification, definitions and validity of exposures and outcomes, including methods of measurement, potential sources of bias including confounding, effect modification, procedures for randomisation (where appropriate), group balance and equivalence. Details of the criteria can be found in the User Guide.22 Each domain is scored (from 0-5) though appraisers are encouraged to take a holistic view to make a judgment in relation to scoring rather than relying solely on the checklist. While this allows the appraisal framework to be used across study designs it also introduces a level of subjectivity to the process. Appraisers are also encouraged to publish scores for each domain rather than only totals so that a more granular understanding of the appraisal is presented. The strength of this framework lies in the comprehensive, consistent and standardised framework provided for the appraisal across a variety of research designs. Overall, all sixteen studies were deemed of sufficient quality to be included in this review, with CCAT scores ranging between 66.5 and 96.365. Each reviewer’s score across each of the domains as well as the average of reviewers total scores are included in Table 2.

* 1. **Data extraction and synthesis**

Features of included studies were extracted in tabular format to facilitate analysis and comparison across studies by one researcher and audited by a second. This table included data on individual studies including year of publication, study duration, study design, study objective and data sources; characteristics of the wildfire event of interest including: fire duration and fire size; exposure measurement including: exposure period; outcomes assessed; findings including: outcomes assessed, statistics and qualitative themes. Pooling of data for meta-analysis was not deemed reasonable given heterogeneity in study designs, methods, exposures and outcomes. Rather, a synthesis was undertaken whereby findings related to specific outcomes, from a range of studies are presented within descriptive themes.

1. **Results**
   1. **Search results**

Database searches identified 480 records. Three records were identified through reference list searches. After duplicates were removed, 364 records were screened by title and abstract. Title and abstract screening resulted in the removal of 343 records for the following reasons – 77 were not original research, 152 had outcomes that were not relevant to the objectives of this study, 61 were not wildfire-specific studies and 53 were not human studies. Twenty one full text articles were assessed for eligibility with four excluded as they were deemed ‘agricultural’ fires and one excluded as it was outlining a protocol for a study that had not yet started.

Sixteen studies published between 2012-2022 met criteria and were included in this review.

One study23 re-reported some outcomes from previously published studies,24,25 however as this study also included re-analysis of some data and a qualitative component, it was deemed worthwhile to be included as a separate body of work.

The search results are summarised in Fig.1 using the Preferred Reporting Items for Systemic Reviews and Meta-Analysis (PRISMA)26 flowchart to depict the process.

* 1. **Study designs**

Of the included studies in this review: thirteen were quantitative (ten retrospective cohort studies,24,25,27-34 one case control study,35 one time stratified case crossover study36 and one longitudinal study37), two used mixed methods,23,38 and one was a qualitative study.39 (Table 3)

* 1. **Study population, exposure measurement and data sources**

Fifteen studies included women who were pregnant or soon to become pregnant at the time of wildfire disaster or wildfire smoke hazard, the exception to this is the De Young et al. study,38 which used feeding an infant 0-36 months of age at the time of exposure to wildfire as inclusion criteria. Eight studies focussed on local populations exposed to a single, specific wildfire event,23-25,28,34,37-39 while seven focussed on longer term exposure to wildfire smoke across fire seasons over a span of years 27,30-32,35,36 and one focussed on exposure to mega-fire flame zones – that is fires over 100,000 acres in size.29

All quantitative studies as well as the quantitative component of the O’Donnell (2017)23 mixed methods study used local administrative neonatal collections for birth statistics. Maternal residential address,23,24,32,34,40 zip code,27,30,33 county,28,29 or maternal municipality 31,35,36 at time of birth were used as a proxy for nearness to fires or smoke. Each study used a different method to determine exposure to the wildfire disaster or wildfire smoke hazard including a mix of land based geographical borders,23-25,29,30 satellite-based imagery or models,27,28,31-36 land-based air quality monitors27,31,33-36 and personal air quality monitors within specific coordinates.28 Detailed information is included in Table 3.

The two mixed methods one qualitative and one longitudinal study used purposive sampling23,37-39 and women were recruited into studies using social media,23,37-39 mainstream media,38,39 online forums,23,37 websites,23,37 and local medical services or community centres23,37 to assist with recruitment. All qualitative studies collected maternal demographic data and all measured exposure as direct exposure to and/or evacuation from a wildfire event. These studies included a demographic survey component, two included a thematic analysis of open-ended responses,37,38 while one included thematic analysis of women’s expressive writing journal entries39 and one included semi-structured interviews.23 Two studies incorporated standardised questionnaires.23,37

**Study findings by theme**

Birthweight and gestational age at birth, including incidence of preterm birth were the most studied outcomes of the quantitative studies, whereas mental health impacts and protective factors were the most studied outcomes in the mixed methods / qualitative studies (Table 4).

* 1. **Birth outcomes findings**

Twelve quantitative studies and the quantitative component of O’Donnell (2017)23 reported on birth outcomes during and after exposure to wildfire smoke or a wildfire disaster.

* + 1. **Birthweight and gestational age at birth**

Eight studies sought to test various hypotheses that exposure to a wildfire disaster would affect birthweight.23-25,29,32-35 All studies considered the relationship between birthweight and gestational age, and used various methods to control for this relationship within analysis. Six studies reported a reduction in birthweight following exposure to a wildfire disaster or wildfire smoke. Findings include: higher rates of incidence of low birthweight (<2500g), (an increase of 0.8% from a base of 7%), and 16.56g lower birthweight (from a base of 3296g) following exposure to mega-fires compared to non-exposure in the USA 2010-201729; 3.8% lower birthweight and 0.034 increase in the probability of low birthweight (<2500g) compared to an unexposed group following wildfire smoke exposure in Colorado, USA between 2007-201332; an increase of 18.55% change in risk associated with low birthweight (<2500g) following an increase of 100 wildfire records in the South region in Brazil 2001- 201835; a 5.7g reduction in birthweight for each µg/m3 increase in trimester average wildfire PM2.5 exposure in the first trimester of pregnancy in Colorado, USA, 2007-201533; 150% higher incidence of very low birthweight babies (<499g) in affected areas in the two months following exposure to the 2009 Black Saturday bushfires, Victoria, Australia compared to not affected areas24; and, lower birthweight at term (-6.1g, 37-41 weeks gestation) for any trimester exposure to the 2003 California wildfires with a -7.0g difference at term for third trimester exposure, and a -9.7g difference at term for second trimester exposure when compared to unexposed pregnancies in years before and after the fires.34

Two studies reported an increase in birthweight following maternal exposure to the 2003 Canberra bushfire.23,25 After controlling for differences in birthweight by sex, male babies born in the severely affected area were on average 197g heavier compared to male babies born in the moderately affected area following in utero exposure to the 2003 Canberra bushfire.23,25 These studies also reported an increased incidence of macrosomia, that is birthweight greater than the 90th centile for gestational age, for male babies following in utero exposure to this bushfire, with the largest increase occurring for males born between 4501-5000g.23,25

Where timing of exposure to wildfire and association with birthweight were considered, results varied. Both first trimester exposure 33,35 and all trimester exposure 32,34 resulted in a reduction in birthweight. Proximity of exposure and severity of exposure to wildfire disaster was also associated with a reduction in birthweight,24,25,29 while elevated exposure to wildfire-related PM2.5 was associated with a reduction in birthweight, with a dose / response relationship observed.33

