Some Unintended Fallout from Defense Policy: Measuring the Effect of Atmospheric Nuclear Testing on American Mortality Patterns

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Abstract

To better understand the health and social costs associated with radioactive pollution and nuclear weapons development, I study a historical period of atmospheric nuclear testing in the 1950s. Using records measuring annual county level fallout patterns for the continental U.S., I analyze how radioactive fallout affects public health in vital statistics records. I find that atmospheric nuclear testing performed in Nevada contributed to substantial and prolonged increases in overall mortality and cancer mortality. These increases in mortality occur over a broader geographic region than previous research would suggest.

JEL Codes: I10; N32; Q50. Keywords: Nuclear Testing, Public Health, Radioactive Fallout, Defense Policy

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Society inhabits a post nuclear age and still bears the legacy of the Cold War even after the specter of nuclear annihilation became less prevalent. Nevertheless, threats posed by nuclear proliferation, the recent suspension of the Nuclear Arms Control Treaty, aggressive posturing from nuclear powers, and an aging civilian nuclear infrastructure all are potential sources of radioactive pollution. Furthermore, the development of nuclear weapons was an inherently polluting affair and social costs of developing these weapons is not fully known. During the 1950s, the United States conducted scores of atmospheric nuclear tests in an area northwest of Las Vegas, Nevada. The medical and scientific literature focuses primarily on studying small numbers of people living near the nuclear test site and extrapolating out cancer risks (Stevens et al., 1990; Kerber et al., 1993; Gilbert et al., 1998, 2010; U.S. Institute of Medicine and National Research Council, 1999). In contrast, this paper measures how fallout from nuclear testing affects human health capital across the continental United States using vital statistics records. Using uncontrolled releases of radioactive material resulting from U.S. atmospheric nuclear testing in the 1950s at the Nevada Test Site (NTS), I study how fallout deposition attributable to NTS tests alter aggregate mortality measures at the county level for the continental United States. This methodology allows me to measure the geographic and temporal extent to which fallout from nuclear testing affects human health capital. Over approximately two decades, the aggregate mortality effect is substantial and suggests that atmospheric nuclear testing contributed to approximately as many deaths as the bombings of Hiroshima and Nagasaki.[1]

Pollution is often the byproduct of economic activity and imposes substantial costs on the public. There is a sizable economics literature quantifying these social costs, but unlike typical pollutants radioactive fallout was not caused by local economic activities.[2] In many settings, the government attempts to address the external costs associated with polluting activities, but there are cases where government policy is the direct cause of harmful pollution. During the Cold War the United States detonated hundreds of nuclear weapons. Prior to 1963 many of these tests were conducted above ground and released tremendous quantities of radioactive material into the atmosphere. One estimate places the total atmospheric release of radioactive material from the NTS at over 12 billion Curies between 1951 and 1963. In comparison, Chernobyl released an estimated 81 million Curies of radioactive material (LeBaron, 1998). Unlike other pollutants, which are often associated with local economic activity, the source of radioactive pollution analyzed in this paper originates from atmospheric nuclear testing conducted between 1951 and 1958 by the United States in Nevada. In the days following atmospheric tests radioactive dust clouds would transit above the United States. The coincidence of simultaneous precipitation while this radiation cloud transited overhead would result in fallout depositing hundreds and even thousands of miles from the NTS.

Recent economic research has show that prenatal exposure to ionizing radiation, that is radiation energetic enough to disrupt matter at the atomic level, adversely affects human capital (Almond et al., 2009b; Black et al., 2017), that exposure to radioactive pollution in older ages can induce cognitive decline (Elsner and Wozny, 2018), and that contamination from nuclear power plant disasters can indirectly cause substantial psychological and economic costs (Lehmann and Wadsworth, 2011; Danzer and Danzer, 2016; Ito and Kuriyama, 2017; Kawaguchi and Yukutake, 2017). This paper contributes to the literature by showing that harmful radioactive material resulting from atmospheric nuclear testing had broad negative effects for public health and that these costs persisted many years after fallout from nuclear tests initially deposited. Previous economic studies measuring the social costs of radioactive pollution have focused primarily upon European and more recently Japanese populations, this paper expands the scope of analysis to North America. Finally, this paper contributes to an inconclusive medical and scientific literature measuring the health effects of low dose exposure to ionizing radiation. Using aggregate measures of public health and the plausibly exogenous nature of fallout deposition from nuclear testing, I provide evidence that low levels of ionizing radiation poses a substantial public health risk.

The scientific and medical research establishes that exposure to ionizing radiation can have substantial adverse effects on human health (National Research Council, 2006;

Simon et al., 2006; Simon and Bouville, 2015). This literature finds that exposure to ionizing radiation is harmful to biological systems, can suppress the immune system, can increase the risk of developing cancers, and even lead to cardiovascular disease (National Research Council, 2006). Exposure to such radiation can damage tissue and DNA in ways that are difficult for the body to repair. Nevertheless, there is still much uncertainty surrounding the health effects of low dose exposure to ionizing radiation and it would take "extraordinarily large studies" to sufficiently ascertain these health risks (Brenner et al., 2003). Nevertheless, exposure to low levels of radiation is not an uncommon occurrence. For example, radon poses a substantial and common public health risk (Price and Gelman, 2006).

With regards to nuclear testing conducted in Nevada during the Cold War, much of the medical and scientific literature studying the health effects of nuclear testing has focused primarily upon small samples of populations who lived in the areas surrounding the NTS.[3] The National Cancer Institute (NCI) has undertaken the responsibility in determining the extent to which the public was exposed to ionizing radiation resulting from these tests (National Cancer Institute, 1997). The NCI focuses primarily on the effects of radioactive iodine-131, establishing human exposure channels, and its contribution toward thyroid cancer. Iodine-131 has a short half-life (8-days), is readily metabolized, and often quickly entered local liquid dairy supplies after cows grazed irradiated pastures. Relative to other radioactive isotopes created by nuclear testing, radioactive iodine is particularly dangerous because it concentrates in the thyroid and causes concentrated tissue damage. During the period of atmospheric testing, liquid dairy production was located near consumers, the scale of production operations was small, most farms reported having milk cows, and local firms formed the majority of the market (Dreicer et al., 1990; Manchester and Blayney, 1997). Many millions of people were likely exposed to ionizing radiation through the consumption of fresh dairy during the 1950s. Measuring the effects of I-131 on mortality patterns not only highlights the health costs of nuclear testing, but also provides evidence of a broader human capital effect.

1 Historical, Scientific, and Medical Background

1.1 History of NTS

From 1945 to 1963, the United States engaged in atmospheric nuclear testing, and many of these military experiments created tremendous quantities of radioactive material and released it into the environment. The U.S. ushered in this atomic age when it detonated its first nuclear bomb on July 16th, 1945 at the Alamogordo Bombing and Gunnery Range. Less than a month later, the U.S. detonated two additional bombs over the cities of Hiroshima and Nagasaki. After World War II, the United States conducted additional atmospheric nuclear tests at Bikini and Enewetak atolls in Pacific Ocean. Nuclear testing expanded and intensified following the Soviet Union's successful test of their own nuclear weapon in 1949.

Figure 1 about here

Since 1945 over 2,000 nuclear weapons have been detonated. The United States is responsible for 1,054 these nuclear tests. From 1945 to 1992, the United States conducted 210 atmospheric tests, 5 underwater tests, and 839 underground nuclear tests (U.S. Department of Energy, 2000; Fehner and Gosling, 2006). Figure 1 plots the number of U.S atomic tests from 1945 to 1992. From 1945 to 1958, the United States engaged in atmospheric nuclear testing. From 1958 to 1961 a testing moratorium between the U.S. and USSR led to a suspension of testing. This agreement ended and led to a small number of U.S. atmospheric tests in 1962. With the signing of the Partial Nuclear Test Ban Treaty in 1963 all atmospheric nuclear tests conducted by the U.S. ceased and went underground. This paper focuses on the effects of atmospheric nuclear testing conducted on the U.S. continent from 1951 to 1958.

Figure 2 about here

After the Soviet Union detonated its first successful nuclear bomb in 1949, U.S. policy makers sought to accelerate the development of its own nuclear capabilities. Initially hesitant towards testing within the continental U.S., security and logistical concerns after the breakout of the Korean War prompted the establishment of the

Nevada Test Site (NTS) (Fehner and Gosling, 2000).[4] Located mostly in Nye County, Nevada, this military zone became the epicenter of the American nuclear weapons program and hosted 928 nuclear tests. This testing occurred from 1951 until 1992. This paper focuses on the most active period of atmospheric testing conducted at the NTS from 1951 to 1958. Figure 2 describes the number, explosive magnitude (measured in kilotons of TNT), and estimated radioactive release from these NTS nuclear tests by year.

