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Identifying exposure pathways mediating adverse birth outcomes near active surface mines in Central Appalachia

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Background: Previous work has determined an association between proximity to active surface mining within Central Appalachia and an increased risk of preterm birth (PTB) and low birthweight (LBW). Multiple potential exposure pathways may exist; however, including inhalation of particulate matter (airshed exposure), or exposure to impacted surface waters (watershed exposure). We hypothesize that this relationship is mediated by exposure to contaminants along one or both of these pathways.

Methods: We geolocated 194,084 birth records through health departments in WV, KY, VA, and TN between 1990 and 2015. We performed a mediation analysis, iteratively including within our models: (a) the percent of active surface mining within 5 km of maternal residence during gestation; (b) the cumulative surface mining airshed trajectories experienced during gestation; and (c) the percent of active surface mining occurring within the watershed of residency during gestation.

Results: Our baseline models found that active surface mining was associated with an increased odds of PTB (1.09, 1.05–1.13) and LBW (1.06, 1.02–1.11), controlling for individual-level predictors. When mediators were added to the baseline model, the association between active mining and birth outcomes became nonsignificant (PTB: 0.48, 0.14–1.58; LBW 0.78, 0.19–3.00), whereas the association between PTB and LBW remained significant by airshed exposure (PTB: 1.14, 1.11–1.18; LBW: 1.06, 1.03–1.10).

Conclusions: Our results found that surface mining airsheds at least partially explained the association between active mining and adverse birth outcomes, consistent with a hypothesis of mediation, while mediation via the watershed pathway was less evident.

Keywords: Mediation; Surface mining; Maternal health; Environmental health; Preterm birth; Low birthweight; Coal mining

Introduction

Communities within the Central Appalachia region, containing areas within Virginia, West Virginia, Kentucky, and Tennessee, experience some of the most severe economic and health disparities across the United States.[1] Although poverty has generally decreased since the mid-1900s, the region has not experienced corresponding expected health gains,[2] and continues to lag behind national poverty estimates, with increased rates of unemployment, lower levels of postsecondary education, and lower life expectancy.[3] Surface mining became more widespread in the 1990s, and represented over 60% of coal mined in 2019.[4] Within Central Appalachia, coal production has declined in the 2010s and there were nearly double the amount of surface mines as underground mines in 2019, despite relatively similar levels of coal production.[4] Surface mining has disrupted the local environment, where the forest is cleared, rocks and topsoil are loosened through explosives to expose the underlying coal seams, and the resultant rubble is dumped into nearby valleys and headstreams.[5,6]

These surface mining activities have been previously associated with adverse health outcomes.[1,7,8] For example, a county-level cross-sectional analysis found higher rates of respiratory disease, hypertension, and kidney disease among populations living in counties with greater coal production, as compared with those living further away from coal mining

What this study adds

Previous work published in *Environmental Epidemiology* has determined an association between living near surface mining activities within Central Appalachia and an increased risk of adverse birth outcomes. The exposure pathways underlying this association; however, remain unclear, including inhalation of particulate matter versus exposure to contaminated water. This work aims to identify the potential exposure pathways underpinning this relationship, which may be mediated by one or both pathways. Our results suggest that the association between surface mining and adverse birth outcomes is driven in part by exposure to airsheds near active surface mining activities, while mediation via watersheds was less clear.

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activities.[9] However, the relative importance of the exposure pathways underlying these associations remains less clear. Previous research outlining the public health impacts of surface mining activities has proposed two possible biological mechanisms to explain these relationships.[8] First, there is evidence that inhalation of particulate matter is increased near-surface mining activities.[10,11] Within Central Appalachia, surface mining activities result in increased emissions of acidic aerosols such as sulfur dioxide and nitrous dioxide,[12] as well as particulate matter smaller than 10 μ in diameter (PM_{10}) as a result of trucks hauling coal.[13] Studies have found that particulate matter collected from nearby surface mines results in increased inflammatory responses and vascular tissue damage in a rodent model[10,11] and increased carcinogenic markers in human lung cells,[14] which is consistent with the higher rates of cardiovascular and lung disease observed in the region.[11] Exposure to air pollution is known to result in a range of adverse health outcomes across life stages, including adverse birth outcomes.[15,16]

Second, exposure to heavy metals in drinking water contaminated by surface mining activities has also been proposed as a causal pathway linking adverse health outcomes and proximity to surface mining activities.[8] However, little research is available that quantifies the *in situ* exposure to heavy metals, water quality, and sources of drinking water used within Appalachia.[1] Although associations between metals in water and increased rates of cancer and chronic disease have been noted, researchers have called for a more thorough investigation of these associations linked specifically to exposure to waterborne contaminants and dose of exposure, whereas controlling for behavioral risk factors such as tobacco use.[8] Despite this lack of evidence, other studies within the field of aquatic ecology have noted elevated concentrations of heavy metals and nonmetallic ions downstream of active and historic surface mining activities, resulting in the loss of aquatic biodiversity within Appalachian headwater streams.[6] Given that these streams are inevitably hydrologically connected to source waters for regional drinking water supplies, degradation of aquatic ecological health potentially indicates important concurrent public health risks.