Eight studies reported on wildfire exposure and gestational age at birth.23-25,27-29,33,36 Findings varied between studies and fire events. Findings included: increased odds of preterm birth after exposure to ‘wildfire-wave’ related PM2.5 with differences between Brazil’s geographic regions and trimester of exposure (OR 1.41 41 [95%CI: 1.31-1.51]) following first trimester exposure in Southeast region, (OR 1.04 [95%CI: 1.01-1.07]) following first trimester exposure in Midwest region, (OR 1.05 [95%CI: 1.01-1.09]) following second trimester exposure in North region and (OR 1.06 [95%CI: 1.04-1.0]) following second trimester exposure in South region36; increased risk of preterm birth following exposure to the 2018 Camp Fire, California, (aRR 1.10 [95% CI: 1.03, 1.17]) when compared to births that occurred a year earlier, with a dose/response effect evident when comparing exposure between the highest and lowest tertiles.28

The incidence of preterm birth in areas affected by fire increased by 50% for babies born at 20-27 weeks gestation in the three months following the 2009 Black Saturday bushfires, Victoria, Australia and both preterm and post term birth increased for second and third trimester exposure to the fires compared to births in areas not affected by fire.24 There was little or no change to gestational age at birth for women who resided in severely-affected areas compared with least affected areas following the 2003 Canberra Bushfires23,25; while each 1µg/m3 increase in concentration of wildfire generated PM2.5 was associated with increased incidence of preterm birth for women exposed to wildfire smoke in Colorado, USA 2007-2015 at any time during pregnancy (OR 1.078 [95% CI: 1.016, 1.139, p=0.013]), with increased effect for second trimester exposure (OR 1.132 [95% CI: 1.088, 1.178, p<0.0001]).33 There was a 1.2% increase in incidence of preterm birth, from a base of 10% for women exposed to mega-fires compared to non-exposure in the USA, 2010-201729; and increased risk of preterm birth with each additional day of wildfire smoke exposure in California, USA, 2006-2012, at any time during pregnancy (RR 0.49% [95% CI: 0.41% - 0.59%]), with a larger effect for second trimester (RR 0.83% [95% CI: 0.71% - 0.96%]) and third trimester (RR 0.68% [95% CI: 0.49% - 0.87%]) exposure.27

* + 1. **Birth Defects**

Two studies examined the association between exposure to wildfire and birth defects.30,31 One study of wildfire exposure in California, USA between 2007-2010 reported that first trimester exposure, compared to no exposure was associated with higher rates of gastroschisis: 7.8 vs 5.7 per 10,000 births (aRR 1.28 [95% CI: 1.07, 1.54]).30 This study also found that pre-pregnancy wildfire exposure (up to 30 days before pregnancy) compared to no pre-pregnancy exposure resulted in higher rates of gastroschisis: 12.5 vs 5.7 per 10.000 births (aRR 2.17 [95% CI: 1.42, 3.52]).30

A study of wildfire-related air pollution exposure in Brazil 2001-2018 reported an increase in exposure to wildfire (measured as an increase in number of wildfire records) increased odds of cleft lip/cleft palate and second trimester exposure (OR 1.007 [95% CO: 1.001, 1.013]), congenital anomalies of the respiratory system following second trimester exposure (OR 1.002 [95% CI: 1.002, 1.023]), and congenital anomalies of the nervous system following first trimester exposure (OR 1.002 [95% CI: 1.001, 1.003]) in the South, North and Midwest regions in Brazil.31

* + 1. **Secondary Sex Ratio**

Changes to secondary sex ratio (proportion of male to female babies at birth) following wildfire exposure was considered in two studies.23,24 One study of the 2009 Black Saturday bushfires found no change to the secondary sex ratio for babies in utero at the time of the fire compared to non-exposed births.24 However, a later analysis which included births that were conceived after the fires showed a statistically significant decrease in the secondary sex ratio, with a male birth rate of 46.6% in the severely affected regions compared with a male birth rate of 51.1% in the remainder of Victoria.23

* + 1. **Other findings: Neonatal Intensive Care Unit (NICU) admission and assisted ventilation following birth**

One study reported each 1µg/m3 increase in concentration of wildfire generated PM2.5 was associated with a negative association between NICU admission and wildfire smoke exposure (OR 0.957 [95% CI: 0.926, 0.989, p= 0.0093]), and a negative association between assisted ventilation following birth following in utero wildfire smoke exposure (OR 0.875 [95% CI: 0.837, 0.915, p <0.0001]).33

* 1. **Childbearing women’s healthcare needs findings**

Five studies reported on childbearing women’s healthcare needs during and after exposure to wildfire smoke or a wildfire disaster.23,33,37-39 The outcomes reported were: gestational diabetes mellitus, gestational hypertension, mental health impacts including fear, stress, trauma and Post Traumatic Stress Disorder (PTSD) and protective effects of social support and resilience; social outcomes including use of alcohol and smoking; violence against women; breastfeeding and infant feeding and access to healthcare.

* + 1. **Health of childbearing women: gestational diabetes mellitus (GDM), gestational hypertension**

One study of the Canberra bushfires found no increase in the incidence of GDM for women who resided in severely-affected or least affected areas during the fires.25 In contrast, a study of wildfire smoke exposure in pregnancy in Colorado between 2007-2015 reported a significant positive association with each 1µg/m3 increase in concentration of wildfire generated PM2.5 and GDM for women exposed in the first trimester (OR 1.144 [95% CI: 1.064, 1.230, p=0.0003]) and also across the entire pregnancy (OR 1.151 [95% CI: 1.034, 1.281, p=0.010]).33

One study reported a dose / response association, with each 1µg/m3 increase in concentration of wildfire generated PM2.5 increasing the odds of gestational hypertension across whole pregnancy (OR 1.204 [95% CI – 1.083, 1.339, p=0.0006]), as well as for first trimester (OR 1.140 [95% CI: 1.071, 1.231, p=0.0001]) and second trimester (OR 1.124 [95% CI – 1.044, 1.211, p=0.0020]) exposure.33

* + 1. **Childbearing women’s experience of wildfires**

Three studies considered mental health impacts of exposure to wildfires on childbearing women.23,37,39 The women in each of these studies were pregnant or breastfeeding infants at the time of exposure to wildfire. These qualitative and longitudinal studies explored outcomes in thematic analysis, used formal screening tools and looked at the possible protective effects of strong social support and personal resilience.

One study hypothesized that peritraumatic stress would predict PTSD-like symptoms in childbearing women exposed to the Fort McMurray wildfire and social support and resilience would be protective factors. Peritraumatic distress and dissociative experiences were positively correlated with PTSD symptoms and with each other. Resilience had a protective effect on PTSD symptoms. Social support and satisfaction with social support were protective for women with less severe PTSD symptoms, however for women who reported very high PTSD symptoms, social support satisfaction no longer provided a protective effect.37

The themes of trauma and fear were identified in two studies. Women identified exposure to wildfire as the most traumatic event in their life, expressing trauma due to the fear of dying, or fear of their family dying or being injured in the fires, or fear of becoming trapped or separated from their family as they evacuated from the fires.23,39 Some women expressed despair due to loss of livestock and pets as well as damage to property and returning to damaged environments while others reported that they often relived wildfire-associated trauma when others in their community retold their experiences of the fires.23

Some women expressed being particularly fearful of both the immediate and long-term effects of wildfire-related stress on their unborn baby, themselves and other family members.39 Concerns about air quality and pre and postnatal smoke exposure effects on themselves and their babies were conveyed by women.23

Women reported that being displaced or evacuated from the family home, leaving partners to defend against fires, or being separated from family members during evacuation was stressful.23,39 In Australia, mandatory bushfire evacuation is not enforced, instead a policy of ‘stay and defend or leave early’ exists, although around half of the women in the O’Donnell (2017)23 study chose to evacuate as the fires approached. In comparison, the whole population of Fort McMurray was under a mandatory evacuation order and left the city as the wildfire approached. Psychological stressors, including pressure to complete paperwork when dealing with government and insurance agencies following the fires, and lack of support around alternate housing after the fires persisted long after the fires were out.23,39