Figure 3 about here

Figure 3 presents NCI estimates for cumulative deposition of radioactive iodine-131 for the continental United States. Notice there is substantial variation in cumulative deposition and there are areas far from the NTS that experienced relatively large quantities of radioactive fallout. The "Downwind" region located primarily in Arizona, Nevada, and Utah experienced tremendous quantities of radioactive fallout. California and the Pacific Northwest, generally did not experience substantial fallout deposition. Many counties in the Great Plains and Midwest in the interior of U.S. also experienced large amounts of deposition. In the Northeast, there is also a cluster of counties that were also substantially exposed to radioactive fallout from NTS testing.

During the 1950's, the public was largely unaware of the dangers that the NTS posed to public health. Often, the Public Health Service (PHS) and Atomic Energy Commission (AEC) sought to dismiss fears regarding the atomic testing. Official government statements made during the testing period asserted that all dangerous radioactive material remained within the confines of the NTS. Often, these organizations failed to adequately warn civilians living around the test site of the health risks associated with these atomic tests (Ball, 1986; Fradkin, 2004; LeBaron, 1998). Furthermore, government officials suppressed and classified research suggesting radiation from these tests posed substantial health risks. For example, the Public Health Service and Centers for Disease Control studied clusters of leukemia and cancer appearing in Nevada and Utah in the 1960s, but the Federal government suppressed results linking leukemia to fallout from nuclear testing (Lyon, 1999).

In the late 1970s, Congress opened a series of hearings regarding the consequences of radioactive fallout resulting from U.S. nuclear testing (United States, 1980). Subsequent Freedom of Information Act requests later revealed that the government knew that NTS activities posed a public health risk and that the AEC had suppressed medical studies highlighting the health dangers (Fradkin, 2004). As a result of these revelations, Congress tasked the Department of Health and Human Services to estimate the amount of radiation the public was exposed to and ascertain the public health risks associated with fallout resulting from atmospheric nuclear testing (National Cancer Institute, 1997; Fehner and Gosling, 2000; Center for Disease Control, 2006).

1.2 Science and Health of Effects of Ionizing Radiation

Ionizing radiation is an invisible environmental threat and is imperceptible without special equipment. Radioactivity generally refers to dangerous particles given off by radioactive decay of matter.[5] The weakest forms of ionizing radiation are alpha particles, and these particles generally cannot penetrate most thin physical barriers. Beta radiation is more dangerous and can penetrate deep into flesh and cause damage. Gamma radiation is the most dangerous form of radioactivity and consists of highly energetic photons. Gamma radiation can travel easily through the body and causes immense damage to biological tissues. When nuclear tests occurred in the Nevada desert many times the testing would vaporized and induce radioactivity in the surrounding soil.[6] As the mushroom cloud carries irradiated debris up into the atmosphere, winds would carry harmful radioactive material. Low altitude winds would carry radioactive debris with dust storms into the "Downwind" region immediately surrounding the NTS. Higher altitude winds carried much of this irradiated matter vast distances where it would precipitated down with rainfall.

The medical and scientific knowledge regarding the effects of human exposure to ionizing radiation comes from many sources. Studies of Japanese atomic bomb survivors and persons living downwind of nuclear test sites provide much of this knowledge. In human population studies of radiation exposure, researchers have measured a variety of negative health and developmental consequences from exposure to ionizing radiation. Studies of atomic bomb survivors and persons exposed during pregnancy demonstrate increased cancer risks, negative developmental and cognitive effects due to radiation exposure (Otake et al., 1993; Otake, 1996; Schull, 1997; Lee, 1999). Researchers studying Chernobyl have found greater incidences of thyroid cancers, and lesions indicative of I-131 poisoning in exposed population (Shibata et al., 2001; Williams, 2002). Researchers studying downwind American populations have also found evidence of increased thyroid cancer and leukemia risks in domestic downwind cohorts (Kerber et al., 1993; Stevens et al., 1990; Gilbert et al., 2010). Together, the medical and scientific literature suggest that exposure to ionizing radiation increases the risks of various types of cancer and can have detrimental effects upon human growth and development. An additional effect of fallout exposure is that it could degrade overall health, inhibit immune responses, increase the risk of cardiovascular disease, and could contribute towards non-cancer related deaths.

Exposure to harmful radioactive fallout can occur either through direct channels or indirect channels. Radioactive material can enter the body if it lands on the skin with radioactive dust. Many people living in the downwind counties surrounding the NTS were exposed to harmful fallout in this matter. People can inhale radioactive material when it is suspended in the air. Inhalation of radioactive dust would be the most likely in the downwind region. Research by the National Cancer Institute (1997) and Center for Disease Control (2006) establishes that the food supply served as the main vector of exposure for most Americans during the atomic testing period. Scientific evidence contemporaneous with the testing period also substantiates that radioactive materials resulting from nuclear fission appeared in crops, people, and animals (Van Middlesworth, 1956; Kulp et al., 1958; Olson, 1962; Beierwaltes et al., 1960; Garner, 1963). Similarly, the PHS also released research corroborating this evidence (Wolff, 1957, 1959; Flemming, 1959, 1960). These government studies often downplayed the risk associated with the levels of radioactive material found in independent studies as alarmist.

The NCI establishes the fresh milk channel as a primary vector through which Americans were exposed to significant quantities of radioactive material. Most Americans would not be exposed to radioactive dust carried by low altitude winds. Instead, high altitude winds would carry the material far from the test site and the material would only deposit on the ground if it happened to be precipitating simultaneously while the radiation cloud was overhead. In the few days following the nuclear test, this radioactive material would deposit on crops and pasture. Some radioactive material would enter wheat and other plant products, but consumption of these products would not necessarily be in the same region where they were produced.

Radioactive iodine-131 has unique characteristics that results in it concentrating in fresh dairy. Unknowingly, dairy cows would consume freshly irradiated grasses before the iodine decays. Since iodine is an essential nutrient that collects in the thyroid, the body metabolizes it and cows secrete excess iodine in milk. Fresh milk, however, during the 1950s and 1960s was generally produced and consumed locally (Dreicer et al., 1990; National Cancer Institute, 1997; Manchester and Blayney, 1997). During the period of atmospheric testing most milk was produced near population centers and delivered daily.[7] In the days following fallout precipitating down in a region, the public would inadvertently consume irradiated fresh milk and this irradiated material would concentrate around the thyroid causing tissue damage and harm. The Chernobyl accident also resulted in the release of radioactive iodine and during the crisis the consumption of irradiated dairy posed a similar public health hazard (Dreicer et al., 1996). The ingestion of irradiated material directly exposes organs and tissue to greater harm than just the environmental presence of ionizing radiation. Most atmospheric testing conducted at the NTS occurred between March and August of the calendar year. This timing coincides with the time of year many cows would be out to pasture.

2 Data and Descriptive Analysis

2.1 Radiation Exposure Data

The radiation deposition and exposure data used in this research is provided by the National Cancer Institute. These records are the most complete estimates of radioactive fallout resulting from nuclear testing conducted in Nevada from 1951 to 1958. In 1983, Congress authorized the Secretary of Heath and Human Services to investigate and measure thyroid resulting from radioactive iodine created by nuclear testing. This came as a result of Congressional investigations into the health effects of the U.S.'s nuclear testing program and the suppression of knowledge by the Atomic Energy Commission that these activities posed a human health risk. The NCI undertook the task of gathering and reconstruction records monitoring radioactive fallout deposition across the United States. With these records and a much denser meteorological station data, the NCI created radioactive fallout deposition estimates for almost all atmospheric nuclear tests conducted between 1951 and 1958. The primary measurement for radiation exposure by county used in this analysis is cumulative annual average iodine 131 deposition per m^2.[89]

The NCI estimated fallout deposition through an interpolation process called kriging. Kriging is a common statistical technique that models conditions between monitoring stations. It is commonly used to estimate meteorological conditions between areas without weather stations. The regions surrounding the NTS had a dense radiation monitoring station network and the continental United States had a separate national radiation monitoring station network.[10] With these monitoring station records, the NCI is able to identify the position radioactive fallout clouds and the rate at which fallout deposits under varying meteorological conditions.

In the regions surrounding the NTS, low altitude winds carried radioactive dust. In these "Downwind" areas visible dust storms carried radioactive matter across the landscape. In these areas, precipitation was not necessary for radioactive pollution to be delivered at the ground level. In areas outside of this "Downwind" region, high altitude winds carried radioactive material and fallout deposited in areas across the United States through precipitation. Most of the irradiated earth generated by nuclear testing was carried kilometers up into the atmosphere with the mushroom cloud. High altitude winds would carry this irradiated material across the continent in the days following the test.

Radioactive material would deposit in areas outside of the "Downwind" region if the radiation cloud happened to be moving overhead while it was raining. The kriging process used by the NCI used radiation monitoring stations to verify the position of the radiation cloud over time. Their algorithm then used a denser rain gauge network from the National Oceanographic and Atmospheric Administration (NOAA) to interpolate fallout deposition as a function of rainfall intensity on the days when the fallout cloud was present. In order to account for potential correlation between the fallout deposition measure and meteorological conditions during a given year, I incorporate data from NOAA's Global Historic Climatology Network (Lawrimore et al., 2011). These data report monthly precipitation totals and monthly average temperatures by county for the continental United States.

