ORIGINAL ARTICLE

The Impact of Coal-Powered Electrical Plants and Coal Ash Impoundments on the Health of Residential Communities

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BACKGROUND In North Carolina, coal-burning power plants remain the major source of electrical production. Coal burning generates coal ash that is stored in landfills and slurry ponds that are often located near residential communities, signifying high potential for environmental contamination and increasing health risks. We reviewed the literature on potential health effects of coal-burning plants to summarize current knowledge on health risks.

METHODS We searched English-language publications issued between January 1, 1987, and December 31, 2017, on PubMed and Google Scholar.

RESULTS The algorithm of identification, screening, eligibility, and inclusion/exclusion we used provided 113 peer-reviewed publications selected for the review. Over the past 30 years, scientists reported that the people living in close proximity to coal-fired plants had higher rates of all-cause and premature mortality, increased risk of respiratory disease and lung cancer, cardiovascular disease, poorer child health, and higher infant mortality. The elevated health risk was associated with exposure to air pollutants from the power plant emissions and to a spectrum of heavy metals and radioactive isotopes in coal ash.

CONCLUSION In North Carolina, further studies are required to profile the severity of the cumulative impacts of multiple air, water, and soil contaminants related to coal-burning power plants and coal ash impoundments on human health and the environment. Prioritized study directions on evaluation of health impacts of coal-burning power plants in North Carolina are suggested.

While energy production using gas, nuclear, and solar power has recently increased in North Carolina, coal-fired electrical power plants remain the major source of net electricity generation: in 2017, 4,363 thousand megawatts (MWh) were generated from coal-fired sources; this is much greater than from nuclear power (the 2nd largest source at 3,811 thousand MWh) or gas-fired plants (the 3rd largest source, at 3,650 thousand MWh) [1]. Generation of electricity from the 14 coal-fired power plants in North Carolina results in the annual exhaust of 19.3 billion gallons of coal ash, with individual emissions ranging from 216 million gallons in Eden to over 4.1 billion gallons in Walnut Cove [2]. Coal-fired power plants can impact human health directly (eg, through immediate exposure to contaminated air and water) and indirectly (via exposure of coal and its by-products in the food chain) [3]. Coal combustion could also contribute to climate change that, in its turn, could lead to a higher frequency of floods, hurricanes, and droughts, a higher risk of development of allergic diseases, a higher prevalence of tick- and mosquito-borne diseases, as well as a higher risk of heat-related mortality [4, A1, A2]. At present, information about the health impact of coal-fired plants on human health, including the health of the residents of communities located in close proximity to coal power plants, remains sparse. We reviewed the literature to highlight the reports on potential health effects of pollution resulting from coal burning and coal ash storage.

Objective, Method, and Inclusion and Exclusion Criteria

The objective of this review was to summarize current knowledge on the health effects potentially associated with exposure to emissions from coal-burning power plants and to environmental contaminants from coal ash impoundments. The literature search, study selection, data extraction, and synthesis were performed between January 17, 2018, and June 19, 2018. We searched for English-language publications that were published between January 1, 1987, and December 31, 2017. To search for information, we used PubMed, Google Scholar, and also searched for additional studies from the reference lists of identified manuscripts that were related to the topic (see Figure 1). The review was performed based on the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines [A3]. The keywords used in the search were "coal," "coal ash," "coal power plant," "coal-burning power plant," "coal ash impoundment," "coal ash pond," and "fly ash." The detailed list of combinations of words for search is shown in Table 1.

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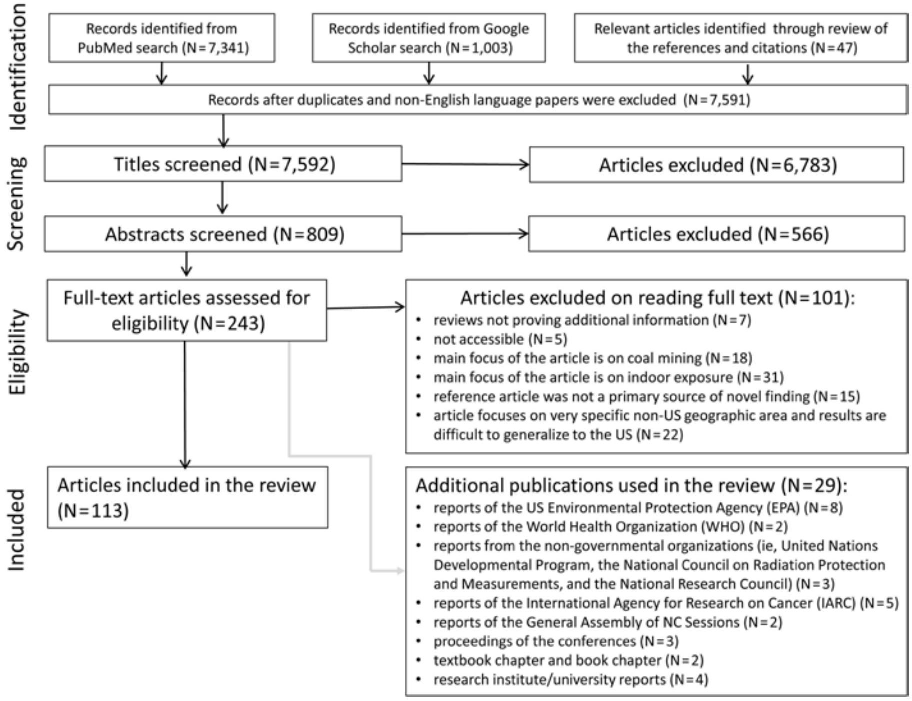
FIGURE 1.
Flow Diagram: Identification, Screening, Eligibility, and Inclusion of Materials in the Review



The review criteria included applicability to the health issues associated with exposure to emissions from coal-burning power plants (directly measured or estimated from models), contamination from coal ash impoundments, and the health impacts of contaminants that are known to be associated with coal power plant emissions: eg, nitrogen oxide (NO_x), sulfur dioxide (SO_2), particulate matter (PM), heavy metals, and radioactive isotopes. To be included in the review, the study had to: 1) focus on health impacts (all-cause or disease-specific mortality, incidence, hospital admissions, emergency department visits, symptoms) potentially associated with coal ash and its components in humans exposed occupationally and/or residentially; 2) include information on pathophysiological mechanisms of health impacts of coal ash and its components in animal studies or *in vitro* studies; or 3) provide information on coal ash or its components that includes discussion of their potential or recognized health hazards. We focused the search on health impacts reported for the United States (ie, across the United States or in certain US states, including North Carolina) because of between-country and between-region differences in coal characteristics, emission control, and the resulting pollution. However, we retained some reports of non-US countries when the results in these publications were unavailable for the United States but presented important findings on coal ash and human health, or those in which the components of the exposure matrix were close to that of the United States.

