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Effect of Waterborne Uranium Exposure on Human Capital Endowment Proxies.

Michael Spanbauer
Department of Economics
Tulane University
mspanbau@tulane.edu

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Abstract

This paper examines the causal relationship between waterborne uranium exposure and birth outcomes in order to more fully understand the external costs of the activities that increase the probability of human exposure to uranium, such as the prevalent military use of depleted uranium munitions. I use the Church Rock Uranium Mill industrial accident as a natural experiment, in which children born in specific counties are exposed to uranium via a contaminated water supply. I examine changes in birth outcomes, which approximate human capital endowment at birth, and I find that waterborne uranium contamination does not manifest via observable decreases in birth outcomes, specifically birth weight, or via changes in gender ratios. I also provide evidence suggesting that migratory responses to the contamination are not driving a change in the population's determinants of birth outcomes. Collectively, these results support modern militaries' claims that the risk of unintentional harm by uranium based weapons are "negligible".

Keywords: Uranium; birth outcomes; human capital endowment; Church Rock
JEL codes: D62; I18; I39; J24

Effect of Waterborne Uranium Exposure on Human Capital Endowment Proxies.

By Michael Spanbauer *

This paper examines the causal relationship between waterborne uranium exposure and birth outcomes in order to more fully understand the external costs of the activities that increase the probability of human exposure to uranium, such as the prevalent military use of depleted uranium munitions. I use the Church Rock Uranium Mill industrial accident as a natural experiment, in which children born in specific counties are exposed to uranium via a contaminated water supply. I examine changes in birth outcomes, which approximate human capital endowment at birth, and I find that waterborne uranium contamination does not manifest via observable decreases in birth outcomes, specifically birth weight, or via changes in gender ratios. I also provide evidence suggesting that migratory responses to the contamination are not driving a change in the population's determinants of birth outcomes. Collectively, these results support modern militaries' claims that the risk of unintentional harm by uranium based weapons are "negligible."

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Uranium is a naturally occurring radioactive metal used in the construction of depleted[1] uranium (DU) munitions. DU munitions are extolled by modern militaries for their ability to penetrate heavy armor plating, but the projectiles also contaminate the surrounding area with uranium dust that is washed by rainfall into a population's water supply, such as rivers

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* Corresponding Author: Michael Spanbauer, mspanbau@tulane.edu, Tulane University Department of Economics, 6832 St. Charles Avenue, Tilton 206, New Orleans, LA 70118. I thank Alan Barreca, James Alm, and Patrick Button of Tulane University's Department of Economics for their feedback. The analyses, interpretations, and conclusions of this article have been reached by the author and not NCHS, which is responsible only for making the data publicly available.

[1] Depleted uranium is the byproduct of the uranium enrichment process, necessary for the construction of nuclear reactors and nuclear weapons. Enriched uranium contains 0.72 percent of the fissile isotope U-235, all remaining uranium is considered "depleted." Depleted uranium is not less harmful, only less suitable for use in nuclear fission.

and wells, causing a significant health risk (Boice, *et al*, 2010; Brown, 2003; Canu, *et al*, 2012; EPA, 2012b; Ritz, 1999). One area of the world that has endured years of exposure to DU munitions is the Persian Gulf; an estimated 340 tonnes[2] of DU were fired during the First Gulf War,[3] and an additional 2,000 tonnes[4] were deployed in the first three weeks of the Second Gulf War,[5] from 19 March 2003 to 30 April 2003 (Brown, 2003). These conflicts, fought in close proximity to civilian environments, dispersed thirty-thousand times more uranium than was contained in the bomb that ended World War II.

Although modern militaries claim that the health effects of DU munitions are negligible (Miller, *et al*, 2008), this paper tests the hypothesis that contaminating a population's water supply with uranium imposes a cost to the exposed population in the form of decreased health stock and human capital endowment at birth, which may lead to reduced economic stability later in life. The foundation of my hypothesis is supported by circumstantial evidence linking uranium to debilitating physiological effects (Boice, *et al*, 2010; Ritz, 1999; Miller, *et al*, 2008). For example, the population of Fallujah, Iraq, developed 4.22 times more cancer cases in than populations not exposed to DU munitions in the period following the United States' 2004 seige (Busby, Hamdan, and Ariabi, 2010). Additionally, nine deaths in the Italian military and wide-spread illnesses in the militaries of France, Netherlands, Spain, Belgium, and Portugal are correlated with handling depleted uranium ammunition (Gupta, 2001).

It would be difficult to directly test this hypothesis using data from war-zones contaminated by uranium-based munitions because wars destroy infrastructure, increase demand for health services, and induce stress; changes that may be negatively correlated with birth outcomes and that may adversely influence future labor market outcomes. I therefore isolate the effect of waterborne uranium exposure on my dependent variables by identifying an incident where a large volume of uranium is quickly introduced to the water supply by an exogenous shock

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[2] 374.786 tons.