2.2 Aggregate Public Health and Mortality Data

To study how radioactive fallout from NTS atmospheric testing may have affected public health broadly across the United States, I use public health data at the county year level from 1946 to 1988. Annual overall mortality, commonly referred to as crude deaths, are provided by Bailey et al. (2016).[11] Since radiation poisoning not only increases cancer risks but can also adversely affect the immune system, this measure proxies for the adverse health effects of atmospheric nuclear testing. If radioactive fallout adversely affects human health and substantial quantities of this material entered local dairy supplies, then it is plausible that overall deaths would increase in more irradiated counties relative to less irradiated counties in the years following fallout deposition.

In addition to this overall death measure, I also collect and use information on annual cancer deaths by county. Cancer has historically been the outcome focus of radiation health studies. For 1946 to 1958, these records were constructed from cause of death tables in the Vital Statistics of the United States. Cancer deaths from 1959 to 1967 were aggregated from the National Center for Health Statistics' Multiple Cause of Death Files (National Center for Health Statistics, 2001b).[12] Cancer deaths from 1968 to 1988 were aggregated at the county year level from the National Center for Health Statistics' Compressed Mortality File (National Center for Health Statistics, 2001a).

Since mortality by age and age adjusted mortality is not available at the county level in the period studied in this paper, I incorporate interpolated measures of population and population by age in the analysis. Information regarding population by age by various age cohort bins come from (Haines, 2010). This information allows me to examine the effect of radiation while controlling for the underlying age distribution of the population in a given county. Haines (2010) also provides additional demographic information, however, county level median household income is only reported starting in 1950.

2.3 Descriptive Analysis

Persons residing in areas far beyond the region of the NTS likely did not know they were inadvertently being exposed to radioactive fallout from nuclear testing conducted in Nevada during the period of testing. While persons in the vicinity experienced visible irradiated dust blowing from the NTS, people living in areas where fallout deposited with rainfall and entered local dairy supplies did not experience a visibly clear and salient connection. Ionizing radiation is an invisible threat that often requires specific tools to detect. Furthermore, scientific knowledge regarding the adverse effects of NTS testing developed mostly after congressional investigations in the late 1970s, Freedom of Information Act requests declassifying AEC and DOE documents, and public health research conducted in the subsequent decades.

Most of this research revolves around epidemiological studies of persons living in regions of the NTS during the period of nuclear testing. To avoid potential confounding issues regarding the differences in exposure between "Downwind" and non-"Downwind" populations and potential avoidance behavior, I restrict the sample to counties where radioactive fallout from NTS nuclear tests is a plausibly exogenous event.[13] Fallout resulting from the coincidence of precipitation occurring as a radioactive material cloud transits kilometers above provides a (un)natural experiment to study how radioactive pollution affects public health.

Tables 1 and 2 about here

Two main samples, overall mortality rate and overall cancer rate, are constructed consisting of counties (or county equivalents) that reported death rates continuously from 1946 to 1988.[14] The first year when county cancer mortality rates are reported in VSUS is 1946 and in 1988 new confidentially rules regarding confidentially reduces the number of counties reporting aggregate mortality measure. Both samples are nearly identical, though there are fewer counties in the cancer sample. Table 1 reports summary statistics for both overall mortality and cancer mortality.[15] To substantiate that radioactive fallout deposition is a unrelated and is a quasi-random event with respect to underlying mortality patterns, I regress cumulative iodine 131 deposition from 1951 to 1958 on annual county overall mortality and cancer rates per 10,000 from 1946 to 1950. These regression results are in Table 2. Without the inclusion of any controls, this total fallout deposition explains approximately zero percent of the variation in county mortality patters, though there is a positive and statistically significant relationship for cancer deaths. This relationship disappears and diminishes substantially with the inclusion of state fixed effects and controls for the age distribution.

The nature of radioactive fallout from NTS nuclear testing consists of a series of events where fallout deposits and where almost every county experience some level of fallout exposure during the testing period. Some counties experience substantial repeated fallout shocks while others may have experience substantial deposition only once. The continuous and repeated nature of nuclear testing during the 1950s results in data that does not create clearly defined "treated" and "untreated" groups. Nevertheless, I create a fallout threshold shock variable of approximately 302 nCi per m^2. This is the median level of deposition that occurred during the most active atmospheric nuclear testing years from 1951 to 1957 (I exclude 1958 from this calculation because very little fallout deposited outside of the Downwind region). Of the 2,990 counties in the empirical sample, 2,837 receive I-131 deposition meeting or exceeding this threshold during at least one year in the testing period.[16] 153 counties do not cross this threshold. These counties are located primarily in Washington, Texas, Oregon, California, and Florida.

Figures 4 and 5 about here

In Figure 4 I graph the mean overall mortality rate per 10,000 residents from 1946 to 1988 for both threshold crossing and non-threshold crossing counties. The overall death rate for non-threshold counties is lower than that of all other counties in the U.S. before the start of atmospheric testing, it starts widening in 1949, and this gap widens during and after the period of nuclear testing. In Figure 5, I compare the Standard Mortality Ratios (SMR) of the two groups and the means suggest that non-threshold counties have a fewer deaths relative to the U.S. average than what their age distributions would suggest.[17] The non-threshold SMR fluctuates, but there is no apparent underling trend. The threshold crossing counties, however, on average start experiencing an increase in SMR during the period of atmospheric nuclear testing and an increase in SMR over time.

Figures 6 and 7 about here

Plotting the overall average mortality rate of non-threshold counties and those that first surpassed the threshold during the most environmentally polluting atmospheric test series in 1957, Operation Plumbbob, in Figure 6 reveal a substantial increase in mortality rates in these threshold counties after they cross this threshold in 1957. In Figure 7, a similar pattern arises with respect to the second most radioactively active atmospheric nuclear test series at the NTS, Operation Upshot Knothole, after 1953.

Figure 8 about here.

In Figure 8, I present a simple quasi-difference in difference analysis to further establish that fallout from nuclear testing adversely affected public U.S. mortality patterns in areas far from the NTS and that this radioactive fallout deposition is unrelated to underlying mortality patterns. On the left-hand side, I measure cumulative deaths per 10,000 residents. On the right-hand side, I construct a fallout "shock" variable that denotes the year fallout deposition in a county exceeds the threshold established above. I flexibly include indicator variables denoting the t years until and after exceeds this radiation shock threshold. The regression accounts for county and year fixed effects and clusters standard errors at the county level.

In the four years preceding this threshold crossing, there is a negative and statistically insignificant effect. In the year of and two years following, the effect becomes positive but not statistically significant. Three years after exceeding this fallout shock, counties experience a strongly positive and statistically significant increases in overall death rates. While the underlying empirical data is less than ideal for a differences in difference analysis, the results above suggest that fallout from nuclear testing is associated with a stark negative health shock. In the subsequent empirical analysis, I use continuous measures of I-131 deposition to quantify the adverse mortality effects of nuclear testing.

3 Measuring Short Term and Long Term Mortality Effects

3.1 Empirical Model

The main empirical analysis of this paper focuses on two different panel regression models to ascertain the geographic and temporal extent of the health cost of atomic testing. The first set of regressions tests whether within county variation in radioactive fallout exposure across years had an immediate effect upon mortality rates using a distributed lag framework. Short-run changes in the mortality from fallout exposure are potentially less vulnerable to potential migration bias than regressions measuring the long-run effects of fallout. These regressions, however do not fully capture the temporal extent of these increases in mortality rates. The negative health effects of radiation poisoning often materialize long after the damage has occurred. A set of long-run regressions employ a distributed lagged framework and pool exposure into five year averages. Estimation of this model measures how persistent the effects of fallout were on mortality rates and accounts for the cumulative effect of fallout exposure over multiple years.

$$y_{it} = \Sigma_{k=0}^{5} \beta_k E_{it-k} + X_{it}\phi + W_{it}\omega + \alpha_i + \gamma_t + \epsilon_{it} \tag{1}$$

Equation (1) describes the full model specification of this paper. This model tests whether radioactive I-131 had a statistically significant effect upon mortality in the years directly following the testing. The outcome denoted by y_{it} measures the number of total or cancer deaths per 10,000 people in a given county i and year t. E_{it-k} denotes fallout deposition per m^2 in thousands of nCi of I-131 and is the exposure variable used to proxy for fallout exposure.[18] X_{it} a vector of interpolated demographic and economic controls measuring the share of county population in a specific age range, share of the population that is white, share of the population with high school degrees or higher, and the log of the median household income. The population age categories control for underlying demographics that affect mortality risk.[19] The age cohorts are chosen as to be consistent across the 1940 to 1990 Censuses and report the share of the population in the following age groups: 0/4, 5/14, 15/24, 25/34, 35/44, 45/54, 55/64, 65/74, and 75+. A vector of twelve monthly precipitation total and twelve average monthly temperatures controls represented by W_{it} control for mortality affecting weather factors that could be correlated with fallout deposition. The variables α_i and γ_t denote county and year fixed effects. These county fixed effects control for time invariant county characteristics.[20] The year fixed effects account for unobserved annual shocks shared across counties. The variable ϵ_{it} denotes the heteroskedastic error term and is clustered at the county level.