The following exclusion criteria were applied: 1) publications that studied health impacts associated with indoor exposure to coal (eg, many of studies from China focus on indoor exposure); 2) referenced articles that were not the primary sources of novel findings; 3) articles that focused on geographic areas/countries with specific environmental exposures and co-factors that differ substantially from respective exposures and co-factors in the United States; and 4) articles that focused on coal mining rather than on emissions from coal-burning power plants.

Results and Discussion

Search results. The flow diagram (ie, algorithm for the identification of publications) is shown in Figure 1. The literature search produced a list of 7,592 titles for screening. Abstract screening identified 809 candidate studies that resulted in 243 full-text articles assessed for eligibility. After applying exclusion criteria, 113 peer-reviewed publications were selected for review. An additional body of 29 non-peer-reviewed publications was included to support the analysis: it included, among others, reports of governmental and non-governmental organizations, research/institution reports, and conference proceedings. The studies covered a range of populations, from newborns to older adults (over 65 years old). In addition to the United States-based studies, several publications from other countries were reviewed: 7 studies from Europe (including Greece, United Kingdom, Belgium, Spain, Czech Republic, and Bulgaria), 2 studies from Turkey, 1 study from Canada, 2 studies from Latin America, and 7 studies from Asia (including India, China, Taiwan, and Korea).

Air pollution. Fly ash (a coal combustion product) represents a significant health hazard: it includes small, spheri-

TABLE 1.
Keywords for Search and Combinations of the Words

Keywords	Words used in combination with the keywords*				
	Words related to health	Words related to demographic factors	Words related to study type	Words related to chemical compounds related to coal ash and the ways of potential contamination	Words related to geographic characteristics/place
Coal Coal ash Fly ash Coal power plant Coal-burning power plant Coal ash impoundment Coal ash pond	Health, health effect, mortality, disease, low birth weight, pregnancy, premature birth, premature death, life expectancy, hospital admission, emergency department visit, cardiovascular, respiratory, neurological, asthma, cancer	Infant, children, rural, community, minorities, income, education	Epidemiology, survey, exposure, excessive risk, relative risk, animal study, *in vitro*	Particulate matter, sulfur dioxide, nitrogen oxide, radioactive compounds, radioactive isotope, heavy metals, arsenic, lead, mercury, vanadium, cobalt, hexavalent chromium, quartz, crystalline silica, cadmium, water contamination, soil contamination, air contamination, spill	North Carolina United States North America

Note: The following use of Boolean operators was performed: each of the key words (listed in Column 1) was searched in combination with each word from Columns 2, 3, 4, and 5 using AND operator. For example, "coal" AND "health;" "coal" AND "children," etc. Then "coal ash" AND "health," "coal ash" AND "children," and so on. The obtained results from each analysis were manually compared and duplicated publications were excluded from the analysis.

cal particulate matter less than 10 µm (PM_{10}), 10-2.5 µm ($PM_{10\text{-}2.5}$, coarse), or 2.5 µm ($PM_{2.5}$) in diameter that, due to its size, could escape emission control devices, remain suspended in air, and upon inhalation penetrate deep into the respiratory tract and deposit in the lungs [5, 6, A4-A7]. It has been shown that repeated exposures to PM can cause irritation of the eyes, nose, throat, and respiratory tract [7]. Exposure to PM is also associated with higher morbidity and mortality from respiratory, cardiovascular and cerebrovascular diseases, and lung cancer [8, A8, A9]. Fine particulates of fly ash deposited in the respiratory system could be enriched up to 10 times in metals compared to bulk ash [9, A10, A11]. The mechanisms of injury to the respiratory tract from PM include inflammation, direct cytotoxicity, and cell death [4]. The impact of PM emissions can be substantial: a 10 µg/m^3 increase in $PM_{2.5}$ concentration in the air has been shown to be associated with up to an 18% increase in cardiovascular deaths [10]. Exposure to $PM_{2.5}$ has been estimated to be a main contributor to premature mortality due to power plant emissions, resulting in PM-related mortality currently having the highest monetized value compared to other pollutants attributable to coal-fired power plants [11,12]. Recent studies have shown that communities located near coal power plants could also be exposed to these inorganic nanoparticles of the combustion-derived nanomaterials that are components of PM due to their extremely small size, they can accumulate even deeper in respiratory tissue [13, A12-A14].

Exposure to gaseous sulfur dioxide (SO_2) emitted by coal-burning power plants has been shown to be associated with exacerbation of respiratory symptoms: SO_2 levels in the air correlated with higher asthma hospitalization rates, particularly among children and older adults (over 65 years old) [14]. Even relatively low SO_2 concentrations (<10 ppb 24-hr average) were associated with increased risk of cardiovascular and respiratory deaths [14].

Multiple studies provide suggestive evidence of associations between the levels of the gaseous pollutant nitrogen dioxide (NO_2), a combustion by-product of coal-fired power plants and fossil fuel from automobiles, and emergency department visits and hospitalizations for asthma, with larger effect estimates for children compared to other age groups [15]. NO_2 at levels within current air quality standards has been shown to be associated with an increased susceptibility to respiratory infections in children with asthma and increased severity of asthma exacerbation [16].