[3] Two major operations occurred, code-named Desert Shield, 2 August 1990 - 17 January 1991, and Desert Storm, 17 January 1991 - 28 February 1991. The latter mission lasted exactly 42 days before the capitulation of the Iraqi forces. The Iraqis surrender has been primarily attributed to the United States warplanes, loaded with PGU-14/B depleted uranium bullets, dispatching the opposition's armored tank divisions.

[4] 2,204.623 tons.

[5] One example of uranium dispersion is the coalition attack on the Headquarters of the Planning and Information Ministry in Baghdad, Iraq. On 9 April 2003, the building was shot 49 times with PGU-14/B depleted uranium bullets (Zecevic, Terzic, Catovic and Serdarevic-Kadic, 2010). Each bullet contained 0.63 lb of depleted uranium, totaling 30.87 lb of uranium. This is equivilant to approximately 1/4th of the uranium used in the Little Boy nuclear bomb.

and where the exposure to the contamination is randomly assigned to a clearly-identifiable population. I then construct a panel dataset by combining samples from the National Center for Health Statistics' natality files with timing and geographic data collected in a survey of archived periodicals. I employ a difference-in-differences model to compare the exposed individuals' birth outcomes with a counter-factual group drawn from uncontaminated areas. The key identifying assumption is that, had the contamination not been introduced into the water supply, the average annual change in these outcomes would have been similar to the observed changes of unexposed individuals.

This analysis builds on a body of research which has established a link between health at birth and human capital endowment. The Fetal Origins Hypothesis (FOH) postulates that adult health is affected by *in utero* conditions[6] (Barker, 1995), and research indicates that children with low birth weight, a metric commonly used to asses health at birth, tend to have reduced IQ, test scores, cognitive development, high school completion rates, and adult earnings; more specifically, a birth weight decrease of 481 grams can lead to a 6 percent decrease of lifetime earnings (Almond, Chay and Lee, 2005; Black, Devereux and Salvanes, 2007; Behrman and Rosenzweig, 2004). Furthermore, Almond and Currie (2011) observe latent effects that lead healthy children to manifest significant abnormalities in adulthood as a result of *in utero* exposure to a harmful substance. These links between health at birth, human capital endowment, and adult socioeconomic outcomes suggest that early childhood or *in utero* exposure to a toxic substance, such as uranium, can plausibly decrease a population's human capital endowment and create lingering adverse economic effects.

The first finding of this paper indicates that exposure to the contamination is not negatively correlated with determinants of birth outcomes, such as parental education and age. This suggests that the contaminated geographic locations did not experience a significant demographic change that adversely affects the population's birth outcomes and therefore supports the validity of my subsequent analysis. The second finding of this paper is that uranium contamination in a population's water supply appears to have a negligible effect

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[6] Lucas, *et al*, (1999) emphasized the importance of proper statistical analysis when interpreting effects of the FOH, Almond and Currie (2011) how *in utero* conditions can cause abnormalities to manifest in adulthood, and additional discussion of the FOH can be found in Therapontos, *et al*, (2009), Kaestner and Lee (2005) and Wehby, *et al*, (2009).

on the exposed population's birth outcomes; my analysis indicates that maternal ingestion of contaminated water does not manifest as a significant adverse change in the available birth metrics, specifically birth weight and gender ratios, and it also indicates that there is no observable culling effect influencing the estimates. The implication of these results is that *in utero* exposure to waterborne uranium contamination does not cause an observable decrease in proxies for human capital endowment at birth, and therefore activities which increase the likelihood of human exposure to uranium contamination may not have significant external effects on the exposed population's birth outcomes and human capital endowment. The conclusions of this analysis align with the military's claims that the unintentional harm caused by DU munitions are negligible.

I. Natural Experiment

A. Regarding the Church Rock Uranium Mill spill

On 16 July 1979 at 5:20 am, a 20-foot section of the Church Rock Uranium Mill's holding pond collapsed. 1,100 tons of solid uranium mill waste and 93,000 gallons of a liquid uranium solution were released into the Rio Puerco, traveled down the Little Colorado river, washed into the Colorado river, and spread through Lake Mead. The course of the rivers brought the contaminants through low-income Native American reservations in Arizona. Residents of these reservations relied on the rivers and lakes for drinking water as well as to irrigate crops, water livestock, catch fish, bathe, and play (Brugge, deLemors, and Bui, 2007), but these water sources quickly became unfit consumption. Precise chronological data on radiation levels downstream are not available, but measurements of water drawn from Lake Mead in 1992 exceeded the federal standards for safe drinking water by 40 percent despite being purified in water-treatment facilities (LVS, 1998).

United Nuclear Corporation, owner of the Church Rock Uranium Mill, later admitted that less than 1 percent of the contamination was removed from the water supply (Brugge, deLemors, and Bui, 2007), implying that residents were subject to uranium exposure up to 7,000 times larger than the "allowable standard" (Johansen, 1997). Despite an official report by the EPA (1983), which states that the Church Rock Uranium Mill spill had almost no adverse effects, historical evidence suggests that the effect of the spill was downplayed by the government. The Navajo Tribal Council's Emergency Services Coordinating Committee asked the Arizona Governor to declare a state of emergency and to assist the tribe with caring for the rapidly increasing number of sick individuals near the contaminated area, but this request, and other similar requests for emergency relief, were denied (Brugge, deLemors, and Bui, 2007). The Navajo Nation turned to the federal government for assistance and on 3 April 2014, 35 years after the event, the federal government awarded the Navajo Nation $1 billion dollars to "address uranium contamination" by attempting to decontaminate the abandoned uranium mines left behind by United Nuclear Corporation and other mining firms (W.I.S.E., 2015).