Surface mining activities have more specifically been shown to correlate with adverse birth outcomes, such as birth defects, low birthweight (LBW), and premature birth. Among nearly 2 million births across four Central Appalachian states, Ahern et al.[17] suggested that rates of birth defects were higher in areas with mountaintop removal as compared with areas with no mountaintop removal, after controlling for covariates. Other studies have further suggested that air pollution containing fine particulate matter, such as particulates resulting from surface mining activities, can reach the fetal placenta and trigger inflammatory responses,[18] which may, in turn, explain associations between air pollution and adverse birth outcomes such as LBW and preterm birth (PTB).[19,20] Within the Central Appalachia region, Ahern et al.[21] have documented an independent risk of LBW among women living within an area with coal mining activities in West Virginia. More recently, Buttling et al.[22] suggested an increased risk of LBW and PTB among women living within 5 km of an active surface mine.

Here, this work builds upon the findings outlined in Buttling et al., to examine the potential underlying pathways mediating the documented association between active surface mining activities and adverse birth outcomes. More specifically, we aim to explore airshed and watershed exposure pathways as potential mediators of the association observed between proximity to active surface mining activities and adverse birth outcomes.[22] We undertake a mediation analysis within a logistic regression modeling framework to examine the odds of PTB, LBW, and term LBW outcomes as predicted by maternal proximity to surface mining activities during gestation from 1990 to 2015, overlaying surface mine airshed and watershed boundaries. To undertake these analyses, we use geolocated birth records spanning four states in the Central Appalachia region, representing nearly 200,000 births over 2.5 decades. Specifically, we hypothesize that increased odds of PTB and LBW associated with proximity to surface mining activities during gestation may be mediated by airshed or watershed pathways, or both, and examine the potential additive effects of these mediators.

Methods

Data

We obtained birth records for four states across Central Appalachia, provided by departments of health in Kentucky (KY), Tennessee (TN), Virginia (VA), and West Virginia (WV) (Figure 1). This dataset is described in detail in Buttling et al.[22]; briefly, a total of 409,394 birth records were obtained from departments of health with street addresses of reported maternal addresses. Records were removed due to missingness in street addresses with many records reporting only mailing addresses (such as a rural route or P.O. box), resulting in a final dataset comprising 194,084 births between 1990 and 2015 with a geocoded maternal residential address. Our previous analysis shows differences in maternal characteristics of births from the original and final dataset are minimal and an additional analysis using a zip-code level exposure variable that allowed the inclusion of most of the original records resulted in similar effect estimates.[22] The exposure variable of interest within this dataset was the proportion of land designated as "active surface mining" within a 5-km radius of the maternal address during the majority gestation year. Pre-mining areas were defined as areas that were classified as actively mined in future years of the study period. Mined areas <40 acres in size were removed from the analysis, as the Office of Surface Mining Reclamation and Enforcement reported that economically viable mines are generally at least 40 acres in size.[23]

More specifically, yearly active surface mining activities were defined using a combination of land cover change and mining permits, obtained from Marston and Kolivras for the years 1986 through 2015 using 30 m resolution Landsat remote sensing imagery.[24] Specifically, this dataset used remote sensing technology and satellite imagery to quantify changes in the extent of surface mining areas greater than 40-acres over the corresponding years among areas where mining permits were requested. For each year, barren land on which vegetation had been removed was identified, and pixels that were tied to other types of land disturbance (such as clear-cutting of timber) were manually excluded. The remaining barren pixels lying within areas permitted for mining within the United States Geological Survey-defined Appalachian coalfields were designated as places where active mining was likely taking place. Active surface mining was delineated from postmining areas through classification of vegetation, where actively mined areas tend to have major land disruption and degradation, whereas postmining areas tend to show some revegetation through reclamation efforts.[25]

To assess the accuracy of the mined area dataset, Marston et al. applied a standard validation process within remote sensing to the identified mined layer. Specifically, 2,250 points were placed within eight randomly selected counties across the Appalachian coalfield region of Central Appalachia. Data from these counties had not previously been used for the initial identification (training) of mined areas. The classification of these points (mined or not) was compared with aerial imagery from the National Agricultural Imagery Program (NAIP, 1 m resolution), land cover data from the National Land Cover Dataset, and Landsat images that were not used for initial classification. The overall classification accuracy was 0.88, or 88%, and the kappa coefficient to measure agreement was also 0.88, indicating "strong" agreement.[26] When errors were identified, they tended to be along the edges of mined areas. If a pixel at the edge of a cleared area is half barren and half forested, the classification process will classify that pixel as one or the other, with the potential for error to occur.