$$y_{it} = \Sigma_{j=0}^{5}\theta_j Avg\_E_{it,j} + X_{it}\phi + W_{it}\omega + \alpha_i + \gamma_t + \epsilon_{it} \tag{2}$$

Equation (2) describes the distributed lag specification for the long-run panel regressions. This model uses a similar framework to that of Equation 1, but the measure of interest consists of lagged five year averages of the I-131 deposition measures. The variable $Avg\_E_{it,j}$ denotes the average deposition term with j lags. This distributed lag structure measures the dynamic mortality response to county level radiation deposition over a longer time horizon. Fallout in the current year is excluded from the regression and only past deposition patterns provide variation. This model uses variation in average fallout deposition one to five years prior, six to ten years prior, eleven to fifteen years prior, sixteen to twenty years prior, and twenty-one to twenty-five years prior to identify the temporal extent to which fallout affected mortality patterns.

The source of identifying variation in the empirical analysis comes from within county variation in radiation deposition across years after controlling for annual shocks, county demographic characteristics, and county weather conditions. Measuring the effect of fallout across time on aggregate mortality rates implicitly assumes that most people who were exposed to radioactive fallout eventually die in the county where they were exposed. This is a particular challenge with respect to the long-run analysis. There is no strong a priori reason to believe that fallout deposition is systematically correlated with migration patterns in such a way that it would affect underlying patterns in county mortality. If migration decisions are not systematically correlated with radiation deposition, then migration bias should attenuate the statistical effect of radiation deposition on mortality as the time between the deposition event and reported deaths widen. Controlling for the age distribution of counties should partially account for the effects of migration on mortality (in as much migration affects the underlying age distribution of the population). Historic migration measures usually use a measure of net migration and is an unsuitable control. Net migration is the difference in population between enumeration years minus birth and plus deaths. County to county migration measure from the IRS become available long after the period of testing in 1978.[21] In the robustness section, I test whether migration might play a biasing factor by analyzing fallout's relationship with population over time. If radiation deposition is related to selective migration, then it might materialize in population. I find little evidence that radioactive I-131 deposition is associated with county level population across U.S. Decennial Censuses.

4 Empirical Results

In the empirical analysis I present four regression specifications. Specification (1) provides an empirical baseline and reports the coefficients after accounting for common annual shocks and county specific time invariant factors. Specification (2) adds population shares by age categories to adjust for the underlying population distributions within counties. Specification (3) adds monthly weather controls to address potential concerns related to fallout's potential relationship to rainfall.[22] Specification (4) includes controls for education, race, and median income. Since county level median income is reported consistently from 1950 onward in Haines (2010), this limits the sample from 1950 to 1988. All coefficients discussed are statistically significant at least at the 10% level.

Tables 3 and 4 about here

For overall mortality rates in Table 3 , there is a strong positive effect of fallout on overall deaths per 10,000 in specification (1) but this affect attenuates after accounting for the age distribution of the population in specification (2). I perform joint significance tests for the fallout deposition lags and for all except one specification find that the lags are statistically significant at least at the 10% level. The addition of weather controls and economic controls increases joint statistical significance of the fallout lags. The marginal effect of a one standard deviation increase in fallout deposition of 247 nCi ranges from 0.299 additional deaths per 10,000 in specification (1) to 0.092 additional deaths in specification (4).

The short-run relationship between fallout deposition and cancer deaths are more pronounced than for overall deaths. Table 4 reports a consistently positive and statistically significant relationship between fallout deposition at the county level and cancer deaths per 10,000 residents. The marginal effect of a one standard deviation increase in fallout deposition of 246 nCi ranges from 0.110 additional deaths per 10,000 in specification (1) to 0.031 additional deaths in specification (3). Across specifications, all the coefficients are jointly significant and different than zero at the less that 1% level.

The short-run regressions suggest that fallout causes increases in overall mortality and cancer mortality in the years following deposition. This positive relationship persists after conditioning mortality rates the age distribution of the population, accounting for contemporaneous weather conditions at the county level, and income plus other demographic factors. Since radioactive fallout material was frequently created during the 1950s, many counties experienced multiple waves of deposition from 1951 to 1958. I pool deposition into five year moving averages to better ascertain the magnitude and temporal extent of these adverse health effects attributable to atmospheric nuclear testing conducted in Nevada. The long-run regressions measure the relationship between fallout deposition and county health patterns up to twenty-five years after fallout landed on the ground.

Table 5 about here

In Table 5 I find a consistent, statistically significant, and positive relationship between fallout deposition and overall mortality rates one to fifteen years following I-131 deposition. The marginal effect of a one standard deviation increase in average I-131 deposition, 139 nCi, one to five years prior on the overall mortality rate ranges from 0.779 in specification (1) to 0.219 in specification (4). For deposition occurring six to ten years prior, the effect on mortality ranges from 0.578 in specification (1) to 0.210 additional deaths in specification (2). For deposition occurring eleven to fifteen years prior, the effect on mortality ranges from 0.409 in specification (1) to 0.163 additional deaths in specification (4).

To estimate the number of deaths attributable to NTS atmospheric testing from

1951 to 1958, I multiply the statistically significant coefficients by population and the respective fallout deposition measure. This approximates the annual county level increase in mortality and by summing these measures up across years, I find that nuclear testing resulted in large increases in overall mortality from 1952 to 1988. Specification (1) accounts for only county time invariant factors and common annual shocks shared across counties. This least restrictive fixed effects model suggests nuclear testing contributed to 429,000 premature deaths over this time period. This estimate decreases to approximately 157,000 premature deaths after accounting for the underlying age distributions in counties in specification (2). The addition of weather controls in specification (3) does not substantively alter the estimates. Accounting for median household income, racial composition, and percent of the population of high school degree or higher in specification (4) reduces the estimated number of deaths to 145,000.

Table 6 about here

In Table 6 I find a strong and positive relationship between deposition and the cancer mortality rate one to fifteen years after fallout deposition occurs. In specifications (1), (2), and (3) I also find evidence that cancer rates decrease in these counties twenty-one to twenty-five years after fallout deposited. The statistical significance of this lag disappears with the inclusion of additional demographic controls. If fallout from nuclear testing contributed to premature deaths, then it is possible that people who would have died from cancer later on in life are not present in the county population decades later. The marginal effect of a one standard deviation increase in average I-131 deposition, 139 nCi, one to five years prior on the cancer mortality rate ranges from 0.214 in specification (1) to 0.114 in specification (3). For deposition occurring six to ten years prior, the effect on cancer deaths ranges from 0.130 in specification (1) to 0.069 additional deaths in specification (2). For deposition occurring eleven to fifteen years prior, the effect on cancer mortality ranges from 0.077 in specification (1) to 0.040 additional deaths in specification (2). For deposition occurring twenty-one to twenty-five years prior, the effect on cancer mortality ranges from -0.108 in specification (1) to -0.055 additional deaths in specification (2).

Following the same "back of the envelope calculations" as for overall mortality, I find that radioactive fallout contributed to tens of thousands of cancer deaths. Specification (1) suggests that fallout contributed to more than 69,000 cancer deaths. Conditioning mortality on the age distribution in a county in specification (2) reduces this estimate to 38,000 cancer deaths and including weather in specification (3) reduces the estimate further to 28,000. Specification (4) suggest a larger value and that fallout from nuclear testing resulted in approximately 50,000 additional cancer deaths from 1952 to 1973.

4.1 Robustness Checks

In addition to the falsification exercise performed in the descriptive analysis, I perform two additional falsification exercises. The results for these exercises are contained in the appendix. The first exercise tests whether or not fallout is spuriously correlated with temporal factors coinciding with fallout exposure. In this falsification exercise, I randomize fallout deposition within years and perform both the short-run and long-run analyses. I find no evidence that fallout is spuriously correlated with unobserved contemporaneous factors that positively affect mortality. The second falsification test seeks to ascertain whether or not fallout deposition is spuriously correlated with unobserved geographic factors that affect mortality patterns. To do this I regress forward lags for radiation deposition on mortality for the period prior to NTS testing. From 1946 to 1950, I find no consistent relationship between fallout and overall mortality rates or cancer death rates.