Shortly after the spill, the executive vice president and CEO of United Nuclear Corporation petitioned Congress for permission to resume mining activities. Permission was granted and mining resumed less than 4 months after the holding pond wall collapsed.

B. Event Selection

My research has uncovered four instances of wide-spread human exposure to unnatural quantities of uranium, of which only the Church Rock event can be used due to the clearly identifiable geographic areas of contamination and the availability of a rich set of publicly available records. Two of the other three instances, namely the use of DU munitions in combat zones and the August 1945 bombing of Hiroshima,[7] can not be utilized because large and protracted military conflicts prevent detailed record-keeping, cause physical damage to people and infrastructure, and also induce unobservable stressors which may be correlated with decreased human capital and labor market outcomes. The final instance occurred on 4 January 1986, when a storage tank in Oklahoma ruptured and released 29,500 tons of gaseous uranium hexaflouride. This event can not be used because the gas disseminated in unknown directions and identification of exposed individuals likely impossible.

It is prudent to acknowledge that other nuclear events and accidents have occurred, such as the testing of nuclear weapons or various reactor malfunctions, but these events can not be used as a natural experiment for this research. Historic usage and testing of nuclear weapons are unsuitable for this analysis because, aside from the single aforementioned

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[7] 64.15 kilograms of uranium were used nuclear weapon, codenamed "Little Boy" (Sublette, 2007)

uranium bomb, the weapons employ a combination of plutonium and high-explosives to reach critical mass.[8] The relative stability of plutonium based weapons made them the preferred design for testing, development and military use; only five uranium bombs were ever constructed (Federation of American Scientists, 1998), four of which were later disassembled due to stability concerns (Nuclear Weapon Archive, 2006). Research shows "plutonium that is ingested from contaminated food or water does not pose a serious threat to humans because the stomach does not absorb plutonium easily, it passes out of the body in the feces" (EPA, 2012b). Additionally, this analysis can not consider a nuclear reactor accident such as Three-mile Island, Chernobyl, Fukushima Daiichi, or Hanford. These events expose people to iodine-130, a radioactive isotope that can cause severe physiological effects in large doses, but is considered "therapeutic" in appropriate doses and, with a half-life 8.2 days, rapidly decays (EPA, 2012a).[9]

Unlike the elements released in the nuclear weapon tests or reactor accidents, uranium is linked with an increased risk of circulatory system diseases (Canu, *et al*, 2012), an increased risk for all types of cancer, and severe liver damage (EPA, 2012c). Due to the different physiological effects of each of these elements, a study examining a plutonium based weapon test or the iodine-130 released during a nuclear reactor accident could not be extrapolated to discuss the effects of civilian exposure to uranium or DU munitions.

II. Methodology

A. Data Sources and Identification

I use county-level natality data from the National Center for Health Statistics (NCHS), collected from 1970 through 1988. Data from years 1970 through 1985 are 50 percent samples of the population, so observations from these years are appropriately weighted. Publicly available data collected after 1988 is unsuitable for analysis because county-level identification was not available for most observations.

Identification of exposed observations is accomplished by evaluating the flow of the Rio

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[8] Critical mass: The smallest amount of fissile material needed for a sustained nuclear chain reaction (Goertzel, 1954)

[9] Uranium exists in three common isotopes with three different half-lives. Uranium-234: 244,000 years. Uranium-235: 700 million years. Uranium-238: 4.47 billion years. (EPA, 2012c)

Puerco, Little Colorado, and Colorado rivers; births occurring in counties with contaminated water flowing through are considered to have received exposure. Figure 1 illustrates the course of the Arizona river network contaminated by the spill. The Rio Puerco flows from east to west, entering the state of Arizona through Apache county. It terminates into the Little Colorado River near the Navajo-Apache county boarder, which flows northwest through Coconino county. The Little Colorado joins the Colorado River approximately in the middle of Coconino county, snakes across the eastern boarder of Mohave county, and drains into Lake Mead, which supplies the drinking water to Mohave County, Arizona. Once the water passes through the Hoover Dam,[10] it travels south through Yuma and La Paz counties[11] (United States Geological Survey, 2014). The control group is comprised of all remaining counties in Arizona.

As this event primarily impacted the Native American residents in the exposed counties, I restrict my natality data to include only the Native American population in both the treatment and the control counties by selecting birth records where either the mother or father identify their race as Native American. A map of all treatment and control counties from which Native American births are observed is presented as Figure 2.