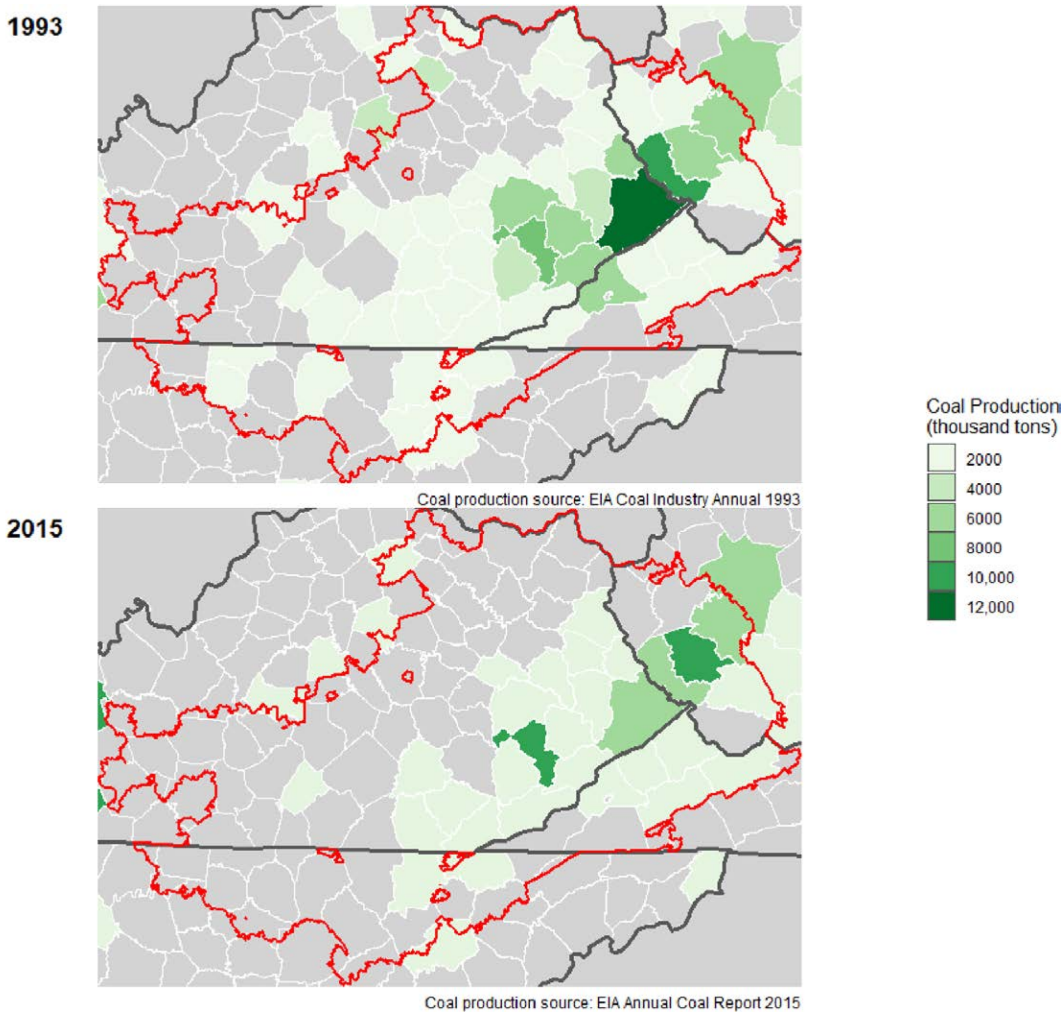

Figure 1. Study area (red) and surface mining coal production (thousand tons) at the county level for 1993 (top) and 2015 (bottom). Coal production data for 2015 and 1993 were obtained from[43] and [44].

Airsheds for each of the active surface mines in each year of analysis were estimated using the HYbrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT4) atmospheric trajectory model,[27] which uses meteorological data to compute atmospheric trajectories, particle dispersion, and air concentrations. Detailed methods using HYSPLIT4 to characterize airsheds of surface mines are described in further detail in McKnight et al.[28] Briefly, we modeled individual airsheds of each active surface mine in the study area. The results of this process were raster data sets (e.g., a pixelated or gridded surface where each pixel or grid square corresponds to a specific geographical location and has an associated value) comprised of frequency values relating to air movement from surface mines per gridded cell. To quantify total exposure in pregnancy from all mines, we summed the frequency values of all airsheds extracted at each maternal address location for the cumulative amount of air from surface mines experienced at the maternal residential address. Watersheds were classified using 10-digit hydrologic unit codes (HUC10) within the United States Geological Survey's Watershed Boundary Dataset, which represent the areal extent of surface water drainage using an aggregated collection of hydrologic unit data and amount of active surface mining within watersheds for each year of the study period was calculated.[29]

Analysis

We employed mediation analyses to explore the potential exposure pathways that could explain associations between living in close proximity to active surface mining activities and increased odds of PTB and LBW described in Buttling et al.[22], accounting for premining differences and additional individual-level covariates available on birth records. Mediation analyses are helpful in exploring the underlying mechanisms underpinning a known relationship between an exposure and outcome.[30] Generally, mediation is suggested when four criteria are met, as outlined in Table 1.[31]