Metals represent an important component of air pollutants associated with coal-burning power plants. For example, a study of air samples in Baltimore, MD, showed that coal-fired power plants contributed to ambient levels of arsenic (16%), iron (13%), cobalt (11%), and chromium (19%), and in less extent to the levels of vanadium (5%), antimony (4.8%), and manganese (2.7%) in the air (ie, respirable fractions) [17].

In North Carolina, air pollution from emissions of coal-burning power plants is regulated by the Clean Smokestacks Act [18] and several other policies. These regulations resulted in significant improvements in overall air quality in the state over the past 2 decades, as well as decreasing trends of respiratory and cardiovascular death rates [19, 20]. Using the estimates from the risk model, it has been recently shown that air quality improvements in North Carolina led to an estimated 1,700 (95%CI = 1500-1800) less (ie, prevented) premature deaths in 2012 [21]. Improvements in health may also be seen in residents distant from coal-fired power plants. For example, studies show that fly ash particles can be transported in the atmosphere up to 30 km from the power station; therefore, the benefits to health from reduced air pollution could be observed even in distant communities [A6, A15]. It has been reported that decreasing emissions from coal power plants in North Carolina also led to improved air quality in 13 neighboring southeastern states and the District of Columbia [21]. Overall, the benefits of improved health after implementation of the Clean Air Act were estimated to be much higher than the implementation costs required for reducing emissions (the health care cost savings to compliance costs ratio was 25:1 in 2010) [A16, 22].

Water and soil contamination. Although pollutants emitted into the air by coal-fired power plants are of concern, another potent hazard is water and soil contamination [A17]. This contamination can come from coal ash impoundments (landfills and slurry ponds) that are designed to dewater the fly ash (a by-product of coal combustion) which is stored in wet form in ash dredge cells. Deposition of fly ash in structurally inadequate impoundments can contaminate ground and nearby surface water with leaking toxins [A18, A19, 23]. When evaluating the potential health hazards from spills from these impoundments, it is important to note that the concentrations of metals in fly ash can be 4–10 times higher than that of the parent coal [7]. The majority of coal ash generated by burning coal is stored in landfills and slurry ponds located in close proximity to residential communities, often those of low income [24].

Similar to air contaminants, important aspects of exposure to coal ash components through water and soil contamination are the polycyclic aromatic hydrocarbons (PAHs) and the spectrum of metals in coal ash (eg, arsenic, mercury, lead, cadmium, vanadium, chromium, nickel, and zinc) that have been shown to be associated with neurotoxic, carcinogenic, teratogenic, and mutagenic effects [17, 25-27, A4, A20-A26]. Beryllium, phosphorus, wolfram (or tungsten), and molybdenum also have environmental relevance to coal ash storage facilities, but currently are not considered in health studies [28]. The summary of potential health effects of the metals associated with coal ash particles is presented in Table 3. High levels of many of these compounds have been registered in the aftermath of one of the largest fly ash releases in US history—the slurry (a mixture of fly ash and water) spill that occurred in 2008 at the Tennessee Valley Authority's (TVA) Kingston Fossil plant [29].

In North Carolina, the results of analysis of major and trace elements in over 300 samples from coal combustion residue (CCR) effluents, surface water from lakes and rivers, and pore water extracted from lake sediments showed that CCR effluents contain high levels of contaminants; in some samples, these levels exceed the US Environmental Protection Agency (EPA) guidelines for drinking water and ecological effects [30]. Even low concentrations of some contaminants (eg, arsenic) could be an issue, because they can be retained in suspended sediments and remobilized with environmental changes. In North Carolina, smaller lakes and hydrological systems have been shown to be more sensitive to CCR effluent contamination, especially during drought periods [30]. Consequently, contamination with metals from coal ash impoundments in North Carolina can be an issue not only for surface water but also for groundwater [30].

Radioactive contaminants. In addition to toxic metals, radioactive contaminants in coal ash are increasingly recognized as environmental hazards associated with coal-fired power plants. In 1978, McBride and coauthors [A27] concluded that population doses of radioactivity from coal-fired plants can be higher than those from pressurized-water or boiling-water nuclear reactors. In 1987, the National Council on Radiation Protection and Measurements concluded that the population-effective dose equivalent of radioactivity from coal-fired electrical plants is 100 times that from the nuclear powered electrical plants [31]. Further studies suggested that potential risk for human health from coal-burning waste is comparable to the effects of nuclear waste [32, A28].

The potential radiation exposure from fly ash is critically dependent on the concentration of radioactive elements in the parent coal. During coal combustion, most of the uranium, thorium, and ruthenium series of isotopes and their decay products are released from the original coal matrix and are distributed between the gas phase and the solid combustion products [7]. High levels of radioactive isotopes of radium (such as ^{226}Ra and ^{228}Ra) have been reported in coal ash, with the levels of radioactivity up to 5 times higher in coal ash than in normal soil [29]. Even at low levels, these isotopes represent health hazards as they can accumulate in the human body (eg, in lungs), gradually enter the blood circulation, and deposit in bones and teeth to remain for life. While no data on specific effects of radium isotopes from coal ash on humans is currently available, studies among clean-up workers following the Chernobyl (Ukraine) nuclear power plant disaster showed that inhaled airborne particles containing radioactive elements can cause bronchial mucosa lesions, with an increased susceptibility to the invasion of microorganisms and pre-neoplastic changes [A29, 33].