B. Outcome Variables and Summary Statistics

Use of the NCHS data permits the analysis of two recognized birth outcome metrics: birth weight and the ratio of extremely low birth weight incidents within a cohort, where extremely low birth weight is defined as a birth occurring with a mass of less than 1500 grams. As previously discussed, birth weight is a metric commonly used to asses health and is linked to human capital endowment at birth. In the data, birth weight is measured in grams and observed at the individual level; I use the log transformation so as to interpret my results in terms of percent-change. Extremely low birth weight is measured as a percentage of the births occurring in a given county and in a given month. Data on other commonly used metrics, such as APGAR score and gestational length, are not available in the data used for this analysis

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[10] No other dams exist between the spill site and the Hoover Dam.

[11] In 1979, La Paz county did not exist. The land that is now La Paz County was part of Yuma County at the time.

In addition to these two metrics of health and human capital endowment at birth, I also explore the ratio of male to female births. Research indicates that male births tend to experience higher numbers of spontaneous abortions when the mother endures stressful conditions (Catalano, Bruckner, & Smith, 2008; Catalano, Bruckner, Hartig, & Ong, 2005). Therefore, a reduction in male births relative to female births can indicate maternal stress following exposure. I use the NCHS data to construct this ratio of male to female births, which is measured as a percentage of the births occurring in a given county and in a given month.

I report the mean and standard deviation of the metrics employed in this analysis in Table 1; full population statistics are listed in column 1, statistics for unexposed individuals are listed in column 2, and individuals exposed to waterborne uranium contamination during the observed time period are listed in column 3. Columns 4 and 5 further examine the exposed individuals by listing the mean values of each metric before and after the exposure occurred.

C. Empirical Model

I employ a difference-in-differences model[12] to evaluate the effect waterborne uranium contamination on individuals, i, born in county c at time t, and I cluster my standard errors at the state level to account for possible serial correlation in birth trends (Bertrand, Duflo, and Mullainathan, 2004).

Observations are assigned a value of $E_{i,c} = 1$ if they are born in the counties that were contaminated by the Church Rock Uranium Mill spill, as identified in Section II.A. I also identify periods of time, $P_{i,t}$, before and after the date of the spill, 16 July 1979. Observations born prior to 16 July 1979 are considered to be in the pre-event group, $P_{i,t} = 0$, and observations born after the event are included in the post-event group. However, average gestational length is 280 days (Jukic, *et al*, 2013), implying observations born immediately following the spill were clearly gestating prior to the event. Therefore post-event observations born within 280 days are assigned a fraction[13] $P_{i,t} = \frac{Spill\ Date - Birth\ Date}{280}$ and subsequent observations are assigned $P_{i,t} = 1$.

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[12] See Ashenfelter (1978), Ashenfelter and Card (1985), and Card and Krueger (1993) for examples and discussions.

[13] Examples of this strategy are found in Donohue and Ayres (2003), Lott and Mustard (2006), and other published works.

I calculate my estimates with and without a set of covariates, $\mathbf{X}$, controlling for characteristics that are causally related to the observed outcomes. These characteristics include gender, mother's age, parent's education, number of prenatal visits, and indications if the birth was a singleton, if it occurred in a hospital and if a doctor was present. Both Almond, Chay and Lee (2005) as well Black, Devereux and Salvanes (2007) recognize these variables as determinants of birth outcomes, and I include them in my model to improve the precision of my estimates.

With this framework, birth weight can be modeled by

$$Y_{i,c,t} = \alpha + \beta E_{i,c} + \gamma P_{i,t} + \delta(E_{i,c} \times P_{i,t}) + \mathbf{X}'_{i,c,t}\mathbf{\Theta} + \lambda_c + \mu_t + \varepsilon_{i,c,t}$$

where the coefficients α, β, γ, δ, and ρ are all unknown parameters, λ_i is a vector of fixed effects controlling for variations caused by county residence, μ_t is a vector of fixed effects controlling for variations caused by month and year of birth, and $\varepsilon_{i,c,t}$ is an idiosyncratic error term assumed to be independent of all other terms in the model. The inclusion of λ and μ (the vectors of fixed effects accounting for location and month of birth) prevent bias from spurious correlations between the timing of the waterborne uranium contamination and other prominent events, while the smaller variations that effect individual observations are captured by the error term. I cluster my standard errors at the state level to account for the possibility of serial correlation in birth trends, as suggested by Bertrand, Duflo, and Mullainathan (2004), and, where appropriate, I use the log-transformation of the outcome variable to aid in interpretation of my results.

I also estimate my model while accounting for county-specific linear time trends. Including linear time trends captures the average change as each additional month passes. This controls for the general direction, or trend, of the outcome in each county. Allowing these time trends to be county-specific allows each county to follow a unique trend as time passes, rather than imposing the assumption that each county's trends are identical over time. It can be seen in the results section that this step is somewhat unnecessary, as results are similar with and without this additional regressor.