Our independent variable of interest was the percent of the land within a 5-km radius of the maternal residential address that was designated as an active surface mine during the majority year of gestation (n = 23,733). Participant characteristics by exposure status are reported in Buttling et al. (2021), and are included in Supplementary Information (eTable S5; http://links.lww.com/EE/A185); http://links.lww.com/EE/A185. Our dependent variables of interest included (1) PTB, defined as birth before 37 weeks of gestation; (2) low birthweight (LBW), defined as birthweight less than 2,500 grams; and (3) term low birthweight (TLBW), defined as birth occurring at ≥37 weeks gestation and birthweight less than 2,500 grams. Using these criteria, we tested whether mediation between proximity to active surface mining activities during the year containing the majority of the pregnancy (majority gestation year) and these adverse birth outcomes occurred via the *airshed* pathway or the *watershed* pathway. We quantified these potential mediators (Figure 2), respectively, as: (1) the cumulative potential exposure to air pollutants via the airshed experienced at the maternal residential address during the majority gestation year, and (2) the percent of land experiencing active surface mining within the watershed of residency during the majority gestation

Table 1.

Mediation Criteria, adapted from[31]

	Criteria Assessed	Statistical Test(s) Used	
1	Independent variable significantly influences the mediator	Unadjusted regression model	Sobel test
2	Independent variable significantly influences the dependent variable (in absence of the mediator)	Adjusted regression model	
3	Mediator significantly and uniquely influences the dependent variable		
4	The effect of the independent variable on the dependent variable shrinks with the addition of the mediator		

year. The cumulative potential exposure to airborne pollutants via the airshed is outlined in further detail within Mcknight et al.[28]; briefly, these values represent the cumulative frequency of air originating from active surface mines, as modeled via the HYSPLIT4 atmospheric trajectory model. Residential addresses associated with higher values have higher potential exposure to surface mining air pollution, including fine particulate matter.

We firstly employed a Sobel test using the *bda* package in R software to quantify whether mediators significantly influenced the relationship between the independent and dependent variables.[32,33] We further performed a logistic regression analysis using the *stats* package within the base R software. Covariates within our model included categorical variables found on birth records including maternal age ("18–35 years," "<18 years," ">35 years"), highest education attained by the mother at the child's birth ("8th grade or less," "9th–12th grade [includes high school graduates]," "Post high-school education [with or without degree]"), race ("White," "Black," "Other"), ethnicity ("Hispanic," "Not Hispanic"), self-reported tobacco use during pregnancy ("Yes," "No"), sex of the child ("Male," "Female"), payment type for birth medical services ("Medicaid," "Private Insurance," "Self-Pay," 'Other"), state ("Kentucky," "Tennessee," "Virginia," and "West Virginia"), and continuous percent of land within 5 km of maternal residence that was not actively experiencing mining activities during the majority gestation year but would be subsequently mined in later years (referred to as "pre-mining" activities), to account for any temporal baseline difference before active mining. Because mining activities tend to show spatial autocorrelation (e.g., active mining tends to move progressively across the landscape and is therefore closely correlated with premining landcover), we further included an interaction term between the amount of pre-mined land and surface mining land within a 5-km buffer of maternal residence. Lastly, to allow for nonlinear temporal trends observed within the data and account for serial autocorrelation, we included a spline with 4 degrees of freedom in the year covariate using the *splines* package within R software. This approach is a mixed effect modeling approach, similar to including random effects in the model, where fixed effects are allowed to vary at inflection (or spline) points, estimated by maximizing a penalized likelihood function.[34] This model builds on the model detailed in Buttling et al.,[22] which can generally be specified as:

$$\text{logit}(y_i) = \beta_0 + \beta_m M_i + \beta_t T_i + \beta_{mt} M_i * T_i + (bs(t)) + \sum_k \delta_k x_{ik}$$

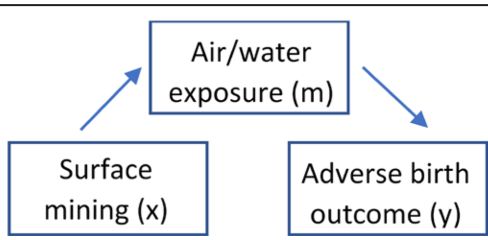

Figure 2. Directed acyclic graph outlining potential mediators of the association between surface mining and adverse birth outcomes.

where logit(y_i) represents the odds of an adverse outcome (PTB, LBW, and TLBW) occurring for a given woman's birth, *i*; M_i represents the % of pre-mining land area within a 5km buffer of the maternal residence of individual *i*; T_i represents the % of active surface mining area within a 5-km buffer of the maternal residence of individual *i*; $\beta_{mt} M_i * T_i$ represents the interaction effect of having land within 5 km of the maternal residence of individual, *i*, that is both likely actively being mined (active mining) and will subsequently be mined (premining); *bs(t)* represents a nonlinear spline with 4 degrees of freedom to fit temporal trends in the data; and x_{ik} represents the suite of fixed covariates *K* as outlined above.[22]