Potential health impacts of coal ash. Coal and coal ash can impact human health at every stage of use—from the initial mining of coal to the post-combustion disposal of coal ash [4, A15]. Unfortunately, research on the health effects of coal ash exposure in humans is limited. Typically, studies of the health impacts of coal ash are based on animal models or *in vitro* experiments. For example, such studies have shown that coal ash particulates can affect lung epithelial and red blood cells causing inflammation, change the sensitivity of epithelia, alter immunological mechanisms and lymphocyte blastogenesis, and are associated with increased risk of cardiopulmonary diseases (eg, pulmonary vasculitis and hypertension) [34, A30-A32]. Occupational studies of workers at coal-burning power plants showed higher risk of malignancies, cytogenetic damages, and chromosomal aberrations [35, 36, A33-A35]. Studies of health and well-being in communities located near landfills or coal ash impoundments are uncommon and are predominantly survey based. For example, a recent study on parents' perception of their children's health and potential impact of coal ash showed that 85% of parents reported their children suffered from respiratory, emotional, and behavioral disorders, and most parents felt helpless in reducing children's exposure [24].

Studies providing quantitative estimates for health outcomes in the United States impacted by coal and coal ash are presented in Table 2. Overall, these studies show higher all-cause mortality; rates of premature deaths (ie, deaths occurring before the average age of death—approximately 75 years old in the United States) and infant mortality; higher risk of cardiovascular and chronic respiratory diseases (including asthma in children); lung cancer; and higher prevalence of low birth weight in newborns reported in association with air pollutants related to coal-burning power plants (see Table 2). In the United States, few studies have quantitatively evaluated the effects of coal power plant emissions in residential communities or larger populations (ie, on county or state levels). Studies with direct measurements of individual or group/community exposures that can provide a scientific rationale for policy changes in the United States or US states are currently not available, and most of the studies on health outcomes in populations living in close or far proximity to coal-burning power plants are model-based (see Table 2). Our performed search did not return the results on quantitative estimates (based on direct measurements of exposure or obtained from the models) on health risks associated with landfills or coal ash impoundments in US states. Several studies from Europe and China showed that increased levels of contaminants related to coal power plant emissions were associated with higher risk of respiratory and cardiovascular diseases, abnormal neurological development in children, poor growth of the fetus, higher rates of premature birth, and increase in all-cause mortality [37, 38, A36]. In one study, increased risks of lung, larynx, and bladder cancer have been reported in populations residing near combustion installations [39]. In studies performed inside and outside the United States, populations with high vulnerability to adverse effects of exposure to power plant emissions included children, pregnant women, older adults, and people with chronic lung infections and chronic obstructive pulmonary disease (COPD) [A37].

Coal ash can impact maternal and child health: maternal exposure to increased levels of SO_2, PM, and NO_2 in the air during pregnancy was associated with lower birth weight in newborns [40]. Countries with baseline medium-to-low infant mortality (eg, Chile, China, Mexico, Thailand, Germany, Australia) had higher infant mortality rates in the regions with higher electricity generation from coal-fired power plants [41]. It has been shown that children exposed prenatally to coal ash containing PAHs had decreased motor, language, and social development later in childhood [A36, 38]. Children from communities located near coal-fired power plants also had more frequent respiratory diseases, emotional, behavioral, and learning disorders, and attention-deficit hyperactivity disorder (ADHD) than children living far from these plants [24, 42, 43, A38-A41]. Chronic exposures of children to PMs, including those from coal ash, have been found to promote chronic inflammation and elevated levels of inflammatory cytokines in the brain, thus being associated with increased risk of diseases of the central nervous system (CNS) [44]. Children are more vulnerable to exposures to coal power plant emissions because of their prolonged time of outdoor activities, greater air consumption relative to lung mass and body weight, and frequent mouth breathing (which allows for less filtering through nasal passages) [45]. Further research is needed to investigate the health effects in children living in communities near coal-fired plants and coal ash impoundments, evaluate the spectrum of air and water contaminants in such communities, and estimate individual exposures to provide information for individual-level analysis of associations between health outcomes and environmental exposures.

An important aspect of the health impact of coal-burning power plants is the size of the at-risk populations. While populations living in close proximity to coal power plants are usually small, the effects on health could be observed in much larger populations living relatively far from the source of exposure. For example, the estimates for use of the Best Available Control Technology (BACT) on 2 old coal-fired power plants in Massachusetts showed that while the maximum annual average benefit occurs within 25-40 km (depending on power plant) from power plant (where less than 10% of the population lives), a majority of benefits could be obtained for the larger population living as far as 100 km from the source [46].

Contaminants in coal ash are also known to impact overall life expectancy: the intense use of coal-fired sources of energy has been shown to predict a 0.5-year decrease in life expectancy in European countries and up to a 3.5-year decrease for developing economies such as India and China [41]. It has been estimated that for every terawatt-hour (TWh) of electricity produced by coal-fired power plants in Europe there are 25 deaths, 225 serious illnesses (including hospital admissions for congestive heart failure and chronic bronchitis), and 13,288 minor illnesses [47]. The type and quality of coal used impact the spectrum of pollutants in emissions and their health hazards after combustion. For example, when lignite—the softest and most polluting form of coal—is used, each TWh of electricity produced results in even more health hazards than cited above for non-lignite

TABLE 2.
Health Outcomes for Air Pollutants Known to Be Associated with Coal-Burning Power Plant Emissions and Studies on Impact of Coal-Burning Plants on Health: Peer-Reviewed Papers That Provide Quantitative Estimates for the US, US States, and Europe (1 Study)