Selective migration might occur over time and this might change the composition of more irradiated counties relative to less irradiated counties. For example, if unhealthy persons systematically migrated towards more irradiated counties than less irradiated counties, then the empirical analysis could overstate the effects of fallout upon mortality patterns. Conversely, if people moving into irradiated counties tended to be healthier, then the models could understate the mortality effects. While county to county migration data could assuage these concerns, there is no publicly available data at the county level during the 1950s and 1960s that can consistently account for migration patterns prior, during, and immediately after the period of nuclear testing. Historic migration patterns are typically inferred by subtracting the differences in populations in enumeration periods, adding deaths, and subtracting births. Using such a migration measure would be questionable given the potential effect of fallout on mortality. Migration data created from tax filings is also only available starting in the late 1970s.[23] If fallout is related to systematic migration, then deposition should have a statistically significant association with population over time. In the Appendix, I include a regression of log population in enumeration years against year interactions for total fallout deposition while controlling for year and county fixed effects. I find little evidence that cumulative fallout deposition in the 1950s is associated with population measures in 1940, 1960, 1970, or 1980.

Finally, in the Appendix I provide a set of alternative regressions specifications. These include using alternative estimates of iodine-131 exposure by using the NCI's estimates for I-131 in milk at the county level, using log mortality rates as done in Barreca et al. (2016), and including Downwind counties in the regression analysis. The empirical results are relatively robust to these specification changes.

Figures 9 and 10 about here

5 Policy Implications of Nuclear Testing

Depending on specification, from 1952 to 1988 between 145,300 and 429,400 excess deaths from all-causes are attributable to atmospheric nuclear testing (for non-"Downwind" Counties). From 1952 to 1988 between 28,600 and 69,800 cancer deaths are attributable to nuclear testing conducted at the NTS during the 1950s. In comparison Simon and Bouville (2015) estimate that fallout from domestic nuclear testing caused an additional 49,000 thyroid cancer cases and up to 11,1000 additional deaths from non-thyroid cancers.[24] In Figures 9 and 10, I present the average annual increase in overall and cancer mortality rates in a given state from 1952 to 1973 according to specifications (4).[25] The states with the greatest increases in crude death rates include not only Nevada and Utah, but also include a number of states east and north of of the NTS. The "back of the envelope" calculations also suggest that New York, New Jersey, and Connecticut experienced substantial increases in mortality due to fallout. Summing together the cumulative number of excess deaths attributable to NTS testing by state suggests states with larger population had more deaths. Nevertheless, Utah stands out as a particular exception in this population size associated pattern and is consistent with the narrative that Utah residents suffered greatly as a result of atmospheric nuclear testing.

America's nuclear weapons program was (and still is) a costly national defense policy. From 1940 to 1996 the estimated cost of America's nuclear weapons program was approximately $9.37 Trillion in 2018$ (Schwartz, 2011). These monetary costs, however, do not fully capture the full social cost of America's nuclear weapons program. Since the 1990's the Federal Government has paid some compensation to victims of America's domestic nuclear weapons program through the Radiation Exposure Compensation Act (RECA). This compensation has focused on workers involved in the nuclear weapons program and those who lived downwind of the NTS during the 1950's. As of 2015 the U.S. Department of Justice has paid out over $2 billion in compensation to victims. According to RECA, only persons living in twenty-two counties during the periods of testing can be considered living "Downwind" of the NTS.[26]

Policy makers often assign accounting values to human lives when evaluating policy decisions. Viscusi (1993) and Viscusi and Aldy (2003) survey these valuations placed on human life. From 1988 to 2000, valuations of human life by U.S. Federal Government agencies ranged between $1.6 million and $9.2 million in 2018$. These values place the value of lost life between $232.6 billion and $3.9 trillion in 2018$. For cancer specific deaths, the values of lives lost range from $45.8 to $111.7 billion. Costa and Kahn (2004) use a hedonic wage regressions on industrial sector mortality risks to back out plausible market values for human life for each decade from 1940 to 1980. Using their values, I estimate the value of total life lost from ground deposition between $723.8 billion and $2.1 trillion. For cancer specific deaths, the values range from $193.8 billion to $478.5 billion. The social cost of excess deaths for all causes attributable to atmospheric testing at the NTS ranges from approximately 2.4 percent to 41.6 percent of the total cost of America's nuclear weapons program. These values, however, likely understate the magnitude of the social costs of this polluting and environmentally destructive activities. Exposure to radioactive fallout likely made millions of people less healthy, negatively affected human capital, and increased the cost of providing health services to these populations. Mortality is an extreme measure of human capital loss and is indicative of other harm.

The cessation of atmospheric nuclear testing drastically reduced the release of harmful radioactive material into the air and likely saved many lives. Two policies restricted atmospheric testing at the NTS. The first was a testing moratorium from 1958 to 1961, which moved almost all nuclear tests underground. The signing of the Partial Nuclear Test Ban Treaty ultimately ended all atmospheric nuclear tests by the U.S. in 1963. The cumulative kilo-tonnage of the atmospheric tests analyzed in this paper's data is 992.4kt. Assuming that kilo-tonnage is proportional to the numbers of additional overall and cancer specific deaths experienced, the models suggest that one additional kiloton detonated near the surface of the NTS would have resulted in between 146 and 432 additional deaths from all causes and between 28 and 70 cancer caused deaths. During the moratorium period the cumulative tonnage of underground testing at the NTS from 1958 to 1963 was 621.9kt. From 1963 to 1992, the total tonnage of nuclear explosions at the NTS was 34,327.9kt, approximately thirty-four times larger than the NTS atmospheric tests (U.S. Department of Energy, 2000).[27]

6 Conclusion

Radioactive fallout generated by NTS activities deposited across the continental U.S. in the days after nuclear tests in the 1950s. Due to the timing of these nuclear detonations and the local structure of liquid dairy production in U.S., millions of people were inadvertently exposed to harmful radioactive iodine through milk in the days after NTS tests. The medical and scientific literature studying the adverse effects of atmospheric nuclear testing have relied on small scale studies of persons living near the NTS. Using insight gained from these localized studies, researchers have extrapolated the potential health effects of fallout from nuclear testing to other geographic regions. These studies, however, have focused primarily on thyroid cancer as an outcome and do not measure the geographic or temporal extent of NTS fallout's potential harm. Using public health records at the county level covering the continental U.S. before, during, and after the period of atmospheric nuclear testing, I measure how fallout depositing far from the NTS region altered mortality patterns across the continent. The areas studied in this paper are exclusively outside of the scope of the Radiation Exposure Compensation Act's "Downwind" region. I find that atmospheric nuclear testing conducted at the Nevada Test Site during the 1950s contributed to tens of thousands of additional cancer deaths. This increase in cancer mortality also coincides with a larger overall mortality effect for deaths from all causes. The value of lives lost far exceeds any compensation that lawmakers have provided to victims of the U.S.'s nuclear weapons program through RECA.

I find that nuclear testing adversely affected human capital in the extreme. These effects are broadly distributed across the U.S. and point to a substantial public health shock. Previous economic research shows that prenatal exposure to ionizing radiation adversely affects educational attainment, IQ scores, and income earnings later in adulthood. Radioactive iodine is readily metabolized and can concentrate in the thyroids of gestating humans (National Cancer Institute, 1997). More recent research also suggests that exposure to radioactive material later in life can hasten the cognitive decline associated with aging. It is plausible, if not probable, that atmospheric nuclear testing inadvertently made an entire generation of people less healthy, less productive, and less well off.

When considering policies related to nuclear technologies and the proliferation of said technologies, decision makers need to adequately weight the social risks associated with these technologies. Low levels of ionizing radiation in the environment can pose a non-trivial public health risk. Much of the world's nuclear infrastructure is aging and the relatively recent Fukushima Daiichi disaster highlights some of the dangers associated with the continued operation of this infrastructure. The specter of nuclear annihilation might have faded with the end of the Cold War, but we still bear the legacy of these nuclear technologies and their risks continue to persist.

Notes

[1]The Manhattan Engineer District (1946) estimate the number of deaths immediately following the bombings of Hiroshima and Nagasaki numbered around 105,000 deaths.

[2]The health and pollution economic literature is broad and some notable examples include: Chay and Greenstone (2003) use changes in air pollution due to recessions to measure the health costs of air pollution. Beach and Hanlon (2017) have shown that coal consumption in 19th Century England had substantial effects on mortality rates and that coal utilization. Barreca et al. (2014) and Clay et al. (2016) study the long-term health consequences of using coal for heating and electricity generation for the United States. Troesken (2008) and Clay et al. (2014) provide historic examples where government decisions relating to the adoption of lead water pipes had long-run effects on public health. Another body of research successfully uses variation in multiple sources of air pollution as a shock to test the fetal origins hypothesis (Almond et al., 2009a; Almond and Currie, 2011; Currie, 2013; Currie et al., 2015; Isen et al., 2017).

[3]The region surrounding the NTS is termed Downwind in the literature and this area consists of the counties in AZ, NV, and UT surrounding the test site.