To explore hypothesized mediation pathways, we tested three model types that iteratively built on each other (Figure 3).[33] Our base adjusted model (Model 0) included the suite of fixed effects described above, including the independent variable of interest (e.g., % surface mining activities in a 5-km buffer). Model 1 included the same suite of variables as Model 0, with the addition of the airshed mediator variable alone, whereas Model 2 included the watershed mediator alone. Lastly, Model 3 included the addition of both the airshed and watershed mediators. All models included an interaction term between premining surface area and active surface area as described above, plus an interaction term between the mediator(s) and exposure variable. We report model performance metrics, including McFadden's pseudo-R^2 statistic, Akaike Information Criterion (AIC), and mean adjusted error (MAE) and root-mean squared error (RMSE) measures. AIC represents a measure of model predictive power as a trade-off with model complexity, with lower values generally representing models with better fit.[35] MAE and RMSE represent model precision and bias, with values closer to zero representing better model fit, whereas pseudo-R^2 values represent variance explained by the model, with values between 0.2 and 0.4 representing reasonable model fit across a range of applications.[36–39]

Results

Sobel test

Results of the Sobel test suggesting evidence of whether mediation is occurring are presented in Table 2. For each dependent variable of interest, we conducted an independent Sobel test exploring whether mediation is occurring via the airshed pathway ($M = air$) and the watershed pathway ($M = water$), with the independent variable of interest defined as proximity to surface mining. Evidence suggested that mediation was occurring via the airshed pathway for PTB and LBW outcomes ($p < 0.001$), whereas evidence was less clear for mediation of TLBW. There was further evidence suggesting that mediation may be occurring via the watershed pathway for PTB ($p = 0.012$) but mediation was less clear for other birth outcomes.

Unadjusted model results

We first explored unadjusted model results for each dependent variable of interest, as outlined in Table 3. Specifically, the results of these unadjusted models are used to test whether the independent variable was significantly associated with the

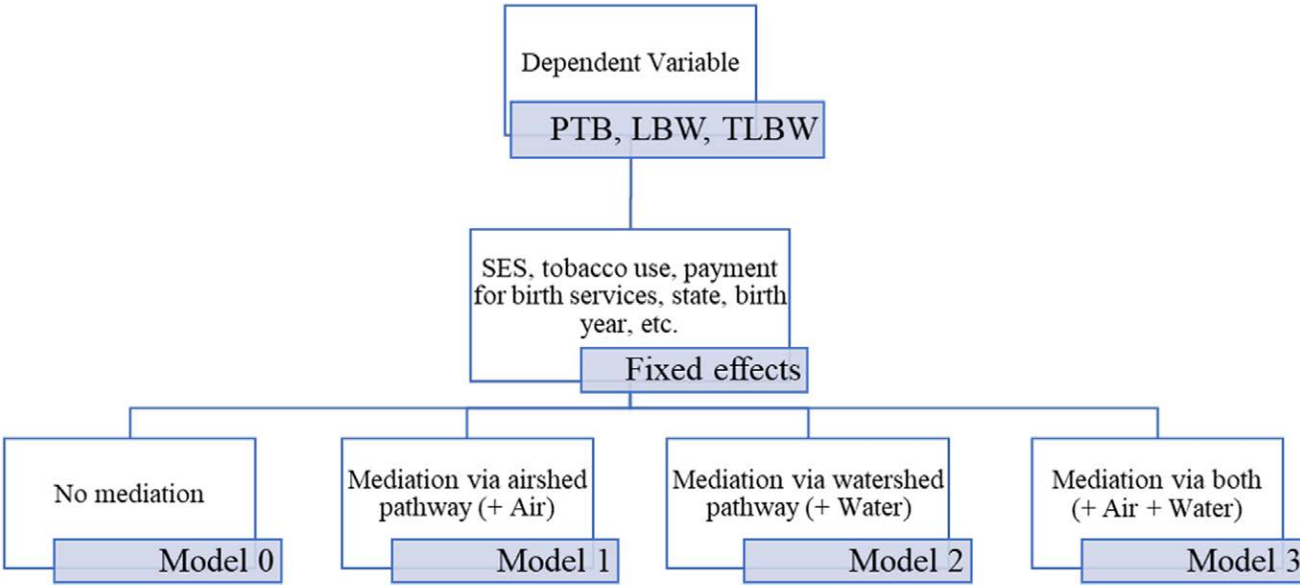

Figure 3. Model diagrams outlining the iterative model building process. Iterative models were built for each dependent variable (e.g., PTB, LBW, and TLBW).

Table 2.

Sobel Test Exploring Mediation via Airshed and Watershed Pathways from Surface Mining Operations on Birth Outcomes

	Z value	Significance
M = air, X = surface mining		
Preterm birth	14.20	9.78×10^{-46}***
Low birthweight	5.66	1.53×10^{-08}***
Term low birthweight	1.12	0.261
M = water, X = surface mining		
Preterm birth	2.522	0.012*
Low birthweight	1.158	0.247
Term low birthweight	1.857	0.063

Significant codes: 0 = "***," 0.001 = "**," and 0.01 = "*."

mediator, a key criterion indicating mediation. Towards this, we found that proximity to surface mining strongly influenced both hypothesized mediator pathways ($p < 0.001$). We further conducted unadjusted models on the dependent variables of interest before conducting adjusted models. Across all outcomes, both mediation pathways were generally strongly significant, with the exception of TLBW. Of note, results tended to be more strongly significant among the airshed mediation pathways, as opposed to the watershed mediation pathway.