Disease or mortality cause	Effects of air pollutants known to be associated with coal-burning power plant emissions: studies on long-term exposure	Studies of impacts of coal-burning power plant emission or study on other measurements related to coal-burning power plants	Area: US, US state, Europe	Authors, year of publication, reference
All-cause mortality	10-µg/m^3 increase in annual average of $PM_{2.5}$ level was associated with 6.8% (95%CI = 4.9–8.7%) and 13.2% (9.5–16.9%) increases in all-cause mortality among persons over 65 years old.	-	Eastern and central US	Zeger et al, 2008 [58]
	10-µg/m^3 increase in annual average $PM_{2.5}$ level was associated with 10.9% (95%CI = 9.0–12.8%) increase in all-cause mortality in the American Cancer Society (ACS) study and 20.8% (14.8–27.1%) increase in the Harvard Six Cities study, among persons over 65 years old.	-	Across the US and Harvard Six City study	Eftim et al, 2008 [59]
	Rate ratio (RR) of increased overall mortality was associated with each 10-µg/m^3 increase in $PM_{2.5}$ when modeled either as the overall mean (RR = 1.16; 95%CI = 1.07–1.26) or as exposure in the year of death (RR = 1.14; 95%CI = 1.06–1.22).	-	Harvard Six City study	Laden et al, 2006 [60]
	-	The model predicted that if all proposed 29 plants were operational, increased average annual $PM_{2.5}$ concentrations would result in 104 cumulative excess deaths over a 6-year period.	(Virginia)	Hermann et al, 2004 [61]
	-	CALPUFF or S-R matrix used: emissions of 7 power plants in northern Georgia result in 500 estimated deaths per year within 500 km of Atlanta, with most of the impacts associated with sulfates.	(Atlanta, Georgia)	Levi et al, 2003 [53]
All-cause mortality, heart failure, and bronchitis incidence	-	For every TWh[1] of electricity produced from coal (non-lignite) there are 25 deaths, 225 illnesses such as congestive heart failure and chronic bronchitis, and 13,288 minor illnesses.	Europe	Markanduya et al [47]
Premature deaths	-	CALMET/CALPUFF model: applying BACT[2] standards to 2 Massachusetts power plants would lead to ≈70 fewer premature deaths per year in this region.	Massachusetts	Levi et al, 2002[46]
	-	CALPUFF model: ≈320 premature deaths occurring per year in the region due to current emissions from 9 Illinois power plants.	Illinois	Levi et al, 2002 [52]
	Significant declines in SO_2 emissions (-20.3%/year) and $PM_{2.5}$ sulfate concentrations (-8.7%/year) since passage of the Clean Smokestacks Act were correlated with the risk model estimates showing decreased risk of premature death attributable to $PM_{2.5}$ sulfate by about 63%, resulting in an estimated 1700 (95%CI = 1500-1800) deaths prevented in 2012.	-	North Carolina	Li et al, 2014 [21]

TABLE 2 CONTINUED.

Disease or mortality cause	Effects of air pollutants known to be associated with coal-burning power plant emissions: studies on long-term exposure	Studies of impacts of coal-burning power plant emission or study on other measurements related to coal-burning power plants	Area: US, US state, Europe	Authors, year of publication, reference
Premature deaths, CVD hospital admissions, pediatric asthma ED visits	-	CALPUFF used: with emission control at 5 older plants in the Washington, DC, area, there are estimated to be 240 fewer premature deaths, 60 fewer CVD hospital admissions, and 160 fewer pediatric asthma ED visits per year due to emissions reduction leading to annual average $PM_{2.5}$ level reduction ranging from 0.009 to 0.9 $\mu g/m^3$.	Washington, DC area	Levy et al, 2002 [51]
Lung cancer	Each 10 $\mu g/m^3$ increase of $PM_{2.5}$ level was associated with increased rate ratio (RR) of lung cancer deaths (RR = 1.27; 95%CI = 0.96–1.69).	-	Harvard Six City study	Laden et al, 2006 [60]
	Each 10-$\mu g/m^3$ elevation in fine particulate air pollution was associated with approximately 8% increased risk of lung cancer mortality.	-	Across the US	Pope et al, 2002 [66]
Respiratory mortality	Decline in emphysema deaths was associated with decreasing levels of SO_2, decline in asthma deaths with lower SO_2 and PM_{10} levels, and decline in pneumonia deaths with lower levels of SO_2 in the air.	-	North Carolina	Kravchenko et al, 2014 [19]
Bronchitis and asthma in children	Bronchitis symptoms in asthmatic children were associated with the yearly variability of $PM_{2.5}$ (OR = 1.09, 95%CI = 1.01-1.17).	-	Southern California	McConnell et al, 2003 [62]
Cardiovascular disease	Each 10 $\mu g/m^3$ increase in $PM_{2.5}$ levels was associated with increased rate ratio (RR) of cardiovascular deaths (RR = 1.28; 95%CI = 1.13–1.44).	-	Harvard Six City study	Laden et al, 2006 [60]
	In females, the relative risk (RR) for coronary heart disease with each 10-$\mu g/m^3$ increase in $PM_{2.5}$ level was 1.42 (95%CI = 1.06–1.90) in the single-pollutant model and 2.00 (1.51–2.64) in the 2-pollutant model (with O3). For a 10-$\mu g/m^3$ increase in $PM_{10-2.5}$ RR = 1.62 and for PM_{10} RR = 1.45. No associations were found in males.	-	California	Chen et al, 2005 [63]
	Increased mortality was reported attributable to ischemic heart disease, dysrhythmias, heart failure, and cardiac arrest. For these cardiovascular causes of death, a 10-$\mu g/m^3$ elevation in fine PM was associated with 8% to 18% increases in mortality risk.	-	Across the US	Pope et al, 2004 [10]
	Each 10-$\mu g/m^3$ elevation in fine particulate air pollution was associated with approximately 6% increased risk of cardiopulmonary mortality.	-	Across the US	Pope et al, 2002 [66]
Diabetes	Modeling approach was used. Study showed that increases in sulfate (SO_4 2-) levels were associated with decreased flow-mediated (10.7%; 95%CI = 17.3-3.5) and nitroglycerin-mediated (5.4%; 95%CI = 10.5-0.1) vascular reactivity in patients with diabetes. Increase in $PM_{2.5}$ level was associated with nitroglycerin-mediated reactivity (7.6%; 95%CI = 12.8-2.1).	-	Massachusetts	O'Neill et al, 2005 [67]

TABLE 2 CONTINUED.