[4]The initial Trinity tests in 1945 were conducted in New Mexico. All other tests conducted prior to the opening of the NTS occurred in the Pacific. The Pacific tests proved logistically costly, slow to implement, and expensive. American leaders sought a convenient testing location and settled on the Nevada Test Site due to its proximity to U.S. government labs, low levels of precipitation, and relatively secluded location (Center for Disease Control, 2006; National Cancer Institute, 1997).

[5]With regards to nuclear testing, there are three radioactive isotopes of concern to human health because of their relative radioactivity, prevalence, and how they are metabolized. These isotopes are iodine-131, strontium-90, and cesium-137. Other isotopes created during nuclear testing are less dangerous to human health because they do not remain in the body for extended periods or because they are created in minuscule quantities. Many other radioactive isotopes pass through the body and are secreted following ingestion. In particular, iodine-131 is a potent radioactive poison. It possesses an eight day half-life, concentrates in the thyroid gland, and emits highly active forms of beta and gamma radiation as it decays (LeBaron, 1998). These traits of I-131 cause acute and rapid damage to tissue surrounding the thyroid. Strontium 90 also appears in plant products in limited quantities. This isotope collects in bones and teeth. Sr-90 possesses a 25 year half-life, diffuses across the body uniformly and emits beta radiation (LeBaron, 1998). Finally, Cs-137, which was released in large quantities during the recent Fukushima Daiichi disaster, collects in fleshy tissue and does not concentrate in any particular organ. It has a half-life of 33 years and emits both alpha and beta radiation (LeBaron, 1998).

[6]The technical term for this process is called neutron activation.

[7]In the late 1950s refrigerated truck adoption increased and deliveries switched to every few days (Dreicer et al., 1990).

[8]There was no radiation monitoring network established for the first three atmospheric tests conducted in 1951 and radiation resulting from these smaller and earlier tests are not included in the data. Furthermore, in 1962 some atmospheric nuclear testing occurred when a nuclear testing moratorium broke down. These tests had a

cumulative yield of less than two kilotons of TNT. The resulting atmospheric release from the 1962 tests were negligible outside of the NTS region.

[9]This radioactive fallout deposition occurred prior to the foundation of the Environmental Protection Agency. Unlike other pollutants, fallout from atmospheric nuclear testing is not the result of local economic activities such as electricity generation. Furthermore, unlike other potential sources of radiation exposure such as radon (inhalation hazard) or water soluble uranium in soil (non-metabolized ingestion hazard), fallout from nuclear tests is time varying and contained radioactive materials that can be readily metabolized.

[10]For additional details on how the NCI constructed these fallout measures, see chapter 3 of (National Cancer Institute, 1997). The number and location of stations fluctuated year to year in the national monitoring station network. The number of stations never exceeded one hundred stations. The NCI also used records from airborne monitors to track the location, altitude, and size radioactive dust clouds when available. The raw radiation monitoring data used in the NCI's kriging is unavailable and the locations for all monitors is not provided by the NCI. The NCI did perform validation exercises comparing the performance of the interpolation techniques against a dense radiation monitoring network surrounding the NTS.

[11]I use deaths by residence rather than occurrence for both over all mortality and cancer mortality. Furthermore, I use aggregate annual data since the timing of when radiation exposure might affect mortality risk is not evident a-priori. While individual level mortality data is available from 1959 on in the National Center for Health Statistics' Multiple Cause of Death Files, these data are not available during the period of testing. As such I am not able to measure the mortality affects of fallout at a finer level of temporal variation.

[12]I thank Michael Haines for the support he provided in geocoding these records.

[13]A total of 27 counties are excluded from the analysis. These include counties listed as Downwind according to the U.S. Justice Department under the Radiation Exposure Compensation Act, five counties that had radiation deposition data reported at a sub

county level in National Cancer Institute (1997), and one additional county in Utah to ensure geographic continuity. These counties are all located in AZ, CA, NV, and UT. A map of this Downwind Region is available in the Appendix.

[14]The state of Massachusetts forgoes reporting county mortality statistics in U.S. Vital Statistics (VSUS) a number of years during the 1950s and is completely omitted from the analysis.

[15]Counties with border changes are merged in the sample according to Horan-Hargis identifiers included in Bailey et al. (2016).

[16]In 1951, 170 counties cross this threshold; 1952 1,323 counties cross this exposure threshold; 1953 767 counties; 1955 88 counties; and 1957 512 counties.

[17]The standard mortality ratio in this figure uses age specific mortality rates for the entire U.S. by year from Mortality.org (University of California and for Demographic Research, 2019). and multiplies these rates by county level populations by age group to calculate the expected number of deaths. Information on the number of people by age for each county are interpolated from historic Census tabulations (Haines, 2010). The standard mortality ratio is overall mortality in a county divided by expect numbers of deaths according to U.S. average and the county's age distribution. This ratio describes whether a county has a higher or lower mortality rate than U.S. average given the county's age distribution.

[18]Multiple yearly lag structures were tried and the results are generally robust with respect to the number of lags.

[19]Information needed to construct age adjusted mortality rates at the county level is not available prior to 1959. U.S. Vital Statistics manuscripts report county mortality rates as county totals.

[20]County fixed effects control for time invariant sources of radiation exposure such as naturally occurring uranium deposits or average radon seepage into basements.

[21]These data are available in ICPSR record 2937 https://doi.org/10.3886/ICPSR02937.v1 and https://www.irs.gov/statistics/soi-tax-stats-migration-data

[22]Annual fallout deposition is relatively uncorrelated with total annual rainfall dur-

ing test years.

[23]Other options include using restricted confidential Census data. Such a process requires Special Sworn Status and approval from the Census Bureau. Generally linking between Censuses is prohibited, though a new process for approving projects that link mandatory surveys together has recently started at the Census Bureau. Such an endeavor is beyond the scope of this paper.

[24]The 95 percent confidence interval for this estimate is 11,300 and 220,000 cases. Without nuclear testing they estimated that 400,000 cases of thyroid cancer would arise naturally in the same population.

[25]In the appendix I provide a table of magnitudes of these estimated effects felt by state. The cut off is 1973 because it is the last year the model would suggest a statistically significant effect for specification (4).

[26]See https://www.justice.gov/civil/common/reca for more details on RECA. A map of the RECA region is available in the appendix.

[27]For the NTS, almost all tests were underground from 1958 to 1963. Some underground tests did not report bomb yields but instead ranges of yields. In these cases bomb yield was taken as the average value. In cases where the bomb yield was greater than a certain value, the lowest value was assigned.

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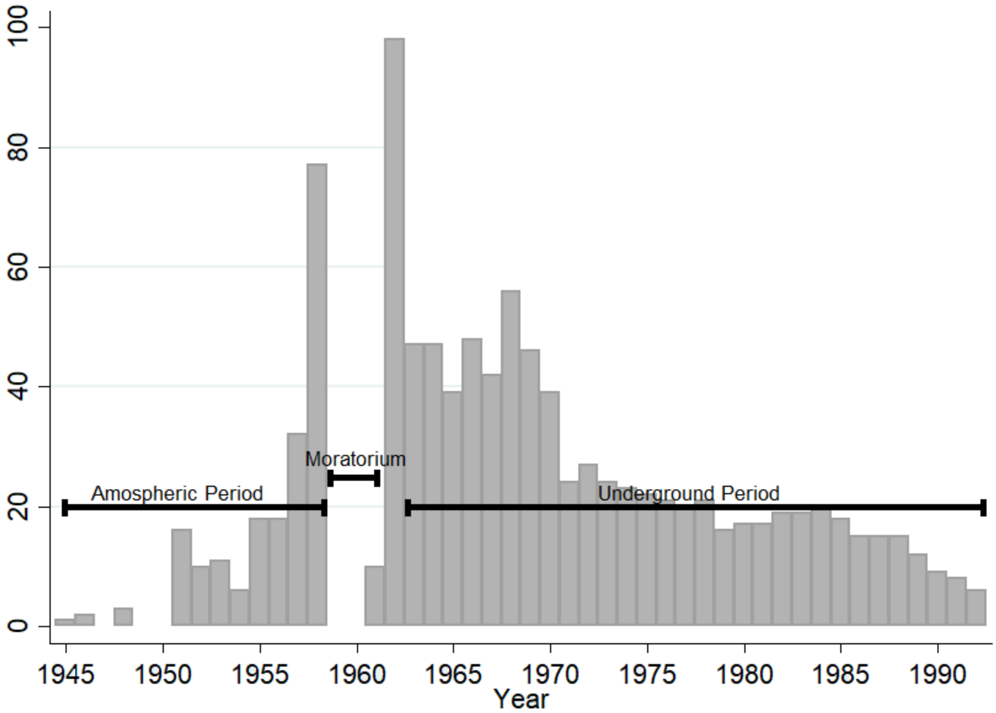

Figure 1: Number of U.S. Nuclear Tests 1945-1993. Source: Created from U.S. Department of Energy 2000 records.