D. Assumptions and Limitations

The difference-in-differences model relies on a key identifying assumption for the estimations to be consistent and unbiased, commonly referred to as the "parallel paths" assumption. This assumption asserts that, in the absence of exposure, the exposed group's average changes would have been similar to the observed individuals who were not exposed to the waterborne contamination. In this analysis, the justifications for this assumption are similar to that of a randomized control trial in the sense that treatment assignment was exogenously determined by the timing of an unpredictable accident and the natural path of a river, suggesting that assignment into the treatment and control group is pseudo-random. This assumption permits the observations from unexposed locations to serve as counterfactuals for what would have happened had the Church Rock holding pond not collapsed.

One potential violation of this model is a form of attrition or selection bias. It is possible that the residents of exposed counties who have the means to relocate could have fled after being adversely affected by the spill. These individuals, who were treated, could then either live in the control counties or live in an area not observed by this analysis. If these individuals move to control counties or unobserved counties while their prior homes remain vacant, then my estimates would be biased towards zero and my results can be interpreted as the lower bound of the treatment effect. However, if these individuals flee and create a sudden surplus of low-cost housing, their vacant homes may be filled by individuals with a higher propensity to give birth to children with lower birth outcomes and lower future adult outcomes.

If these unobserved migration patterns exist, and if they are negatively correlated with birth outcomes, then the effects measured by this analysis illustrate a significant change the demographic composition of the affected area rather than a physiological change to a static group of exposed persons. Although a significant decrease in human capital endowment caused by either mechanism is socially undesirable, I acknowledge that a limitation of this analysis is the inability to confidently distinguish between these two mechanisms. However, I provide evidence in Table 2 suggesting that there is not a negative correlation between birth determinants and unobserved migration trends; supporting my hypothesis that waterborne uranium contamination causes adverse physiological changes and negatively affects the outcomes of the exposed population.

III. Results

A. Contamination Response

I have thus far discussed the mechanism by which the uranium contamination has caused *in utero* and childhood exposure, the link between *in utero* exposure and birth outcomes, and the implications of birth outcomes for an individual's human capital endowment. I now examine correlations between the contamination event and the determinants of birth outcomes. The purpose of this check is to ascertain if my analysis is biased by unobserved migration trends that are negatively correlated with birth outcomes. Mother's age, parental education, and level of prenatal care are all considered to be determinants of health at birth (Almond, Chay & Lee, 2005) and examining these determinants as outcome variables can lend insight to the population's reaction to the event. Table 2, Panels A and B, report regression results using the following determinants as the binary outcome variables: mother being of recommended childbearing age, mother being a high school graduate, father being a high school graduate, mother receiving the recommended prenatal care during pregnancy.

A statistically significant decrease in these categories would suggest a migratory response within the population that is negatively correlated with birth outcomes, implying that the results of this analysis are at least partially driven by change in the population's demographics. Conversely, a statistically significant increase in these categories would suggest that an unobserved migratory response has the potential to improved birth outcomes and therefore my primary analysis would underestimate the true harm caused by exposure.

It can be seen in Table 2, Panel A, that point estimates for mother's age and father's education are negative in sign, but are small in magnitude and statistically insignificant. However, the proportion of mothers completing high school and the proportion of mothers receiving prenatal care significantly increases following the event. I introduce county specific time trends in Panel B and thereby relax the assumption that each county experiences identical trends in high school completion and medical care over time. All estimates for determinants of birth converge towards zero with the inclusion of this set of controls. Together, this suggest thats there is no significant demographic response to the event that would artificially inflate the magnitude of my results; these results therefore support the validity of the subsequent analysis.

B. Outcomes at Birth

I now turn to discuss the results of my analysis, which numerically evaluate the causal effects of uranium exposure on these outcomes.

Figure IV, Panel A, depicts the mean annual birth weight over time for the treatment and control groups. A visual inspection of this graph shows a mild decrease in average birth weight immediately following the event, but it is difficult to draw strong conclusions from this graph given the presence of other swings in mean weight observed in both the treatment and control group, some which are larger in magnitude. Panels B through D present other metrics for assessing birth outcomes; percent of cohort born with extremely low weight (mass < 1500 grams), percent of cohort born male, and the size of each cohort over time.[14] Each of these remaining plots is similar to Panel A in the sense that there is no clear visual proof of waterborne uranium contamination adversely influencing the post-treatment birth trends of the exposed population.

Tables 3 and 4 support this visual inference by reporting my estimates for the same four birth metrics presented in Figure IV. Results in Table 3 should be interpreted as the percent-change in birth weight caused by exposure to the waterborne uranium contamination. Results are consistent in sign and small in magnitude, ranging from seven-hundredths of one percent up to two tenths of one percent, and not statistically significant. In nominal terms, this translates to a change of approximately 2.3 – 6.7 grams from the mean birth weight of 3327.5 grams. In Table 4, Panel A presents the change in the probability of experiencing extremely low birth weight as a result of exposure, Panel B presents the change in the probability of experiencing a male birth, and Panel C presents the percent-change in the treatment group's cohort size following exposure to the contamination. In all cases, point estimates are small and close to zero. Furthermore, given the small standard errors for these estimates, it is reasonable to conclude that any effects of *in utero* exposure to waterborne uranium contamination do not manifest via the birth outcome metrics available for this analysis.