Disease or mortality cause	Effects of air pollutants known to be associated with coal-burning power plant emissions: studies on long-term exposure	Studies of impacts of coal-burning power plant emission or study on other measurements related to coal-burning power plants	Area: US, US state, Europe	Authors, year of publication, reference
Low birth weight	In multiple linear regression analysis, exposure to 10-$\mu g/m^3$ increase in PM_{10} level in the 3rd trimester of pregnancy can be associated with a birth weight reduction of 11 g (95%CI = 2.3-19.8 g). PM_{10} was not found to be associated with the risk of low birth weight in logistic regression analysis.	-	Nevada	Chen et al, 2002 [64]
Infant mortality	Adjusted odds ratio (OR) of 1.16 (95%CI = 1.06–1.27) was obtained for a 10-$\mu g/m^3$ increase in PM_{10} level for respiratory causes of infant mortality.	-	Across the US	Woodruff et al, 2008 [65]

[1]Terawatt-hour.
[2]Best Available Control Technology.

coal—approximately 33 deaths, 298 serious illnesses, and 17,676 minor illnesses [47]. In the United States, lignite comprises 7% of coal production by weight and 5% by energy intensity, with Texas and North Dakota being the main lignite producers [A42]. When the numbers of excess deaths and illnesses in Europe [47] have been recalculated to estimate the worldwide health toll associated with air pollution due to coal combustion, the emissions have been estimated to be associated with 210,000 deaths, almost 2 million serious illnesses, and over 151 million minor illnesses per year (calculations were made without including potential effects of climate change) [4].

Why are future studies required? Our understanding of environmental exposures from coal-fired power plants and their associated health risks remains limited. Occupational and environmental health standards have not been developed for most metals or the specialty extraction solvents found in coal and coal ash, largely due to the limited information on their toxic effects on human health and ecosystems [A43]. The specific health effects of exposure to these pollutants among workers and residential communities remain largely unknown; therefore, monitoring of populations at risk for these environmental exposures is needed [48]. At this time, it is not possible to estimate the specific health impacts of coal ash components due to a lack of information on the rate at which they are entrained into the atmosphere, as well as the chemical, physical, and synergistic properties that impact morbidity and mortality in each particular geographic area. Longer-term monitoring is needed to better quantify emissions of individual coal-powered plants. Even if all power plants had identical control equipment, coal sulfur content, and combustion efficiencies, damages per kilowatt-hour would still vary substantially due to the differences in exposures per unit of emission [11]. Future studies are also needed on linking ambient contaminants, radionuclide concentrations, and ambient meteorological characteristics with human population exposures.

In efforts to begin to evaluate potential contaminations from coal ash impoundments, the US EPA developed the Coal Ash Dam Hazard Ratings [23], which show that North Carolina has the highest number of coal ash sites in the southeastern region of the United States that are defined as highly hazardous (ie, when a dam failure is likely to cause loss of human lives) (see Figure 2). In fact, 7 out of 14 sites in North Carolina are highly hazardous [23], and 6 other sites are EPA-rated as significantly hazardous (ie, when a dam failure is likely to cause significant economic loss, environment damage, or damages to infrastructure). Only one site in North Carolina is rated as low-hazard (ie, when a dam failure would only result in low economic or environment losses) (see Figure 2). Additional concerns such as unlined impoundments (that may not restrict toxic pollutants from seeping into surrounding groundwater, rivers, and lakes) and impoundments in poor condition (more likely to leak and contaminate groundwater, surface water, or surrounding property) have been reported at all North Carolina coal ash sites [23].

While there is an overall improvement in air quality due to retirement of older coal-fired plants and the use of scrubbers to reduce airborne emissions in North Carolina, the coal ash impoundments still could contribute to contaminations in nearby communities. No studies with direct measurements of exposure and health status are currently available in the communities adjacent to landfills or coal ash impoundments in the United States. Certain health and ecological risk assessments showed that human health estimates within the coal ash site property boundaries were pri-

FIGURE 2.
Location of Coal Ash Impoundments in NC and the US Environmental Protection Agency Hazards

This figure is available in its entirety in the online edition of the NCMJ.

Source. www.Southeastcoalash.org.

TABLE 3.
Potential Health Effects Reported for Metals Related to Coal-Burning Power Plant Emissions: Summary of Health Impacts Obtained from the Literature Overview

Metal	Conditions/diseases correlated with exposure	Information on particular aspects of exposure	Recognition by official agencies as a hazardous substance for humans
Lead	Abdominal pain, memory loss, damage of developing nervous system in fetus, miscarriages, and intellectual disabilities in children [A47].	There is no known level of lead exposure that is considered safe. The neurological effects of lead are believed to be irreversible.	The World Health Organization (WHO) has recognized lead as one of 10 chemicals of major public health concern [A48]. Classified as the coal ash component that constitutes a major environmental health problem [A49].
Mercury	Exposure of pregnant women can cause lower intelligence levels, delayed neurodevelopment, and changes in vision and memory in the offspring [A50]. Affects fetus development with toxic effects on central and peripheral nervous system (including cognitive and motor dysfunction), gastrointestinal and immune systems, as well as on lung, kidneys (may cause kidney failure), skin, and eyes [A51].	Emitted into the atmosphere from coal-burning power plants and deposited into waterways, converted to methylmercury, and passed up the aquatic food chain [A51, A52]. Humans ingest mercury with consumption of methylmercury contaminated fish [A50].	The WHO considered it one of the top 10 chemicals of major public health concern [A50].
Vanadium	Occupational exposure is associated with tremor, nausea, transient coronary insufficiency, cardiac arrhythmias, anemia, leukopenia, and lung inflammation (the latter is reported for high-dose exposures) [A53]. Modest dose-related increase in inflammation in lung and cardiovascular symptoms (arrhythmia) [A53, A54]. May augment lung carcinogenesis in susceptible individuals through oxidative stress-mediated pathways [A55]. Data on the effects of low-dose vanadium exposure on hematopoiesis are inconsistent [A56].	Excessive intake of vanadium has been recognized as potentially dangerous for human health [A57].	The International Agency for Research on Cancer (IARC) has determined that vanadium is possibly carcinogenic to humans [A58].
Cobalt	Impact on cardiovascular and respiratory systems following cobalt exposure near or even slightly under the current occupational exposure limit [A59]. Associated with hematological and endocrine dysfunctions [A60].	It is an essential trace element but is toxic in higher concentrations [A61].	IARC has reported carcinogenic potential and reproductive toxicity of cobalt [A62].
Hexavalent chromium	Can damage the upper respiratory tract [A57]. Reported toxic effects for chronic exposure to chromium include dermatitis, bronchopulmonary disorders, kidney disease, liver damage, diseases of the circulatory system, lung cancer, and complications of pregnancy and labor [A63]. In occupational studies, increased incidences of genotoxic effects such as chromosomal aberrations have been reported [A63]. Associations have been reported between occupational exposure to chromium (VI) compounds and mortality due to lung cancer [A63].	Chromium in its hexavalent oxidation state is widely recognized as potentially carcinogenic and highly soluble [A64], whereas trivalent Cr (III) is less soluble and of much less concern to human health.	IARC has classified chromium (IV) in Group I (carcinogenic to humans) [32, A63].