Table 3.

Unadjusted Model Exploring Birth Outcomes by Exposure to Surface Mining via Airshed and Watershed Mediation

Covariates	β	SE	Significance
Preterm Birth			
PTB – air	0.138	0.009	<2 × 10–16***
PTB – water	0.061	0.015	2.59 × 10–05***
Low Birthweight			
LBW – air	0.069	0.011	7.04 × 10–11***
LBW – water	0.047	0.017	0.00473**
Term Low Birthweight			
TLBW – air	0.028	0.017	0.0928
TLBW – water	0.069	0.026	0.00865**
Mediators			
Surface mining – air	0.228	0.002	<2 × 10–16***
Surface mining – water	0.729	0.002	<2 × 10–16***

Significant codes: 0 = "***," 0.001 = "**," 0.01 = "*."
LBW, low birthweight; PTB, preterm birth; TLBW, term low birthweight.

Adjusted model results

To test the remaining criteria (Table 1) for whether mediation occurred between adverse birth outcomes and proximity to surface mining, we iteratively conducted a logistic regression with the addition of mediating variables. Full model results are listed in eTable S1; http://links.lww.com/EE/A185–eTable S3; http://links.lww.com/EE/A185. Overall, in our baseline models (e.g., without the addition of mediation pathways), we found that sociodemographic characteristics such as older age (>35 years), self-reported tobacco use during pregnancy, having a female child, race, and type of payment used to cover birth services (e.g., Medicaid and "Other") were associated with increased odds of PTB, LBW, and TLBW outcomes. We further found significant differences in the odds of PTB across states, with women giving birth in Central Appalachian counties within Tennessee at higher odds of having a PTB and women giving birth in Virginia at lower odds, as compared with women giving birth in Kentucky. Across all outcomes, self-reported tobacco use during pregnancy resulted in the highest odds ratios of adverse birth outcomes as compared with other sociodemographic characteristics within the model, particularly for TLBW (OR: 3.06, 95% confidence interval [CI] = 2.80, 3.35).

To explore mediation pathways, we first examined whether the independent variable was significantly associated with the dependent variables in absence of the mediators (mediation criterion #2), denoted as Model 0. We found proximity to surface mining was associated with PTB, such that a 1% increase in the amount of land within a 5-km buffer around the maternal address being mined was associated with a 9% increase in the odds of having PTB (OR: 1.09; 1.05, 1.13) and 6% increase in the odds of LBW (OR: 1.06, 1.02, 1.11). In practical terms, the highest percentage of surface mining within a 5-km buffer surrounding a maternal address was observed to be just over 15%, with a mean of under 1% (0.13%).

To test whether mediators were significantly and uniquely associated with the dependent variable (mediation criterion #3), we added the airshed pathway variable (Model 1), watershed pathway variable (Model 2), and both (Model 3). Results of the adjusted models are shown in Table 4. The airshed pathway was strongly significant in the PTB model ($p < 0.001$) and LBW model ($p = 0.004$), even after the addition of the watershed pathway in Model 3. Evidence

Table 4.

Selected Adjusted Model Results Exploring Birth Outcomes by Exposure to Surface Mining via Airshed and Watershed Mediation

Covariates	Model 0 OR (95% CI)	Model 1 OR (95% CI)	Model 2 OR (95% CI)	Model 3 OR (95% CI)
Preterm Birth				
% Active mining	1.09 (1.05, 1.13)	0.69 (0.38, 1.22)	1.10 (1.04, 1.16)	0.48 (0.14, 1.58)
Airshed exposure		1.12 (1.09, 1.15)		1.14 (1.11, 1.18)
Watershed exposure			1.07 (1.01, 1.12)	1.38 (0.45, 4.17)
Low Birthweight				
% Active mining	1.06 (1.02, 1.11)	0.81 (0.42, 1.53)	1.06 (1.00, 1.13)	0.78 (0.20, 3.07)
Airshed exposure		1.05 (1.01, 1.08)		1.06 (1.03, 1.10)
Watershed exposure			0.99 (0.93, 1.06)	0.63 (0.16, 2.35)
Term Low Birthweight				
% Active mining	1.00 (0.93,1.06)	0.87 (0.28, 2.64)	0.98 (0.88, 1.09)	0.32 (0.03, 3.27)
Airshed exposure		1.02 (0.97, 1.07)		1.00 (0.94, 1.05)
Watershed exposure			1.04 (0.94, 1.14)	0.77 (0.10, 5.66)

of watershed mediation was less clear among all outcomes, and among TLBW, evidence of mediation via either airshed or watershed pathways was lacking. Table 4 and Figure 4 show whether the effect of the independent variable was reduced after the addition of the mediating variables, outlining the odds ratio and 95% CIs of proximity to surface mining in predicting each birth outcome. Beige lines represent the base model (Model 0) with no mediation variables, whereas pink represents the addition of the airshed variable alone (Model 1), maroon represents the addition of the watershed variable alone (Model 2), and brown represents the addition of both air and watershed variables together (Model 3). Across all outcomes, the odds of PTB, LBW, and TLBW as explained by proximity to surface mining were reduced with the addition of the airshed mediator, either alone (Model 1) or combined (Model 3). Interestingly, the association between surface mining and birth outcomes became nonsignificant among PTB and LBW in the models