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[14] Data on other commonly used metrics, such as APGAR score and gestational length, are not available in the data used for this analysis.

IV. Summary and Conclusion

In this article I examine the effects of exposure to waterborne uranium contamination. I isolate these effects by selecting an event which psudo-randomly assigns exposure to waterborne uranium and then I quantify these effects by analyzing changes in birth outcomes, which approximate human capital endowment at birth.

I present evidence indicating that this event is not negatively correlated with adverse changes in several determinants of birth outcomes, addressing the natural concern that an undesirable change could be driven by a structural change in the population following the contamination event. I then asses the changes in birth outcomes and find that prenatal exposure to uranium by means of maternal ingestion of contaminated water does not manifest as an adverse change in the available birth metrics, specifically birth weight and gender ratios. Despite the possibility of these estimates being a lower bound of a significant adverse effect of treatment, the evidence presented in this article suggests does not support my hypothesis that *in utero* uranium exposure measurably influences birth outcomes.

The novel contribution of this analysis is my method for isolating and exploring the effect of waterborne uranium contamination on human capital endowment proxies. Although the results of this test are inconclusive, the foundations of my analysis can be used in future research into the external costs of utilizing depleted uranium munitions; these munitions are known to leach uranium into the water supply and can therefore cause uranium exposure in a manner similar to the Church Rock accident. Other studies on major nuclear events cannot be extrapolated in this manner because the primary radionuclides released in those events produce distinctly different physiological effects (Campaign for Nuclear Disarmament, 2011; Comprehensive Nuclear-Test-Ban Treaty Preparatory Committee, 2012; EPA, 2012; EPA, 2015).

The contamination caused by the Church Rock Uranium Mill spill is a tragedy, as is the uranium contamination caused by the use of depleted uranium munitions in conflicts fought near civilian areas and agricultural lands. Although the results of this analysis do not contradict the claims that risks associated with exposure to depleted uranium munitions are "negligible," we do not yet fully understand the long-term effects of uranium-based weapons on the health and economic stability of the civilians living near the war zones. If the goal is destruction, then these weapons are effective. However, if the goal is to create long term stability in the conflict zone by "winning the hearts and minds of the people" (Berman, *et al.*, 2011; US Army Field Manual 3-24), then more research is required to ensure we are not poisoning the very people we seek to protect.

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Table 1—Summary Statistics: Mean (S.D.) Values of Observed Birth and Adult Metrics

	All Counties, Full Sample	Unexposed Counties, Full Sample	Exposed Counties, Full Sample	Exposed Counties, Before Exposure	Exposed Counties, After Exposure
Birth Weight	3327.5	3381.6	3300.5	3276.7	3319.6
	(551.1)	(573.1)	(537.8)	(534.5)	(539.8)
% Births < 1500 g	0.0084	0.0093	0.0079	0.0079	0.0085
	(0.09)	(0.10)	(0.09)	(0.08)	(0.09)
% Male Birth	0.503	0.498	0.505	0.506	0.504
	(0.50)	(0.50)	(0.50)	(0.50)	(0.50)

Notes: Summary statistics for birth outcomes before and after exposure event. Exposed and unexposed counties defined in Figures 1 and 2.

Source: National Center for Health Statistics (1972-1988).

Table 2—Effect of Event on Determinants of Birth

Panel 2a: Without Controlling for Time Trends

	Mom C.B. Age	Mom H.S. Grad.	Dad H.S. Grad.	Rec. Prenatal Care
Effect of Exposure	-0.0184	0.1076***	-0.0185	0.0767***
	(0.0141)	(0.0215)	(0.0326)	(0.0178)
Year×Month FE's	Yes	Yes	Yes	Yes
County FE's	Yes	Yes	Yes	Yes
Covariate Set	Yes	Yes	Yes	Yes
Observations	96,412	96,412	96,412	96,412

Panel 2b: Controlling for Time Trends

	Mom C.B. Age	Mom H.S. Grad.	Dad H.S. Grad.	Rec. Prenatal Care
Effect of Exposure	-0.0137	0.0335	0.0034	0.0288
	(0.0202)	(0.0265)	(0.0383)	(0.0539)
Year×Month FE's	Yes	Yes	Yes	Yes
County FE's	Yes	Yes	Yes	Yes
Covariate Set	Yes	Yes	Yes	Yes
Linear Time Trends	Yes	Yes	Yes	Yes
Observations	96,412	96,412	96,412	96,412

Notes: Results are interpreted as the percent change population demographic. Difference-in-differences analysis using covariates as outcome variables. Covariates include: Mother of recommended childbearing age, Mother graduated high school, Father graduated high school, and provision of recommended prenatal care. Regressions calculated using Year×Month and State×County Fixed Effects, a partial set of Covariates, and county-specific Linear Time Trends. Treatment and control groups defined in Figures 1 and 2. Robust standard errors are reported in parenthesis and are clustered at the county level. (* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$)

Source: National Center for Health Statistics (1976-1984).