Practices and strategies that foster resilience were identified as major themes in two studies. Women reported that expressive writing was therapeutic as it offered an opportunity for self-reflection, re-valuation and clarity.39 Journal writing, sharing stories of the evacuation, connecting with faith, meditation, yoga, breathing and physical exercise were identified as useful while coping with the evacuation and the aftermath of the fires.23,39 Formal counselling was identified by some women as effective to achieve positive recovery from trauma.23,39 Many women found that the fire experience resulted in personal, interpersonal and community post-traumatic growth, with adaptability and acceptance of change accelerating the healing process.23,39

The theme of relationships and changes to relationships was a focus of the experiences of women who participated in three studies.23,38,39 Some women reported positive relationship changes following the evacuation from the fire, that included becoming more appreciative of relationships with family, friends and new connections that were made with others in the community who had also experienced the fire.39

Conversely, for others, the fire and its aftermath had a negative effect on relationships that in some cases lasted for years. Some reported that the evacuation, and financial, emotional and mental stressors following the fires caused relationship strain on intimate partnerships23,38 and problems with extended family, particularly if they evacuated to households unused to having small children around or that did not have an understanding of what the fire-affected community had gone through.38

* + 1. **Social outcomes and violence against women**

An examination of women’s tobacco use and alcohol consumption following wildfire exposure found that while several women started smoking following the fires, overall maternal cigarette smoking declined following the fires, and only a small number of women reported that they consumed more alcohol following the fires.23 Women reported increased stress if their partners exhibited alcohol-related problems following evacuation from wildfires.39

While included studies did not report on specific incidences of violence against women following wildfire exposure, some women identified past domestic violence as being a source of historical trauma when recounting trauma incurred during exposure to wildfire.39 Some women recounted tension within intimate relationships and intimate relationship breakdown in the aftermath of fires.23,39

* + 1. **Breastfeeding / infant feeding**

One study reported that infant feeding was adversely affected during and after evacuation from the Fort McMurray wildfire.38 Breastfeeding women reported that there was no access to lactation support, a lack of safe and private places in which to feed their baby or use a breast pump, and some reported pressure from family members to wean their baby or introduce solids. Many reported that breastfeeding was a source of comfort and support and assisted to sooth their infants during the evacuation. However, during and after the evacuation breastfeeding rates declined and substitute feeding increased, many women perceived their breastmilk supply was adversely affected by exposure to the wildfires and the uncertainty of evacuation. Some breastfeeding women reported being provided with artificial formula even though they did not need it.38

* + 1. **Access to healthcare**

Women’s access to healthcare during evacuation and exposure to wildfire events was examined four studies.23,37-39 Participants in the these studies lived in well-resourced settings and there were no reports of women being unable to access healthcare services, although some women reported that they were unable to access their usual healthcare providers following evacuation from the fire.38

Women were satisfied with healthcare support they received after the fire, especially support from doctors, midwives and maternal and child health nurses and were able to access medications and prenatal vitamins.23 Some women reported an increase in antenatal care appointments following the fire – mostly attributable to managing stress from the fires.23 Some women reported that while counselling was available after the fires, it was generally not considered adequate and was provided in a community setting that was not private.23

* 1. **Limitations of included studies**

Assessment of the quality of the primary studies included in this review was undertaken using the CCAT, and scores are included in Table 2. This assessment included an evaluation of identification of bias, judgement of methodological quality, and consideration of the value and suitability of the information presented in each study to answer the research question. A degree of subjectivity is introduced to the process, limiting the replicability of appraisal and scoring. Further, critical appraisal tools have been criticised for lacking a strong evidence base.41 Scoring systems can imply that each domain is of equal weight and total scores for two different studies can suggest that they are of equal quality, where this may not be the case.

A lack of precision for maternal exposure to wildfire smoke was identified within each of the quantitative studies. Generally, limitations were twofold: maternal exposure was estimated based on maternal residential address, zip code, county, or municipality at time of birth; and particulate matter exposure levels were estimated from satellite data rather than assessment at an individual level. Exposure measurement was not uniform and none of the studies relied on personal air quality monitoring, although Costello (2021)28 incorporated data from personal pollution sensors data within specific coordinates. Using address to define exposure did not account for actual time spent in the exposure location or actual levels of smoke exposure, particularly for women who relocated or evacuated during fires or smoky periods. A lack of precision for spatial data may result in exposure misclassification bias in studies that rely on satellite imaging of smoke plumes as smoke on satellites may not necessarily correlate with smoke exposure at ground level, and satellite imaging may not be reliable on cloudy days.

Most quantitative studies in this review relied on forms of categorical data to describe birth outcomes and this may have impacted the accuracy of analyses, which may make it more difficult to compare results across studies. Two studies relied on birthweight analysis based on categorical 500g increments24,25 rather than considering birthweight as a continuous variable. Four studies only included month and year of birth, which may have affected the accuracy of attributing gestation and trimester of exposure to conclusions around timing of exposure.23-25,33

Variance in study results may be attributed to methodological heterogeneity. There were challenges in comparing results across studies due to differences in inclusion and exclusion criteria, for example four studies included births between 37 weeks – 42 weeks gestation,31,34-36 one study included births between 30 – 42 weeks gestation,33 one study included births up to 42 weeks gestation,32 one study included births between 23 – 41 weeks gestation,27 while the other studies included registered births over 20 weeks gestation.23-25,28,30

Similarly, there were differences in the way included studies attributed gestational age at the limits of study periods. It is therefore possible that fixed cohort bias exists in some studies. Other biases may be present in included studies, for example due to conditioning on intermediates around gestational age, or an underestimation of adverse outcomes as a result of wildfire exposure as included studies do not consider the extent to which wildfire exposure may have led to spontaneous abortion or stillbirth.

Limitations for qualitative studies included the passage of time and recall bias with study surveys and interviews occurring between six and 23 months after fire exposure. Small sample sizes in the qualitative studies may limit the generalisability of findings, however in this review synthesis of findings was possible across all four studies. Similar themes emerged across studies indicating that content saturation occurred and identified themes that are universal to childbearing women’s experience of wildfire exposure across well-resourced settings.

1. **Discussion**

Changes to birthweight, including both lighter and heavier babies, as well as changes to gestational age at birth are associated with increased infant mortality and morbidity.42 Shifts in population-based distribution of birthweight or increased incidence of preterm birth have broader public health implications including child development challenges and health issues in adolescence and beyond.43

This review found that exposure to wildfire disaster is associated with changes to birthweight and length of gestation, with the weight of evidence toward a reduction in both following exposure. Causal factors are complex, however are likely to include an intersection of maternal exposure to PM2.5 with a dose / response effect present in several studies, and prenatal maternal stress responses to disaster at both a personal and population level.