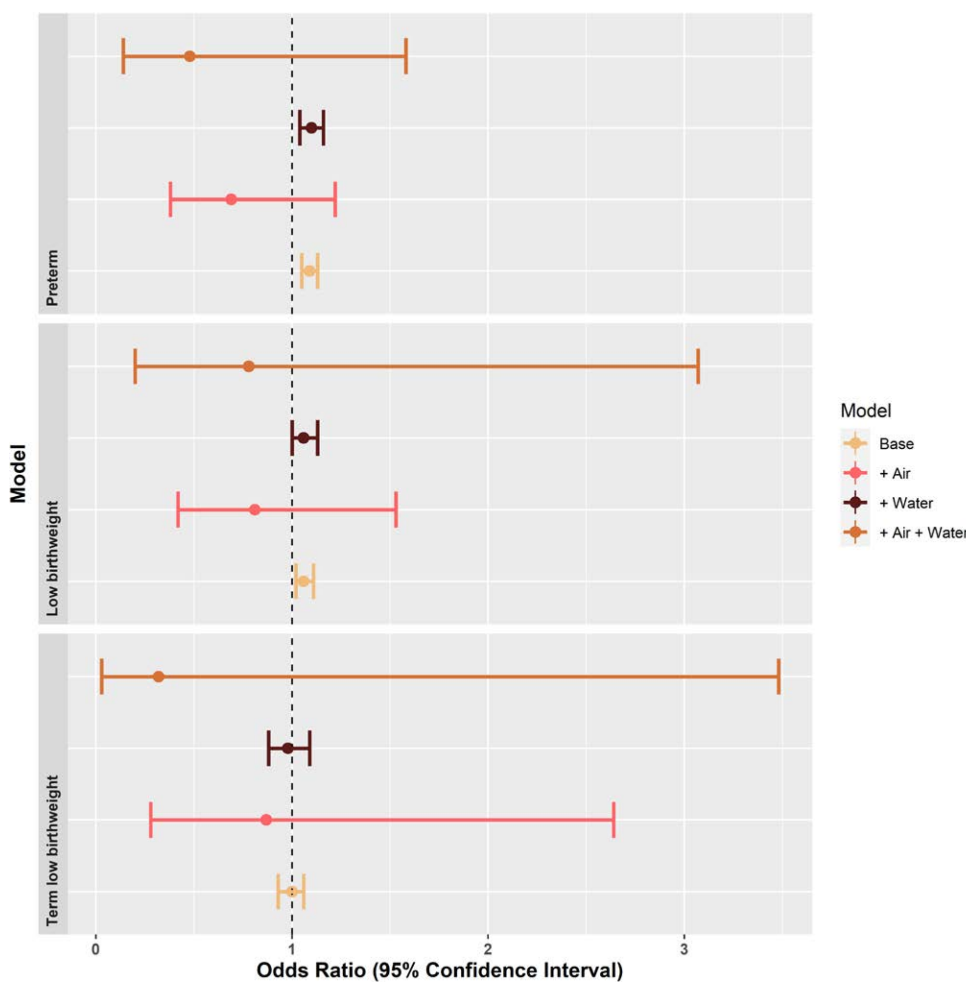

Figure 4. Odds ratios for proximity to active surface mining in predicting adverse birth outcomes. Beige represents the baseline model (no mediators); pink represents the addition of the airshed mediator alone to the baseline model; maroon represents the addition of the watershed mediator alone to the baseline model; brown represents the addition of the watershed mediator + airshed mediator to the baseline model. Dots represent point estimates of odds ratios and lines represent upper and lower 95% confidence intervals. Lines crossing 1 indicate nonsignificance.

including the airshed mediator (pink/brown), but remained significant among models with the watershed mediator alone (maroon), with the exception of TLBW, which was not significant regardless of the addition of mediators.

Discussion

Previous studies have suggested proximity to surface mining activities is associated with an increased odds of adverse health outcomes,[7] including adverse birth outcomes,[22] and birth defects.[17,21] The direct and indirect causal pathways underlying these associations; however, remain less clear.[40] Here, we aimed to clarify these associations by exploring hypothesized mediating pathways linking exposure to coal mining activities and resultant birth outcomes. Overall, we found evidence that living within airsheds of active surface mines is associated with higher odds of PTB and LBW outcomes, with airsheds mediating the effect of living in close proximity to surface mines on these birth outcomes. Specifically, the airshed pathway met all four mediation criteria (Table 1): (1) the airshed pathway was significantly associated with active surface mining (Table 3); (2) proximity to active surface mining was significantly associated with both PTB and LBW outcomes in the absence of the airshed pathway (eTable S1; http://links.lww.com/EE/A185 and eTable S2; http://links.lww.com/EE/A185, Model 0); (3) the airshed pathway significantly and uniquely was associated with PTB and LBW outcomes (eTable S1; http://links.lww.com/EE/A185 and eTable S2; http://links.lww.com/EE/A185, Model 1); and (4) the association between proximity to active surface mining sites and both PTB and LBW outcomes was reduced with the addition of the airshed pathway (Table 4). Evidence of mediation was less clear for TLBW. Although criteria 1 and 4 were met, the effect of proximity to active surface mining on TLBW was not significant to suggest an association. Although mediation was not clear, this outcome was strongly explained by maternal age at birth, race, self-reported tobacco use, payment type for birth services, and child sex, with the highest odds of TLBW among those reporting tobacco use (OR: 3.06, 2.80, 3.35).