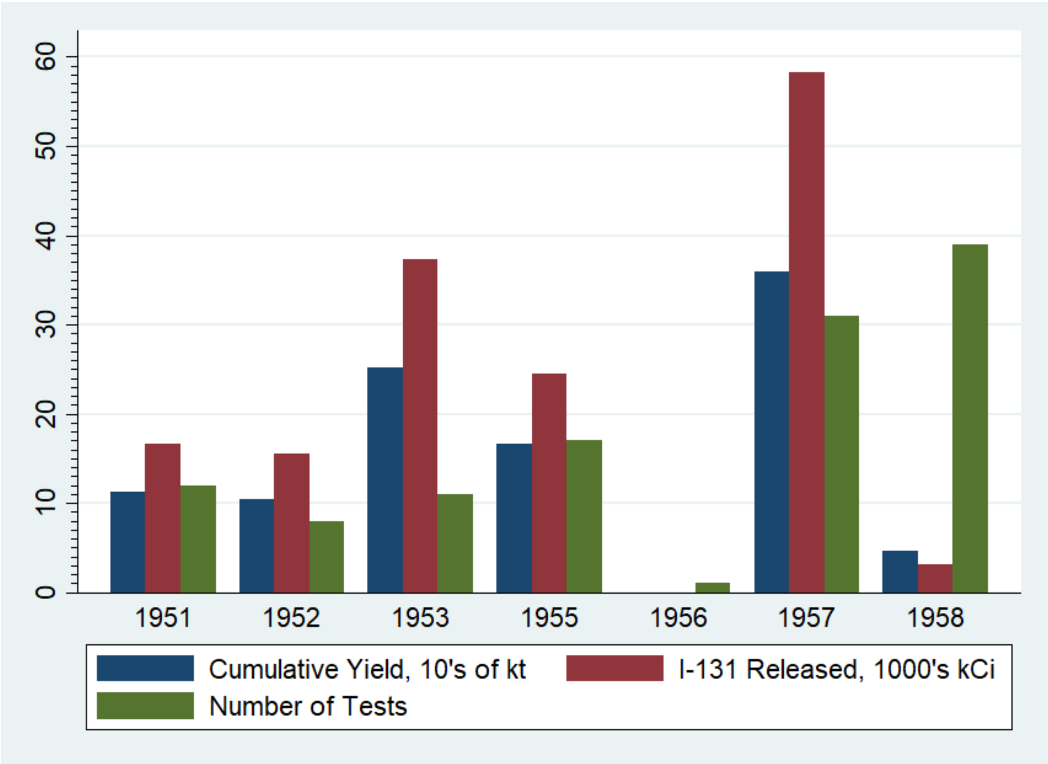

Figure 2: Annual Cumulative Atmospheric Yields, Atmospheric I-131 Releases, and Number of Tests for the NTS, 1951-1958. Source: Created from National Cancer Institute (1997) records.

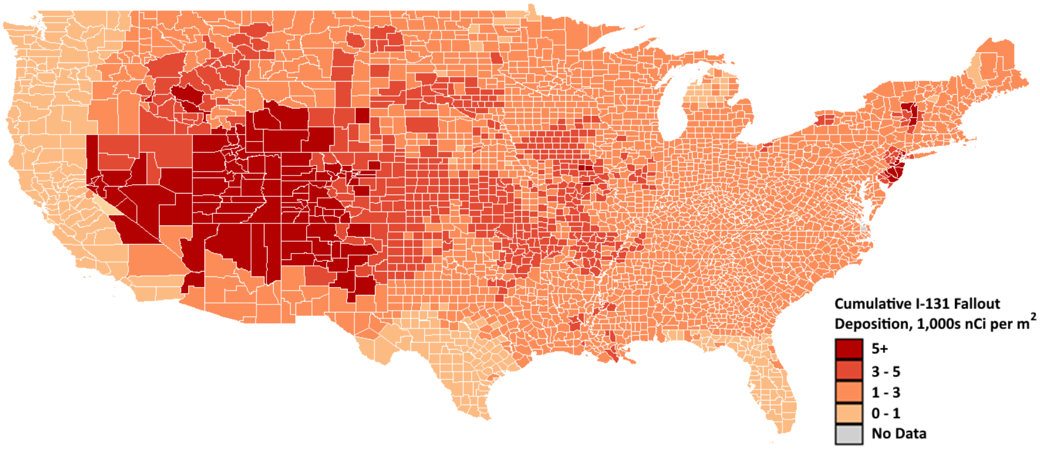

Figure 3: Cumulative Radioactive I-131 Deposition per m^2 for NTS Atmospheric Tests conducted from 1951-1958. Source: Created from National Cancer Institute (1997) records.

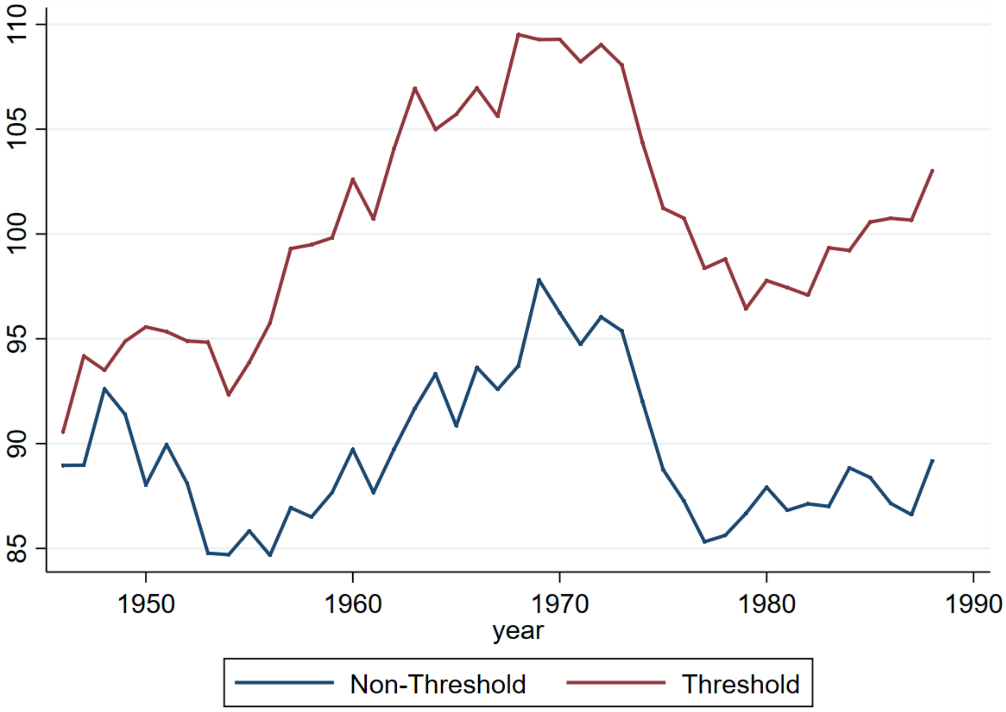

Figure 4: Average Annual Overall Death Rates, Counties Surpassing Fallout Deposition Threshold vs Counties always Below Threshold. Source: Author's calculations.

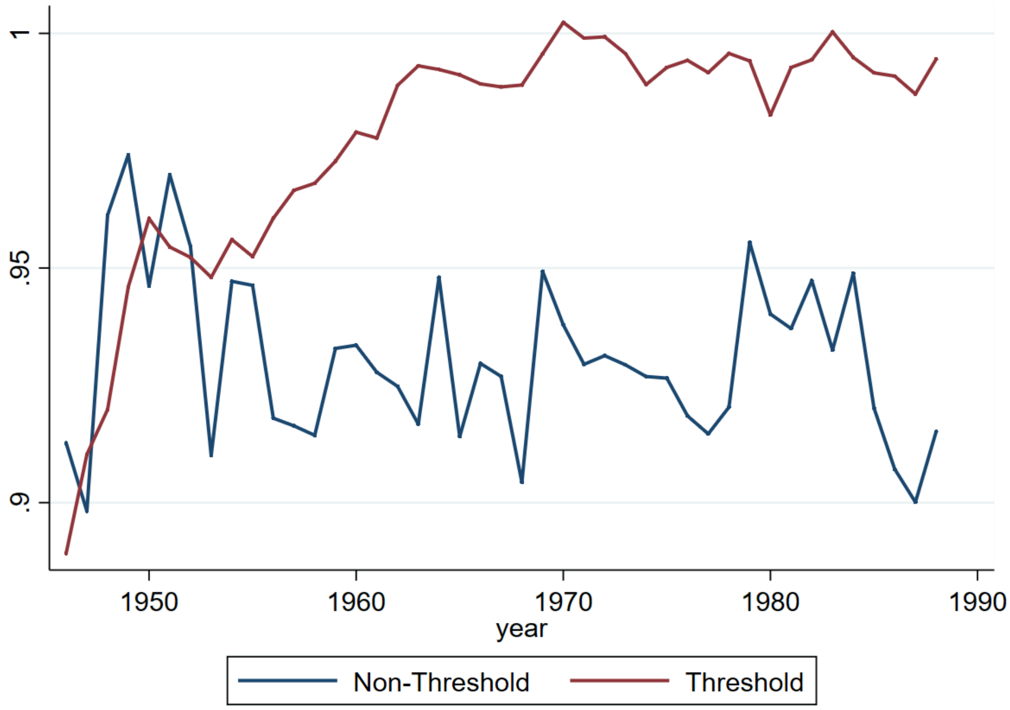

Figure 5: Average Annual Standard Mortality Ratio by Counties Surpassing Fallout Deposition Threshold, U.S. National Average Mortality Baseline: Source: Author's calculations.