Maternal exposure to PM2.5 is associated with a reduction in birthweight12,13 and an increase in incidence of cleft palate.15 Wildfire smoke is a major contributor to air particulate pollution, a complex source of PM2.5 and is a risk to human health.10 The contribution of wildfire generated PM2.5 to atmospheric PM2.5 concentrations has risen since 2000 in North America, and is expected to continue to increase in fire-prone areas.44 Concentrations of PM2.5 exceed ambient PM2.5 concentrations during active wildfire events.11,44 Wildfire generated PM2.5 is made up of a heterogeneous mix of chemicals depending on the type of biomass burned and burning conditions, and this PM2.5 can remain in the atmosphere for long periods during fire seasons and can be transported over long distances.10 One recent study reported that wildfire generated PM2.5 may be more toxic and cause more harm than equal doses of ambient PM2.5.11

A life history theory hypothesis suggests exposure to wildfire disasters is associated with increased prenatal maternal stress, which in turn may trigger reproductive trade-offs such as reduced maternal investment in a current pregnancy leading to lower birthweight and/or reduced gestation.23 Prenatal maternal stress may also lead to poor fetal health outcomes, including abnormal fetal neurodevelopment45 and offspring behaviour46; impaired physiology47,48; childhood sleep disorder49; and immune dysfunction.50 These can be mediated via multiple mechanisms including epigenetic modifications for example DNA methylation changes,51,52 and altered maternal53 and atypical offspring microbiome.54,55

Exposure to wildfires may have an effect on the prevalence of post-dates pregnancies, with fewer inductions of labour occurring potentially due to fire acuity disrupting obstetric care, or women making different decisions about timing of birth due to wildfire exposure.24 However, prolonged gestation following extreme maternal stress may be an adaptive strategy, whereby birth is delayed until women perceive conditions have improved, with the risk of post-term birth outweighing the risk of birth in a stochastic environment.56

Exposure to wildfires may be associated with an increased prevalence of GDM among exposed women, with maternal stress, maternal diet and exercise and exposure to fine particulate matter contributors to increased risk. Women who report high stress levels in first and second trimesters of pregnancy are more than twice as likely to develop GDM than women who do not perceive themselves stressed.57 Stress may have a negative effect on food choice,58 so it is feasible that maternal dietary choices during and after exposure to wildfires may have an impact on the fetus and/or maternal glucose levels.

Women exposed to wildfires reported that while there was not widespread interruption to food supply during the fires, they were concerned about their own nutrition and dietary choices while evacuated.23,38,39 Furthermore, hot smoky weather and public health advice to remain indoors may have reduced women’s usual exercise regimes.23,25 Exposure to elevated levels of ambient PM2.5 during preconception, first and second trimesters of pregnancy has been associated with increased rates of GDM among exposed women in the USA.16-18 Exposure to other fire and smoke disasters in Australia has also demonstrated an association between PM2.5 smoke exposure and GDM.59

The effect of wildfire exposure may extend beyond women directly affected by fire events. While the numbers of women directly exposed to acute wildfire disaster may be small, many more women can be exposed at a distance, whether that be to emergency sirens, evacuation from wildfire prone areas as a precautionary measure, through exposure to wildfire smoke and through social media and media broadcast.

This secondary exposure to wildfire disaster may have longer term consequences for some less exposed women. Population-wide impacts on birth outcomes including a reduction in birthweight and gestational age at birth for women who were not directly affected by the disaster was reported following the September 11 terrorist attacks,60,61 and it is possible that this non-direct impact may also be present for childbearing women who are exposed to wildfires in a non-acute setting.

Similarly, birthweight and gestation at birth are negatively affected following maternal exposure to terrorist attacks,62-65 and natural disasters, for example following Cyclone Yasi, 2011,66 Hurricane Katrina, 2005,67 and the Quebec Ice Storm, 1998.68,69 Natural disasters such as earthquakes also affect birthweight and length of gestation with some studies reporting sex-specific differences in results.7,9,70

Timing of exposure to acute wildfire events may influence the secondary sex ratio. Sex-specific response to in utero stressors is well studied, albeit an area of debate. The female fetus may have a greater capacity to respond to prenatal maternal stress, possibly due to double X genome adaptability.9 Similarly, male genetic frailty may mean that male fetuses are less resilient, or conception of male fetuses is reduced during periods of maternal or population-based stress.71 Changes to the secondary sex ratio has previously been demonstrated following population-wide stress events including earthquakes,7,8,72-74 and terrorist attacks.71

Women who are exposed to a traumatic event, like a wildfire disaster are at risk of mental health morbidity and may develop PTSD-like symptoms and insomnia immediately after the event, with some developing major depression and/or PTSD.75,76 The stress response following exposure to disaster is highly individualised; past traumatic experience as well as degree of traumatic exposure, for example fearing for one’s life, witnessing death, losing a family member, being evacuated or losing property is a key factor in predicting development of post traumatic morbidity including development of PTSD or PTSD-like symptoms.77

Exposure to wildfire smoke has a negative effect on psychological wellbeing.78 Exposure to multiple disasters over time has a cumulative effect on mental health morbidity, with increased depression and anxiety symptoms reported in Australian adults exposed to COVID-19 restrictions who had previously been exposed to smoke from the Black Summer bushfires compared to those only exposed to COVID-19 restrictions.79 Following Hurricane Katrina, severity of exposure, proximity to disaster, and repeated exposure to disasters impacted on childbearing women’s mental health experience.67,80

Across the broader population, exposure to the Australian Black Saturday and Ash Wednesday bushfire disasters had medium term to life-long impacts for affected populations. Although mental health morbidity decreased over time, rates of PTSD, depression, severe distress, and heavy alcohol use remained higher in exposed populations and persisted for many years after exposure.81,82

This review identified social connectedness, satisfaction with social support, resilience and being able to frame disaster exposure in a way that promotes post-traumatic growth as protective for childbearing women’s mental health and wellbeing. Demonstrating resilience and seeking out social support as an active coping strategy is associated with less mental health morbidity following trauma than social withdrawal or avoidant coping strategies.83 Higher self-reported peritraumatic distress following disaster exposure is correlated to higher levels of anxiety and depression over time, whereas a neutral or positive cognitive appraisal of disaster is protective for anxiety and depression.84

This review found that women sought out and had access to healthcare support following wildfire disasters. Collaborative healthcare support in partnership with a known midwife has a protective effect for women’s mental health and a positive effect on perception of subjective stress and depression.85 Having access to a known midwife through midwifery-led continuity of care may be protective for childbearing women exposed to wildfire disaster; as among other profound benefits for childbearing women and their babies, is protective for preterm birth.86

* 1. **Strengths and limitations**

Strengths of this review include: a comprehensive search strategy, screening and independent quality assessment of included studies by two researchers. New searches were undertaken regularly to identify contemporary studies. While the search strategy was intentionally broad – and included search terms to identify wildfire-related studies concerned with pregnancy, birth and maternal outcomes during the antenatal intrapartum and postnatal periods, it is possible that this strategy did not identify all studies within the intended scope of this review.

Findings were informed by a small number of studies with diverse methodologies, differences in exposure definitions, and varying inclusion and exclusion criteria. Thus, review results should be interpreted with some caution. This review was limited to studies published in English, so it is possible this study does not capture research from all regions afflicted by wildfires. Most studies in this review were set in well-resourced high-income countries, where women did not experience disruption to healthcare services. Consequently, the experience of women included in this review may not reflect the experience of women exposed to wildfire disasters in other settings.

1. **Conclusion**

The effect of wildfire disaster on women and their babies can be profound, with changes to birthweight, length of gestation, and includes findings suggestive of increased rates of gestational hypertension, GDM, fetal macrosomia and increased incidence of some birth defects. Timing of exposure, severity and proximity to the wildfires increases morbidity. Following wildfire exposure, women’s health may be impacted by increased mental health acuity including development of PTSD-like symptoms in the short-term.

Public health interventions that promote social connectedness, foster personal resilience, and include prompt referral to supportive healthcare including midwifery-led continuity of care, and mental health programmes should be developed in areas prone to wildfire disaster, and implemented following wildfire disaster exposure.

1. **Recommendations for research**

This study highlighted several gaps in existing literature. There is a need for more systematic and detailed identification of the impacts of wildfires on a greater range of birth and maternal outcomes over the short and long-term impact as this evidence base is needed to improve outcomes for childbearing women and their babies. There is also a need for longitudinal studies to define windows of susceptibility to wildfire smoke and wildfire generated PM2.5 concentrations on birth outcomes, health and the healthcare needs of childbearing women with more precision.

Additionally, it is important that access to maternity and child health services, reproductive and family planning services, and mental health support following wildfire disaster be evaluated. This evidence will inform the development of effective clinical and public health strategies to further support the needs of childbearing women following exposure to a wildfire disaster.