TABLE 3—EFFECT OF EXPOSURE BIRTH WEIGHT

	(1)	(2)	(3)	(4)
Effect of Exposure	0.0012	0.0007	0.0020	0.0016
	(0.0052)	(0.0054)	(0.0085)	(0.0096)
Mother younger than 20		-0.0268***		-0.0269***
		(0.0025)		(0.0025)
Mother older than 35		0.0252***		0.0253***
		(0.0041)		(0.0042)
M. Edu. less than H.S.		-0.0010		-0.0009
		(0.0032)		(0.0032)
M. Edu. only H.S.		-0.0025		-0.0025
		(0.0019)		(0.0019)
F. Edu. less than H.S.		-0.0176***		-0.0177***
		(0.0022)		(0.0022)
F. Edu. only H.S.		-0.0050***		-0.0051***
		(0.0012)		(0.0012)
Female		-0.0248***		-0.0248***
		(0.0018)		(0.0018)
No prenatal care		-0.0183***		-0.0182***
		(0.0030)		(0.0029)
Plurality		-0.3655***		-0.3653***
		(0.0261)		(0.0261)
Year×Month FE's	Yes	Yes	Yes	Yes
State×County FE's	Yes	Yes	Yes	Yes
Linear Time Trends	-	-	Yes	Yes
Observations	96,412	96,412	96,412	96,412

Notes: Results are interpreted as the percent change in birth weight. Difference-in-differences analysis of exposure groups calculated using Year×Month and State×County Fixed Effects, and county-specific Linear Time Trends. Treatment and control groups defined in Figures 1 and 2. Robust standard errors are reported in parenthesis and are clustered at the county level. (* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$)

Source: National Center for Health Statistics (1972-1988).

Table 4—Effect of Contamination Exposure on Birth Outcomes

Table 4a: Probability of Extremely Low Birth Weight

	(1)	(2)	(3)	(4)
Effect of Exposure	-0.0032 (0.0021)	-0.0030 (0.0021)	-0.0006 (0.0049)	-0.0003 (0.0049)
Year×Month, County FE's	Yes	Yes	Yes	Yes
Covariate Set	-	Yes	-	Yes
Linear Time Trends	-	-	Yes	Yes
Observations	4,536	4,536	4,536	4,536

Table 4b: M:F Gender Ratio

	(1)	(2)	(3)	(4)
Effect of Exposure	-0.0086 (0.0125)	-0.0099 (0.0116)	0.0055 (0.0360)	0.0002 (0.0308)
Year×Month, County FE's	Yes	Yes	Yes	Yes
Covariate Set	-	Yes	-	Yes
Linear Time Trends	-	-	Yes	Yes
Observations	4,536	4,536	4,536	4,536

Table 4c: Cohort Size

	(1)	(2)	(3)	(4)
Effect of Exposure	-0.0553 (0.0885)	-0.0573 (0.0885)	-0.0530 (0.0691)	-0.0595 (0.0670)
Year×Month, County FE's	Yes	Yes	Yes	Yes
Covariate Set	-	Yes	-	Yes
Linear Time Trends	-	-	Yes	Yes
Observations	4,536	4,536	4,536	4,536

Notes: Results for Panels A and B are interpreted as the change in the probability of experiencing the measured outcome, while results for Panel C are interpreted as the percent change in cohort size. Difference-in-differences analysis of exposure groups calculated using Year×Month and State×County Fixed Effects, and county-specific Linear Time Trends. Treatment and control groups defined in Figures 1 and 2. Robust standard errors are reported in parenthesis and are clustered at the county level. (* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$)
Source: National Center for Health Statistics (1972-1988).

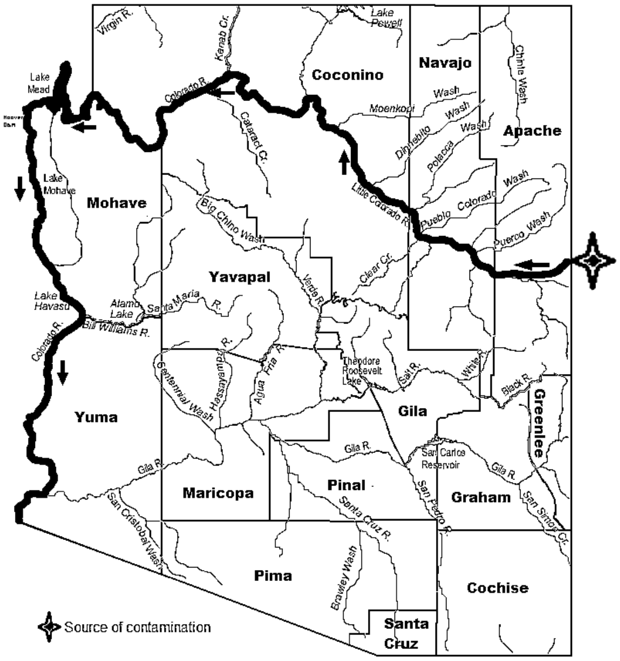


FIGURE 1. MAP OF CONTAMINATION SPREAD

Note: The Church Rock uranium mill holding pond failure released 1,100 tons of solid uranium mill waste and 93,000 gallons of liquid uranium tailing solution into the Rio Puerco, which connects to the Little Colorado and the Colorado river. Boundaries of contaminated waterways are not drawn to scale. Contaminated waterways are exaggerated in size to enhance visibility for the reader.