Evidence for mediation along the watershed pathway across outcomes was less clear. Although the watershed pathway was significantly associated with active surface mining, and the effect of surface mining on the dependent variables was generally reduced with its addition, the watershed pathway was not significantly and uniquely associated with the adverse birth outcomes, as evidenced in Table 4 (Model 3). These findings are in line with results from the Sobel test (Table 2), which suggested mediation along the airshed pathway for PTB and LBW, but not along the watershed pathway.

These findings suggest that the most likely exposure pathway underlying the association between active surface mining and PTB and LBW outcomes likely occurs via air, potentially influenced by particulate matter emissions from coal mining activities. Evidence suggested mediation via the watershed pathway was less likely, which is unsurprising given the pathway between water pollution and drinking water is more complex than exposure to air pollution. For example, the majority of residents in this region are served by municipal drinking water, which is treated before distribution and consumption[41]; adverse changes to source water quality will only have an impact if these treatment systems fail. In addition, it is well-documented that changes in household water quality can alter consumption source patterns: specific to this region, a residential survey conducted in West Virginia found that perceptions of poor water quality within the area resulted in behavior changes among the respondents, such as consuming bottled water over tap water.[42] Exposure to developmental toxicants via contamination of surface or groundwaters, therefore, represents a potential indirect exposure pathway, which might be alleviated by water treatment before reaching the household tap or alternative drinking water sources (e.g., bottled water).

These analyses should be considered within the context of their associated limitations. First, we did not directly measure air pollutants or water pollutants, but instead used proxy atmospheric models and geological boundaries. For example, we used satellite imagery to designate temporal surface mining activities based on mine permits and barren land cover; whereas this classification likely represents active surface mining activities because the change in landcover due to surface mining is stark, it does not capture on-the-ground information about mining activities and air or water emissions. Using these proxies, therefore, does not quantify an individual's actual exposure to air and water pollutants, heavy metals, etc., and future research could aim to better characterize individual exposure via prospective studies. Further, the time scale of the main exposure variable (proximity to active surface mining) is annual due to limitations in obtaining reliable imagery of surface mining activity on a monthly timescale.[24] We calculated an airshed for each mine for every year of the study time period and matched the relevant year's cumulative airshed frequency value to a birth record's gestational majority year. Given that we had one mine boundary for each year, we were not able to calculate airsheds at a finer time scale than one year (e.g., at the gestational trimester level). Although we do not expect that mine boundaries shift significantly at a finer time scale, exploring exposure during the gestational trimester represents a promising opportunity for future study.

Second, our analyses are limited to women with an identifiable street address (e.g., excluding post office boxes, etc.). It was necessary; however, to restrict our analyses at this level to link individual births to surface mining airsheds and watersheds. Our previous analyses using ZIP code level exposures that allowed for the inclusion of most birth records in the dataset showed that ZIP code and street-level analyses provided similar results,[22] increasing our confidence that the current analysis is minimally biased due to this limitation. Third, our analyses rely on secondary data sources and are therefore limited to socioeconomic and demographic characteristics existing on birth records. Namely, tobacco use within these records was self-reported, which may not represent actual tobacco use in pregnancy. Further, other important characteristics such as illicit substance use, household income, etc. were not included in our analyses, as these covariates did not exist on birth records, and could be a source of potential bias in the present analysis. However, while these non-observed maternal characteristics could be associated both with mothers' place of residence and birth outcomes, active surface mining is estimated yearly, such that birth outcomes from the same area before or after active surface mining are compared with births in which gestation occurs during active mining. Future research could incorporate additional area-level sociodemographic characteristics within a hierarchical framework.

Conclusions

Surface mining activities have dramatically altered the Central Appalachia landscape, and the environmental and public health consequences are still being characterized. Although previous literature links proximity to surface mining activities and resultant adverse birth outcomes, the exposure pathways underlying these associations remain poorly understood. Our study represents a novel mediation analysis using nearly 200,000 geolocated birth records spanning four states in Central Appalachia from 1990 to 2015 to explore airshed and watershed exposure pathways as mediators of the relationship between surface mining activities and adverse birth outcomes. Our findings suggest that the airshed pathway mediates the association between surface mining activities and PTB and LBW outcomes, but evidence of mediation via the watershed pathway was less clear.

Conflicts of interest statement

The authors declare that they have no conflicts of interest with regard to the content of this report.

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Data use agreements with state health agencies prohibit authors from sharing birth record data used in the analysis. Satellite-derived datasets are publicly available, or available on request. Code required to replicate results are available upon request.

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