1. **CRediT author statement**

Jo Evans: conceptualisation, methodology, formal analysis, writing – original draft. Amita Bansal: conceptualisation, writing: review and editing. Danielle Schoenaker: conceptualisation, writing: review and editing. Nicolas Cherbuin: conceptualisation, writing: review and editing. Michael Peek: conceptualisation, writing: review and editing. Deborah Davis: conceptualisation, supervision, validation, writing: review and editing. All authors approved the final version for submission.

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**Table 1. Formal search strategy**

|  |  |
| --- | --- |
| SCOPUS (including Medline and Embase), CINAHL, PubMed | bushfire or wildfire or "bush fire" or "wild fire" or "wildland fire"  AND pregnan\* or prenatal or antenatal or postnatal or labour or birth or lactat\* or breastfe\* or matern\* or baby or newborn or infant or mother or "domestic violence" or "family violence" or "mental health" |
| Google Scholar | (bushfire OR wildfire)  AND (pregnant OR pregnancy OR prenatal OR labour OR birth OR lactation OR lactating OR maternal OR maternity OR baby OR newborn OR infant OR birth outcome) |

**Table 2. – Crowe Critical Appraisal Tool (CCAT) scores for the 16 studies included in this review**

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
|  | Heft-Neal et al., 2022 | | Requia, Amini et al., 2022 | | Requia, Paptheodorou et al., 2022 | | Costello, 2021 | | Jones & McDermott, 2021 | | Park et al, 2022 | | Requia et al., 2021 | | McCoy & Zhao, 2021 | | Abdo et al., 2019 | | O'Donnell & Behie, 2015 | | O'Donnell & Behie, 2013 | | Holstius et al., 2012 | | O'Donnell, 2017 | | Brémault-Phillips et al., 2020 | | Verstraeten et al., 2020 | | DeYoung et al., 2018 | |
| **CCAT Domains** | R1\* | R2\*\* | R1 | R2 | R1 | R2 | R1 | R2 | R1 | R2 | R1 | R2 | R1 | R2 | R1 | R2 | R1 | R2 | R1 | R2 | R1 | R2 | R1 | R2 | R1 | R2 | R1 | R2 | R1 | R2 | R1 | R2 |
| Preliminaries | 5 | 5 | 4 | 3 | 4 | 4 | 3 | 4 | 4 | 2 | 4 | 5 | 3 | 3 | 3 | 2 | 5 | 5 | 4 | 4 | 5 | 4 | 4 | 4.5 | 5 | 5 | 5 | 4 | 5 | 4 | 3 | 2 |
| Introduction | 4 | 5 | 4 | 3.5 | 4 | 4 | 3 | 3 | 4 | 3 | 5 | 5 | 4 | 3 | 3 | 4 | 5 | 5 | 4 | 4 | 4 | 5 | 4 | 5 | 5 | 4.5 | 4 | 2 | 4 | 4.5 | 3 | 3.5 |
| Design | 5 | 5 | 5 | 5 | 4 | 4 | 4 | 4 | 3 | 3 | 4 | 4 | 4 | 4 | 4 | 3 | 5 | 5 | 3 | 4 | 3 | 3 | 4 | 4.5 | 4 | 5 | 4 | 4.5 | 5 | 4 | 4 | 3.5 |
| Sampling | 5 | 5 | 4 | 5 | 4 | 4 | 4 | 4 | 4 | 3 | 4 | 4 | 4 | 4 | 3 | 2 | 4 | 4 | 4 | 4.5 | 4 | 3 | 4 | 5 | 4 | 4.5 | 3 | 3 | 5 | 3.5 | 4 | 3 |
| Data Collection | 5 | 4 | 4 | 4 | 4 | 4 | 4 | 5 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 5 | 4 | 5 | 3 | 3 | 4 | 5 | 5 | 4.5 | 4 | 4 | 4 | 4 | 4 | 2.5 |
| Ethical Matters | 4 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 4 | 4 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 4 | 5 | 5 | 5 | 5 | 5 | 4 | 3.5 | 4 | 4 |
| Results | 5 | 5 | 4 | 4 | 4 | 4 | 3 | 4 | 4 | 4 | 5 | 5 | 3 | 4 | 3 | 3.5 | 5 | 5 | 4 | 4 | 4 | 4 | 4 | 4.5 | 4 | 5 | 5 | 4.5 | 4 | 4 | 4 | 2 |
| Discussion | 5 | 5 | 4 | 5 | 4 | 5 | 3 | 4 | 4 | 4 | 5 | 5 | 4 | 4 | 2 | 2.5 | 5 | 5 | 4 | 4.5 | 5 | 5 | 4 | 4 | 5 | 5 | 5 | 4.5 | 5 | 4 | 4 | 3 |
| **AVERAGE CCAT score**  **/ 100** | **96.25** | | **85.62** | | **83.75** | | **77.5** | | **72.5** | | **91.25** | | **77.5** | | **66.5** | | **96.365** | | **83.75** | | **81.5** | | **88.125** | | **94.375** | | **83.175** | | **85.625** | | **66.875** | |

**CCAT domains and items assessed within the domain** (Refer to: Crowe Critical Appraisal Tool (CCAT) User Guide Version 1.4 (Crowe, 2013) for further detail)

Preliminaries – Title; Abstract; Text

Introduction – Background; Objectives

Design – Research Design; Intervention, Treatment, Exposure; Outcome, Output, Predictor, Measure; Bias

Sampling – Sampling method; Sample size; Sampling protocol

Data Collection – Collection method; Collection protocol

Ethical matters – Participant ethics; Researcher ethics

Results – Analysis, Integration, Interpretation method; Essential analysis; Outcome, Output, Predictor analysis