marily associated with people trespassing on the property and occupational exposure to the surface waters seeping from coal ash basins and soils contaminated by those seeps [49]. One study has suggested limiting human health risks to such constituents of potential concern as arsenic, lead, and zinc [A34]. However, no studies with direct measurements of exposure and health status are currently available in the communities adjacent to landfills or coal ash impoundments in the United States. The higher risk of seeping from unlined or poorly lined coal ash impoundments in North Carolina

TABLE 3 CONTINUED.

Metal	Conditions/diseases correlated with exposure	Information on particular aspects of exposure	Recognition by official agencies as a hazardous substance for humans
Arsenic	Long-term exposure can increase the risk of cancers of bladder and lung, skin damage (pigmentation changes and hyperkeratosis), developmental effects, cardiovascular disease, neurotoxicity, diabetes, and liver damage [A57, A65]. Long-term exposure is associated with neurotoxicity, including Alzheimer's disease [A66, A67].	The evidence on carcinogenic effect is compelling for both the inhalation and ingestion routes of exposure. There is evidence of dose-response relationships within exposed populations for both types of exposure [A68].	Carcinogen recognized by IARC [A65, A68, A69]
Quartz and crystalline silica	Higher concentrations of coal-derived components of ash of ultrafine size quartz and nanoparticles (<50 nm) of crystalline silica correlated with increased risk of lung cancer [A70].	The IARC Working Group noted that "carcinogenicity may be dependent on inherent characteristics of the crystalline silica or on external factors affecting its biological activity or distribution of its polymorphs [A71]."	IARC reclassified quartz and crystalline silica from a class 2 to a class 1 carcinogen based on sufficient evidence of its carcinogenicity in both humans and experimental animals [13].
Cadmium	Is associated with increased lung cancer risk [A65,]. Affects digestive and respiratory systems, skin, kidney, and skeletal system (osteoporosis) [A73, A74].	Cadmium exposure at an early age should be limited as much as possible to prevent direct effects on children and to prevent accumulation, which may have serious health effects manifesting at older ages [A75].	Cadmium is recognized as a toxic metal that constitutes a major environmental health concern [A49].

Note: A detailed discussion on radioactive components in coal ash is presented in the text.

(compared to other states in the southeastern United States where the number of highly hazardous coal ash impoundments is lower than in North Carolina [42]) makes evaluation of the health in residential communities located in close proximity to coal-burning power plants and/or coal ash impoundments very important.

The Coal Ash Management Act of North Carolina [50] now requires that the Department of Environment and Natural Resources of (NC DENR) evaluate each coal combustion residuals landfill currently operating in the state and assesses the risks to public health, safety, and welfare. No later than August 1, 2019, several coal combustion residuals surface impoundments in North Carolina "shall be deemed high-priority" and closed in conformance with this act. These sites include coal impoundments owned and operated by Duke Energy Progress (in Rockingham, New Hanover, and Buncombe counties) and the sites owned and operated by Duke Energy Carolinas (in Gaston County) [50].

Nonlinearities and thresholds in concentration response functions influence the precision of evaluation of the health risks: ie, it is unclear which factor would be dominant or what is the magnitude of variability in marginal damages across power plants [11]. Due to the complicated effects of multiple factors affecting population exposures caused by coal plant emissions, modeling approaches are widely used to evaluate potential health impacts of coal ash on human health in addition to conventional epidemiological studies. For example, complex chemistry transport models have been used to analyze health-related hazards of power plant emissions with the focus on the relationships between plant emissions and population exposures (eg, models such as CALPUFF or the Community Multiscale Air Quality model) [12, 46, 51-53, A44]. However, the degree to which the results from one geographic setting are transferable to another setting remains unclear, as does the question of whether control strategies that effectively treat emissions from one source will work for other sources of contamination [11]. Future prognoses of the health impacts on the residents exposed to coal ash require long-term follow-ups of various population groups that include children, pregnant women, persons exposed *in utero*, and individuals with pre-existing bronchopulmonary and cardiovascular diseases [29].

In North Carolina, 87% of the recently proposed coal ash sites are in areas with >25% of minority residents or low-income areas [54]. The possibility of coal ash contaminating surface and groundwater generates health concerns as many of the existing and planned coal ash sites in North Carolina are located in rural areas where private water wells still represent an important source of drinking water [55]. It is crucial to develop a plan for North Carolina that will account for these rural areas and minimize potential health impacts for residential populations. Future studies will help to develop new strategies for private well testing [56].