Source: United States Geological Survey, 2014.

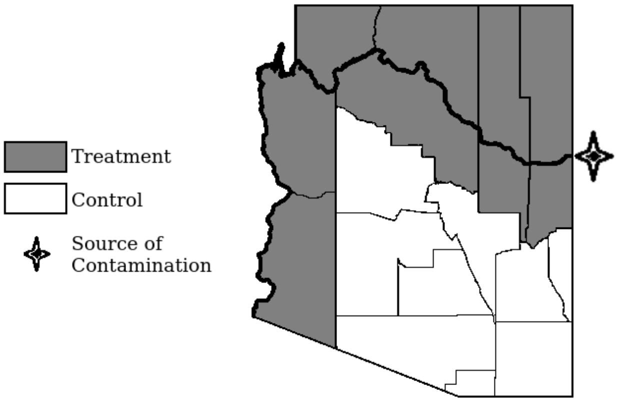
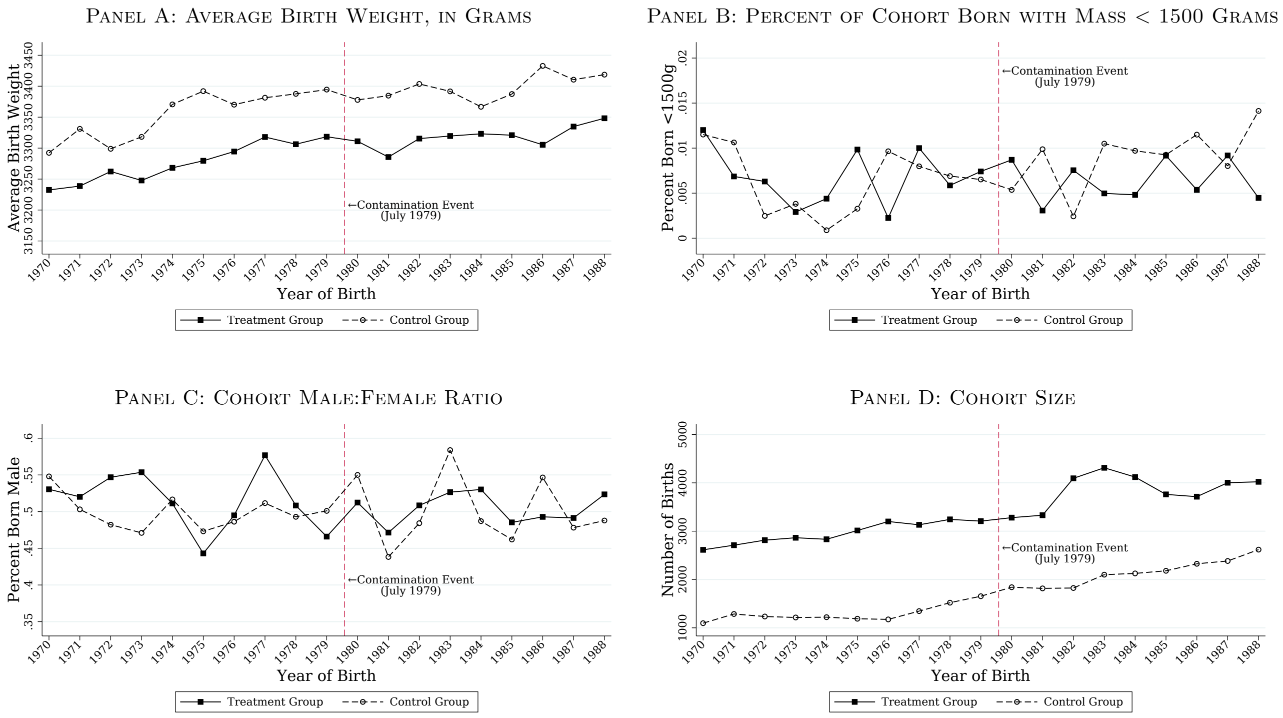


FIGURE 2. MAP OF TREATMENT AND CONTROL GROUPS FOR BIRTH OUTCOME ANALYSIS

Note: Counties are assigned to treatment and control groups according to the spread of contamination shown in Figure 1. Treated counties therefore include Apache, Navajo, Coconino, Mohave and Yuma Counties, Arizona, as well as Clark County, Nevada. Notice that in 1979, La Paz County was part of Yuma; this detail is accounted for in all of my analyses.



Panel A: Average Birth Weight, in Grams

Panel B: Percent of Cohort Born with Mass < 1500 Grams

Panel C: Cohort Male:Female Ratio

Panel D: Cohort Size

Figure 3. Birth Outcomes Over Time

Note: Birth outcomes over time for treated and untreated Native American Populations. Treatment and control groups defined in Figures 1 and 2.

Source: National Center for Health Statistics (1976-1984).