Discussion – Interpretation; Generalisation; Concluding remarks

\* Reviewer 1

\*\* Reviewer 2

**Table 3. Characteristics of the 16 studies included in this review**

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Author / Year / Title** | **Location / Event of interest** | **Study design** | **Data sources** | **Exposure measurement** | **Outcomes assessed / findings** |
| Heft-Neal, S., Driscoll, A., Yang, W., Shaw, G., & Burke, M  2022  Associations between wildfire smoke exposure during pregnancy and risk of preterm birth in California. | California, USA  Wildfire smoke exposure  2006-2012 | Retrospective cohort study of 3,002,014 births between 2006-2012 | Administrative data - birth certificate data from Vital Records, Department of Health, California  Satellite imagery: National Oceanic and Atmospheric Administration (NOAA) satellite-based Hazard Mapping System and geostationary operational environmental satellite system (GOES)  Daily PM2.5 levels: Daily and Annual PM2.5 Concentrations for the Contiguous United States, 1-km Grids dataset | Exposure window: in utero at time of wildfire smoke exposure  Temporal-spatial  Wildfire smoke plumes were assembled using satellite imaging and combined with 1 × 1km gridded estimates of surface PM2.5. Smoke exposure was assigned to individual pregnancies at the maternal zip-code level.  Comparison – dose / response measured as median wildfire smoke exposure and each additional day of wildfire smoke exposure | Risk of preterm birth at median smoke exposure (7 days)   * 3.4% increase   Each additional day of exposure increased relative risk of preterm birth   * (RR 0.49% [95% CI: 0.41% - 0.59%]) (Entire pregnancy) * (RR 0.83% [95% CI: 0.71% - 0.96%]) (2nd trimester) * (RR 0.68% [95% CI: 0.49% - 0.87%]) (3rd trimester) |
| Requia, W.J., Amini, H., Adams, M.D., & Schwartz, J.D.  2022  Birth weight following pregnancy wildfire smoke exposure in more than 1.5 million newborns in Brazil: A nationwide case control study. | Brazil  Wildfire smoke exposure  2001-2018 | Case control study of 1,602,471 observations between 2001-2018 | Administrative data – birth certificate data from Ministry of Health – Brazil  Satellite imagery: National Institute of Spatial Research – Brazil / Instituto Nacional de Pesquisas Espaciais (INPE) in a 1km x 1km grid  Ambient air pollution including daily PM2.5 levels and weather data: Environmental Information System for Health - / Instituto Nacional de Pesquisas Espaciais (INPE)  Precipitation data derived from the Climate Prediction centre and National Oceanic and Atmospheric Administration (NOAA) | Exposure window: in utero at time of wildfire smoke exposure  Temporal-spatial  Spatial resolution of birth data was based on the mother’s home municipality. 5572 municipalities were grouped into five regions  Average PM2.5 and meteorological covariates were calculated for each trimester within the boundaries of the mother’s home municipality  Comparison – dose / response measured as an increase of 100 wildfire records | Risk of low birth weight increased following wildfire smoke exposure by   * (18.55% [95%CI: 13.66 −23.65%]) (1st trimester exposure in South region – that is a percentage change in risk associated with an increase of 100 wildfire records) |
| Requia, W.J., Papatheodorou, S., Koutrakis, P., Mukherjee, R., & Roig, H.L.  2022  Increased preterm birth following maternal wildfire smoke exposure in Brazil. | Brazil  Wildfire smoke exposure  2001-2018 | Time-stratified case-crossover study of 190,911 preterm births 2001-2018 | Administrative data – birth certificate data from Ministry of Health – Brazil  Satellite imagery: National Institute of Spatial Research – Brazil / Instituto Nacional de Pesquisas Espaciais (INPE) at an image resolution from 375 m × 375 m to 5 km × 4 km  Ambient air pollution and weather data: Environmental Information System for Health - / Instituto Nacional de Pesquisas Espaciais (INPE)  PM2.5: ground observations of the Aerosol Robotic Network (AERONET)  Precipitation data derived from the Climate Prediction centre and National Oceanic and Atmospheric Administration (NOAA) | Exposure window: in utero at time of wildfire smoke exposure  Each trimester exposure was based on the average of daily estimated wildfire exposure, pollutant concentrations (PM2.5, CO, NO2, and O3) and meteorological variables  Spatial resolution of birth data was based on the mother’s home municipality. 5572 municipalities were grouped into five regions  Comparison – exposure to a ‘wildfire wave’ vs non-exposure. The ‘wildfire wave’ concept was adopted to capture periods with high wildfire occurrences: a ‘wildfire wave’ was any average value of wildfire records and PM2.5 concentration that exceeded the 90th percentile of the time series | Risk of preterm birth increased following exposure to PM2.5 during a ‘wildfire wave’   * (OR 1.41 [95%CI: 1.31-1.51]) first trimester exposure in Southeast region * (OR 1.04 [95%CI: 1.01-1.07]) first trimester exposure in Midwest region * (OR 1.05 [95%CI: 1.01-1.09]) second trimester exposure in North region * (OR 1.06 [95%CI: 1.04-1.07]) second trimester exposure in South region |
| Costello, J.  2021  Air quality and preterm birth: distance to highways, exposure to wildfires, and effect modification by COVID-19 | San Francisco Bay area, USA  “Camp Fire” November 2018  (12 day event) | Retrospective cohort study of 68,006 births of women who were pregnant during the fire dates in 2017 or 2018 | Administrative data - Vital Records, Department of Health, California and hospital records from California Office of Statewide Planning and Development  Daily average PM2.5 levels: data from Purple Air personal pollution sensors data within specific coordinates  Wildfire smoke mapping: Geostationary Operational Environmental Satellite (GOES) | Exposure window: pregnancies which overlapped the full fire period (12 days) and lived within the study extent.  Comparison – exposed vs unexposed. An unexposed status was assigned to pregnancies that occurred during the same time period and study area, but one year earlier – in November 2017. | Risk of preterm birth following exposure to the Camp Fire was associated with:   * (aRR 1.1 [95% CI: 1.03, 1.17])   The level of PM2.5 exposure was associated with preterm birth   * (aRR 1.17 [95% CI: 1.05, 1.29]) (comparing exposure in the highest tertile to the lowest tertile |
| Jones, B.A., & McDermott, S.  2021  Infant health outcomes in mega-fire affected communities | USA  Any mega-fire > 100,000 acres in size  2010-2017 | Retrospective cohort study of 689,762 births between 2010-2017 | Administrative data - neonatal collection: Centres for Disease Control and Prevention (CDC) National Centre for Health Statistics (NCHS)  Sources of mega-fires: Geospatial Multi-Agency Coordination Group (GeoMAC)  Weather data: National Oceanic and Atmospheric Administration (NOAA) National Centres for Environmental Information (NCEI) | Exposure window: in utero at time of mega-fire (wildfire >100,000 acres) flame zone exposure  Temporal-spatial  Wildfire perimeter shapefiles and acres burned data were obtained from the GeoMAC system. These data were matched to maternal county of residence geodata to ascertain exposure.  Comparison – exposed vs non-exposed | Risk of low birthweight following mega-fire exposure compared to non-exposed   * 0.8% increase of low birthweight (<2500g) (from a base of 7%)   Risk of preterm birth following mega-fire exposure compared to non-exposed   * 1.2 % increase of preterm birth <37/40 (from a base of 10%) |
| Park, B.Y., Boles, I., Monavvari, S., Patel, S., Alvarez, A., Phan, M., Perez., & Yao, R.  2021  The association between wildfire exposure in pregnancy and foetal gastroschisis: A population-based cohort study. | California, USA  Wildfire exposure  2007-2010 | Retrospective cohort study of 2,093,185 births 2007-2010 | Administrative data – The Office of Statewide Health Planning Birth File (OSHPD), California  Geospatial fire imaging from The California Department of Forestry and Fire Protection (CAL FIRE) | Exposure window: preconception (30 days prior to pregnancy) or in utero at time of wildfire exposure  Geospatial  Wildfire exposure was defined as the mother’s primary residence zip code within 15 miles of the edge of a wildfire  Comparison – exposed vs non-exposed | Risk of gastroschisis increased following the following exposure to wildfire compared to no exposure:   * 7.8 vs 5.7 per 10.000 births (aRR 1.28 [95%CI: 1.07, 1.54]) first trimester exposure * 12.5 vs 5.7 per 10,000 births (aRR 2.21 [95%CI: 1.40, 3.48]) pre conception exposure (up to 30 days prior to pregnancy) |
| Requia, W.J., Kill. E., Papatheodorou, S., Koutrakis, P., & Schwartz, J.D.  2021  Prenatal exposure to wildfire-related air pollution and birth defects in Brazil. | Brazil  Wildfire smoke exposure  2001-2018 | Retrospective cohort study of 16,825,497 births between 2001-2018 | Administrative data – birth certificate data from Ministry of Health – Brazil  Satellite imagery: National Institute of Spatial Research – Brazil / Instituto Nacional de Pesquisas Espaciais (INPE)  Ambient air pollution including daily PM2.5 levels and weather data: Environmental Information System for Health - / Instituto Nacional de Pesquisas Espaciais (INPE)  Precipitation data derived from the Climate Prediction centre and National Oceanic and Atmospheric Administration (NOAA) | Exposure window: in utero at time of wildfire smoke exposure  Temporal-spatial  Spatial resolution of birth data was based on the mothers home municipality. 5572 municipalities were grouped into five regions  Birth defects were categorised using International Statistical Classification of Diseases and Related Health Problems (ICD) codes  Comparison – dose / response – sum of wildfire records | Cleft lip / palate – increased incidence following exposure   * (OR 1.007 [95% CI: 1.001; 1.013]) (2nd trimester)   Congenital anomalies of the respiratory system increased following exposure   * (OR 1.007 [95% CI: 1.002; 1.023]) (2nd trimester exposure)   Congenital anomalies of the nervous system increased following exposure   * (OR 1.002 [95% CI: 1.001; 1.003]) (1st trimester exposure in South, North and Midwestern regions) |
| McCoy, S.J., & Zhao, X.  2020  Wildfire and infant health: a geospatial approach to estimating the health impacts of wildfire smoke exposure | Colorado, USA  Wildfire smoke exposure  2007-2013 | Retrospective cohort study of 90,779 births between 2007-2013 | Administrative data - neonatal collection: Colorado Vital Records Registry, Colorado Department of Public Health and Environment (CDPHE)  Dates of smoke exposure: Geospatial Multi-Agency Coordination Group (GeoMAC) and Monitoring Trends in Burn Severity (MTBS)  Satellite imagery: University of Wisconsin-Madison Space Science and Engineering Centre | Exposure window: in utero at time of wildfire smoke exposure  Temporal-spatial:  Reconstruction of wildfire smoke plumes using daily satellite images over the first four days following fire ignition within Colorado State were linked to the latitude and longitude of maternal residential address to determine exposure.  Comparison – exposed vs non-exposed | Birthweight following exposure   * 3.8% reduction in birthweight following exposure   Low birthweight following exposure   * 0.034 increased risk of low birthweight (<2500g) |