The use of coal for power generation remains a great concern because even with reduced SO_2, NO_2, and PM emissions, coal-burning power plants remain intensive sources of energy that continue to produce a substantial amount of air pollution and by-products of combustion that may impact nearby communities [41, 47, A45, A46]. Based on this review, a summary of prioritized study directions on evaluation of health impacts of coal-burning power plants in North Carolina has been made (see Table 4). It shows multiple aspects of future studies in North Carolina that will provide information on exposures from coal-burning power plant emissions and health outcomes in residential populations, thus providing a scientific rationale for policy changes and public health interventions. Because coal as a source of energy is still actively used in North Carolina, health risks associated with multiple contaminants continue to induce a wide range of health problems [57]. Reported health risks include (but are not limited to) increased risk of all-cause mortality [53, 58-60], premature mortality [11, 21, 46, 52, 61], respiratory [16, 51, 62] and cardiovascular [10, 51, 63] diseases, as well as increased risk of respiratory cancer [39], low birth weight [40, 64], higher risk of developmental and behavioral disorders in infants and children [24, 42, 43, A41], and infant mortality [65]. Detailed analysis of these health impacts in North Carolina, particularly in communities near coal-fired powered plants, requires site-specific evaluations. Further studies are required to profile the severity of the cumulative impacts of multiple air, water, and soil contaminants related to coal power plants and coal ash impoundments on human health and the environment. Therefore, attention to these issues in North Carolina is a necessary step toward a healthy North Carolina population. NCMJ

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TABLE 4.
Summary of Prioritized Study Directions on Evaluation of Health Impacts of Coal-Burning Power Plants in NC

This table is available in its entirety in the online edition of the NCMJ.

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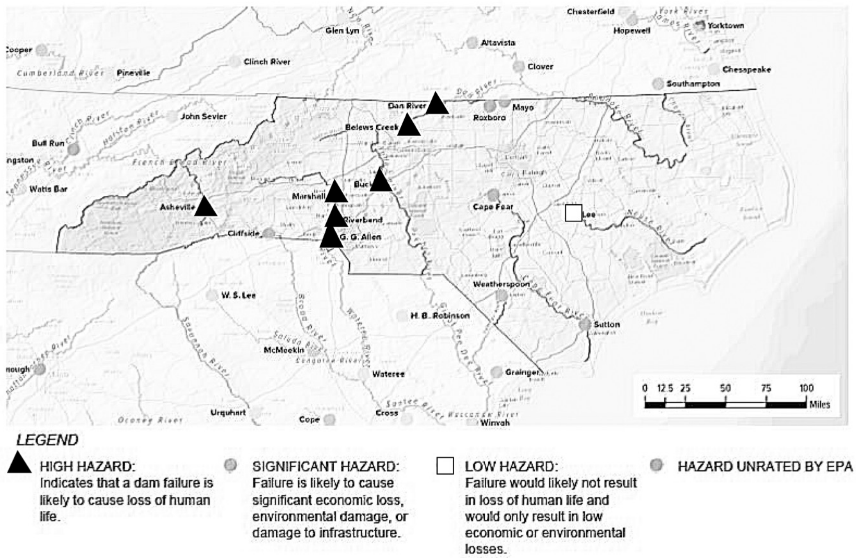
APPENDIX 3.
References

This table is available in its entirety in the online edition of the NCMJ.

FIGURE 2.
Location of Coal Ash Impoundments in North Carolina and the US Environmental Protection Agency Hazards



Source: www.Southeastcoalash.org

79503 APPENDIX 2.

TABLE 4.
Summary of Prioritized Study Directions on Evaluation of Health Impacts of Coal-Burning Power Plants in North Carolina

The aspects of future studies	Brief description of study directions
Information needed for	• What are the ranges of community level and individual-level exposures to air contaminants and policy updates associated with emissions in NC communities located in close proximity to coal-burning power plants?
	• What are the ranges of community level and individual-level exposures to water (well water, surface water, and groundwater) and soil contaminants associated with coal ash storage sites in NC communities located in close proximity to these sites?
	• Are there increased risks of incidence of and/or mortality from certain diseases associated with coal power plant emissions or coal ash impoundments in NC? How do these risks change in NC respective to changes in the levels of air and water or soil pollutants?
	• What will be the results of projections of potential health benefits in NC populations (at different scale – from community to county and to NC) if emissions from coal power plants are further reduced and lining and dam conditions at coal ash storage sites are improved?
	• What will be the costs of health benefits resulting from improving environmental conditions at coal-burning power plants?
	• What is the association between the distance from coal power plant or coal ash impoundments and health effects that can be quantified precisely?
Diseases/health outcomes of primary interest	• Respiratory disease, with specific focus on asthma, chronic bronchitis, emphysema, pneumonia, and influenza. Age-group specific analysis in children, young adults (21-44 years old), people aged 45-64, and over 65.
	• Lung cancer, with histologic subtype analyses, stage at diagnosis, access and adherence to treatment, and patient survival.
	• Cardiovascular disease, including ischemic heart disease, myocardial infarction, cardiac arrhythmia, and heart failure. Age-group specific analysis among younger residents (aged 21-44), people aged 45-64, and over 65.
	• Maternal and child health: pregnancy complications, low birth weight, infant mortality, developmental and behavioral disorders in children.
	• Premature mortality.
Variables of primary interest	• Community based survey that would provide individual information on symptoms, quality of life, availability of medical care, history of residence, local water/food consumption, time spent outdoors, and occupational exposure.
	• Information on disease incidence, prevalence, severity, hospital admissions, ED visits, and mortality.
	• Individual-level information on co-factors including income, education, smoking, etc.
	• Monitoring of health of populations living near retired and active coal-burning power plants in NC for further assessments of health.
Environmental measures/ assessments to be further analyzed with health data	• Measures of NO_x, SO_2, $PM_{2.5}$, $PM_{2.5\text{-}10}$, and PM_{10} levels in the air • Analysis of different types of PMs (by their chemical compounds) and their associations with specific health outcomes.
	• Measurements of PAHs[1], heavy metals, and radioactive isotopes in CCR[2] effluents, potentially contaminated surface waters (from lakes and rivers), and pore water extracted from lake sediments.
Weather/climate-related factors to account for in future studies on health impacts	• Season-specific analysis, including summer months in NC with heat waves and high humidity. • Events of heavy rains and floods in the areas where coal ash impoundments are located.

[1]polycyclic aromatic hydrocarbons.
[2]coal combustion residues.

79503 APPENDIX 3.
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