| Abdo, M., Ward, I., O'Dell, K., Ford, B., Pierce, J.R., Fischer, E.V., & Crooks, J.L.  2019  Impact of Wildfire Smoke on Adverse Pregnancy Outcomes in Colorado, 2007-2015 | Colorado, USA  Wildfire smoke exposure  2007-2015 | Retrospective cohort study of 535,895 births between 2007-2015 | Administrative data - neonatal collection: Colorado Vital Records Registry, Colorado Department of Public Health and Environment (CDPHE)  Satellite imagery: National Oceanic and Atmospheric Administration (NOAA) satellite-based Hazard Mapping System  Air quality monitoring: US EPA Air Quality System (AQS) | Exposure window: in utero at time of wildfire smoke exposure  Temporal-spatial  Wildfire smoke PM2.5 and non-smoke PM2.5 characterized by combining both satellite imagery and ground-based PM2.5 monitors. Daily concentrations were matched to maternal ZIP code using the mean of the concentrations in a 15 × 15 km grid to estimate exposure  Comparison – concentration of PM2.5 by zip code | Birthweight – reduction following exposure   * 5.7g for each µg/m3 increase in trimester average wildfire PM2.5 exposure (1st trimester)   Preterm Birth – increased incidence following exposure   * (OR 1.078 [95% CI: 1.016, 1.139, p=0.013]) (any trimester) * (OR 1.132 [95% CI: 1.088, 1.178, p<0.0001]) (2nd trimester)   Gestational Diabetes Melitis - increased incidence following exposure   * (OR 1.151 [95% CI: 1.034, 1.281, p=0.010]) (any trimester) * (OR 1.144 [95% CI: 1.064, 1.230, p=0.0003]) (1st trimester)   Gestational Hypertension – increased incidence following exposure   * (OR1.204 [95% CI – 1.083, 1.339, p=0.0006]) (any trimester) * (OR 1.140 [95% CI: 1.071, 1.231, p=0.0001]) (1st trimester) * (OR 1.124 [95% CI - 1.044, 1.211, p=0.0020]) (2nd trimester)   NICU admission – reduced incidence following exposure   * (OR 0.957 [95% CI: 0.926, 0.989, p= 0.0093]) (any trimester)   Assisted Ventilation – reduced incidence following exposure   * (OR 0.875 [95% CI: 0.837, 0.915, p <0.0001]) (any trimester) |
| O'Donnell, M.H., & Behie, A.M.  2015  Effects of wildfire disaster exposure on male birth weight in an Australian population | Canberra, ACT, Australia  “Canberra bushfire” 18 January 2003  (10 day event) | Retrospective cohort study of 48,408 births between 2000-2010 | Administrative data - neonatal collection: ACT Government Health Directorate Epidemiology Section (Population Health Informatics)  Fire-affected Statistical Local Area geodata | Exposure window: in utero at time of Canberra Bushfire (births occurred between Feb - Oct 2009) in fire-affected statistical local government areas  Geospatial  Comparison - fire exposure was divided into Statistical Local Areas (SLA) described as ‘severely affected’ - areas where deaths and property damage occurred; ‘moderately affected’ - where property damage occurred, and; ‘least affected’ where no damage occurred and linked to maternal residential address at the time of the fires | Male birthweight   * 197 g heavier in the severely affected area compared with the moderately affected area (F = 5.73, P<0.003, df = 2) * increased incidence in number of male neonates born at >4000 g with the largest difference occurring in male babies born between 4501 - 5000g |
| O'Donnell, M.H., & Behie, A.M.  2013  Effects of bushfire stress on birth outcomes: A cohort study of the 2009 Victorian Black Saturday bushfires | Victoria, Australia  “Black Saturday bushfire”  7 February 2009  (31 day event) | Retrospective cohort study of 73,831 births between 2006-2009  Births over 20 weeks gestation in Victoria | Administrative neonatal collection: Victorian consultative council on Obstetric and Paediatric Mortality and Morbidity - Victorian State Department of Health  Fire-affected Local Government Area geodata | Exposure window: in utero at time of Black Saturday fires (births occurred between Feb - Oct 2009 in fire-affected local government areas  Geospatial  Comparison - fire exposure was divided into ‘fire-affected’; and ‘not affected’ local government areas (LGA) and linked to maternal residential address at the time of the fires | When compared to births in non-exposed areas:  Low birthweight in the 2 months following exposure   * increased incidence of very low birthweight <499g (increased by 150%) [z=2.6 p=0.001] * increased incidence of very low birthweight 1000-1499g [z=2.8 p=0.001]   Gestational Age – 3rd trimester exposure   * increased incidence of post term >41/40 birth [z=1.5 p=0.043] * increased incidence of preterm 28-31/40 birth [z=0.5 p=0.043] * increased incidence of preterm 32-36/40 birth [z=0.5 p=0.043]   Gestational Age – 2nd trimester exposure:   * increased incidence of preterm 20-27/40 birth (50% increase) [z value 2.0 p=0.043] * increased incidence of preterm 32-36/40 birth [z=1.1 p=0.022] * increased incidence of post term >41/40 birth [z=1.0 p=0.022]   Gestational Age – 1st trimester exposure:   * increased incidence of post term >41/40 birth [z=1.8 p=0.000] |
| Holstius, D.M., Reid, C.E., Jesdale, B.M., & Morello-Frosch, R.  2012  Birth weight following pregnancy during the 2003 Southern California wildfires | South Coast Air Basin, California, USA  Southern California wildfire  October 2003  (20 day event) | Retrospective cohort study of 886,034 births between 1 Jan 2001 - 31 Dec 2005 | Administrative neonatal collection: Birth Statistical Master File (Centre for Health Statistics, Dept Health Services, California, USA)  Satellite imagery: Moderate Resolution Imaging Spectroradiometer (NASA)  Dates of smoke exposure: Dept Forestry and Fire Protection, California | Exposure window: in utero at time of fires - 21 October 2003 - 10 Nov 2003  Temporal-spatial  The window of potential exposure was identified using government reporting and satellite imagery. Primary analysis used temporal contrast as the basis for exposure assessment, however sensitivity analysis included spatial contrast based on the proximity of maternal residence to PM10 monitors. This exposure was further classified as low exposure (average PM10 measures of < 40 µg/m3 during fires) and high exposure > 40 µg/m3  Comparison – exposed pregnancies compared to non-exposed pregnancies in years before / after the fires | Mean birthweight at term - reduction following exposure compared to non-exposed pregnancies from earlier / later years   * 6.1g lower [95% CI: -8.7, -3.5g] (any trimester) * 7.0g lower [95% CI: -11.8, -2.2g] (3rd trimester) * 9.7g lower [95% CI: -14.5, -4.8g] (2nd trimester) |
| O'Donnell, M.H.  2017  Effects of bushfire exposure on prenatal and early life development in humans: A life history perspective | Canberra, ACT  “Canberra bushfire” 18 January 2003  (10 day event)  Victoria, Australia  “Black Saturday bushfires” 7 February 2009  (31 day event) | Mixed Methods  Retrospective cohort study of 122,239 births between 2000 - 2012  Survey  Semi-structured interviews | Administrative neonatal collection:   * ACT Government Health Directorate Epidemiology Section (Population Health Informatics) * Victorian consultative council on Obstetric and Paediatric Mortality and Morbidity - Victorian State Dept Health   Fire-affected Statistical and Local Government Area geodata  Self-selected survey and interview participants recruited via social media and internet forums, government websites and healthcare providers  Survey (30 questions) – 43 respondents  Semi-structured interviews - 7 participants | Exposure window: in utero at time of fires  Geospatial  For the Canberra bushfires:  Fire exposure was divided into Statistical Local Areas (SLA) described as ‘severely affected’ - areas where deaths and property damage occurred; ‘moderately affected’ - where property damage occurred, and; ‘least affected’ where no damage occurred and linked to maternal residential address at the time of the fires  For the Black Saturday Bushfires:  Fire exposure was divided into ‘fire-affected’; and ‘not affected’ local government areas (LGA) and linked to maternal residential address at the time of the fires | Secondary Sex Ratio – decrease in male births   * 🡫 male birth rate 46.6% (severely affected region) compared to 51.1% in the remainder of Victoria (p=0.03)   Qualitative themes explored:   * Trauma, fear and risk * Evacuation, displacement, separation, effect on relationships * Resilience and resilience strategies * Social outcomes – tobacco and alcohol use, violence against women * Access to healthcare, support and counselling |
| Brémault-Phillips, S., Pike, A., Olson, J., Severson, E., & Olson D.  2020  Expressive writing for wildfire-affected pregnant women: Themes of challenge and resilience | Fort McMurray, Alberta, Canada  Fort McMurray Wood Buffalo wildfire  May 2016  (32 day event) | Qualitative analysis of expressing writing journals | 54 self-selected participants recruited via social and mainstream media completed:   * a questionnaire and demographic survey * expressive writing exercises via electronic journal entries | Resident of Fort McMurray Wood Buffalo in May 2016, evacuated from Fort McMurray because of the wildfire, and pregnant at the time of the wildfire or became pregnant within six months of the wildfire | Qualitative themes explored following exposure and evacuation:   * Fear – for one’s life or the life of a loved one, loss of home or possessions, inability to mother, long term consequences * Relationships – improvement / deterioration of, new connections, marriage difficulty, deteriorating mental health * Trauma – due to fire/previous trauma/domestic violence, due to loss, * Resilience practices/strategies: writing, breathing techniques, positive self-talk, disclosing experience, physical, mental and social practices, cultivating positivity and optimism, therapy * Characteristics of resilience: post-traumatic growth, adaptability, emotional/social connectedness, composure, reasoning |
| Verstraeten, B.S., Elgbeili, G., Hyle, A., King, S., & Olson, D.M.  2020  Maternal Mental Health after a Wildfire: Effects of Social Support in the Fort McMurray Wood Buffalo Study | Fort McMurray, Alberta, Canada  Fort McMurray Wood Buffalo wildfire  May 2016  (32 day event) | Longitudinal study | 200 self-selected participants recruited via social media, online forums, the study website, and flyers distributed in community centres completed:   * a demographic survey * Impact of Event Scale (Revised) IES-R * PDI / PDEQ (Peritraumatic experiences) * The Social Support Questionnaire * The Connor-Davidson Resilience Scale | Resident of Fort McMurray Wood Buffalo in May 2016, evacuated from Fort McMurray because of the wildfire, and pregnant at the time of the wildfire or became pregnant within six months of the wildfire | Severe PTSD-like symptoms correlated with:   * increased peritraumatic distress * increased dissociative experiences   Greater social support satisfaction associated with less severe PTSD-like symptoms when peritraumatic distress is below average (social support satisfaction is not protective where peritraumatic distress is high) |
| DeYoung, S.E., Chase, J., Branco, M.P., & Park, B.  2018  The Effect of Mass Evacuation on Infant Feeding: The Case of the 2016 Fort McMurray Wildfire | Fort McMurray, Alberta, Canada  Fort McMurray Wood Buffalo wildfire  May 2016  (32 day event) | Mixed Methods  Survey  Qualitative analysis of free text | 164 participants recruited through purposive sampling recruited via social media and local mainstream newspapers completed a 30 question survey which consisted of both open ended items and items with categorical responses. | Resident of Fort McMurray Wood Buffalo in May 2016, evacuated from Fort McMurray because of the wildfire and also feeding infants (birth - 36 months) during the evacuation and aftermath of fire | Infant feeding:   * decreased exclusive breastfeeding with women more likely to have exclusively breastfed infants prior to exposure / evacuation (OR 1.96) * increased artificial formula feeding (10.9% before vs 12.3% after evacuation)   Qualitative themes:   * Evacuation stressors – lack of social support, logistics of evacuation * Food security / nutrition concerns – lack of healthy options/choice * Perception of low supply / lactation concerns – pressure to wean, lack of privacy, lack of lactation support * Breastfeeding as a source of comfort and security |

**Table 4. Summary of findings by theme**

|  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Study | Birthweight | Gestational age | Birth defect | Gestational diabetes mellitus | Secondary Sex Ratio | Gestational Hypertension | NICU admission / Assisted ventilation | Mental Health impacts and protective factors | Social outcomes and Domestic Violence | Breastfeeding / infant feeding | Access to healthcare |
| Heft-Neal et al., 2022 |  | D |  |  |  |  |  |  |  |  |  |
| Requia, Amini et al., 2022 | D |  |  |  |  |  |  |  |  |  |  |
| Requia, Papatheodorou et al., 2022 |  | D |  |  |  |  |  |  |  |  |  |
| Costello, 2021 |  | D |  |  |  |  |  |  |  |  |  |
| Jones & McDermott, 2021 | D | D |  |  |  |  |  |  |  |  |  |
| Park et al., 2021 |  |  | I |  |  |  |  |  |  |  |  |
| Requia et al., 2021 |  |  | I |  |  |  |  |  |  |  |  |
| McCoy & Zhao, 2020 | D |  |  |  |  |  |  |  |  |  |  |
| Abdo et al., 2019 | D | D |  | I |  | I | D |  |  |  |  |
| O'Donnell & Behie, 2015 | I | NE |  | NE |  |  |  |  |  |  |  |
| O'Donnell & Behie, 2013 | D | D/I |  |  | NE |  |  |  |  |  |  |
| Holstius et al., 2012 | D |  |  |  |  |  |  |  |  |  |  |
| O'Donnell, 2017 | I | NE |  |  | D |  |  | \* | \* |  | \* |
| Brémault-Phillips et al., 2020 |  |  |  |  |  |  |  | \* | \* |  | \* |
| Verstraeten et al., 2020 |  |  |  |  |  |  |  | \* |  |  | \* |
| DeYoung et al., 2018 |  |  |  |  |  |  |  |  |  | \* | \* |

|  |  |
| --- | --- |
| D | Decrease |
| I | Increase |
| NE | No effect |
| \* | Thematic qualitative finding |

Diagram

Description automatically generated