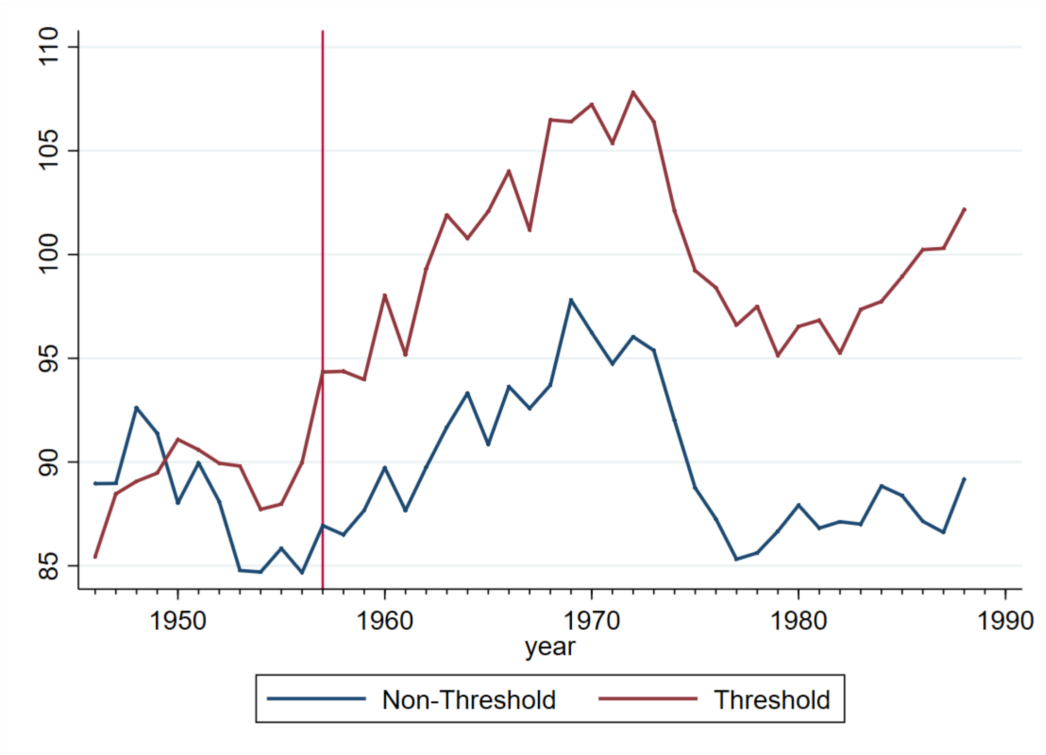

Figure 6: Average Annual Overall Death Rates by Counties Surpassing in 1957 Fall-out Deposition Threshold vs Counties always Below Threshold. Source: Author's calculations.

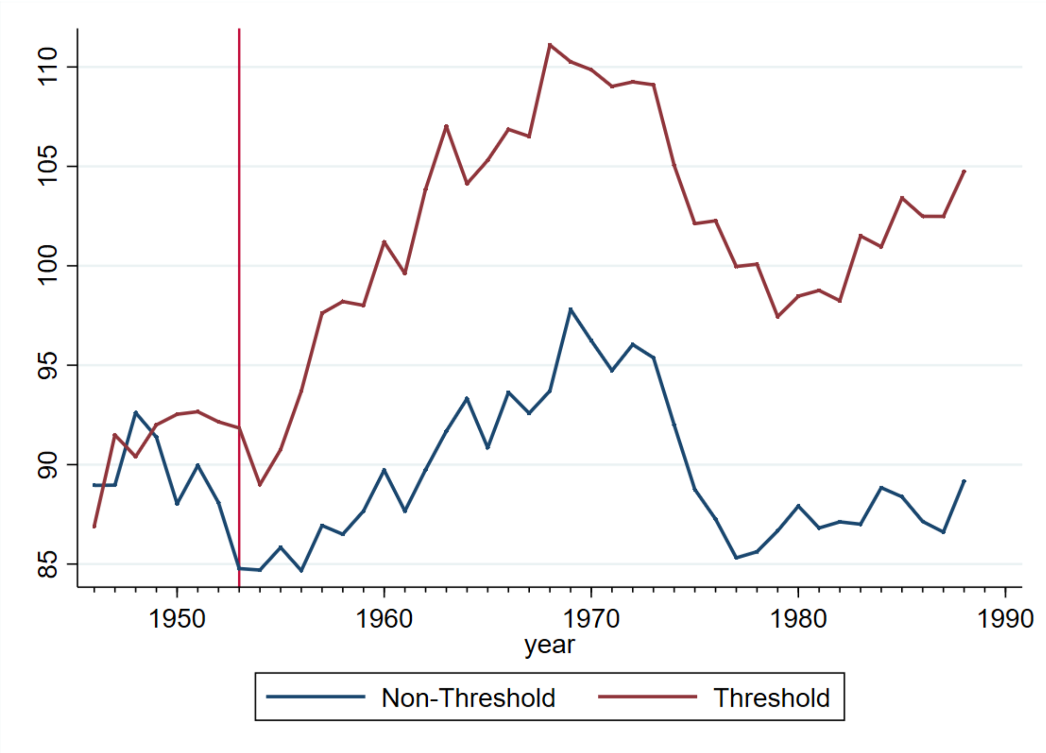

Figure 7: Average Annual Overall Death Rates by Counties Surpassing in 1953 Fallout Deposition Threshold vs Counties always Below Threshold. Source: Author's calculations.

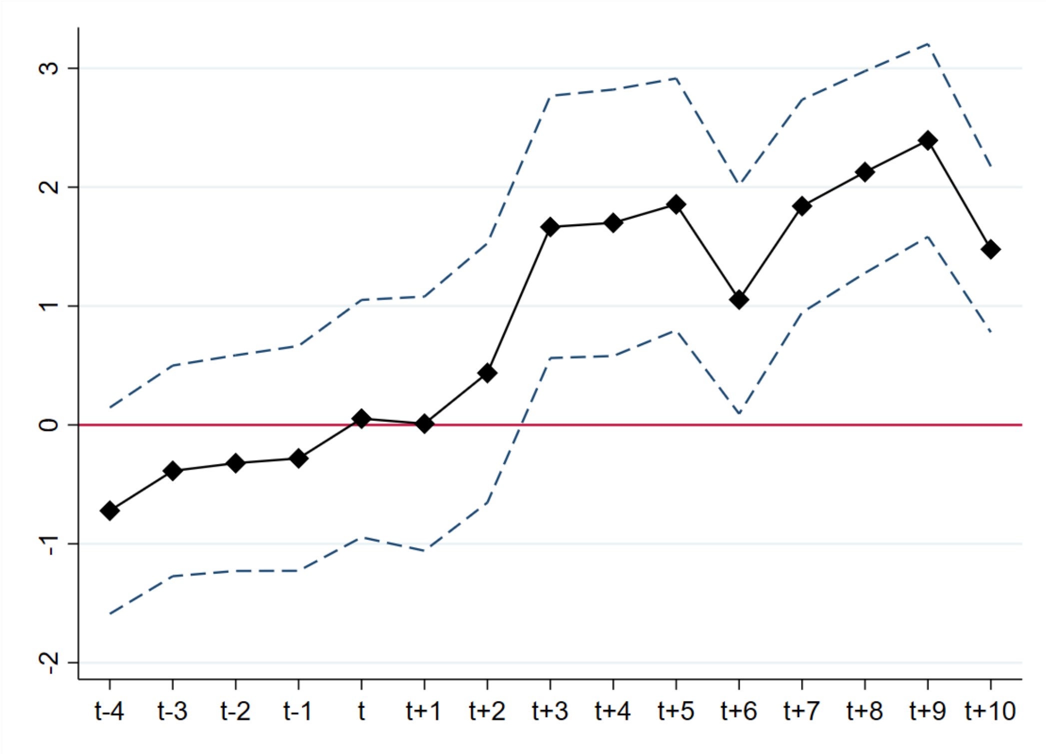

Figure 8: Fixed Effects Coefficient Plot of Indicator Variables Denoting 't" Years Before and After Fallout Deposition Threshold is Crossed. Source: Author's calculations.

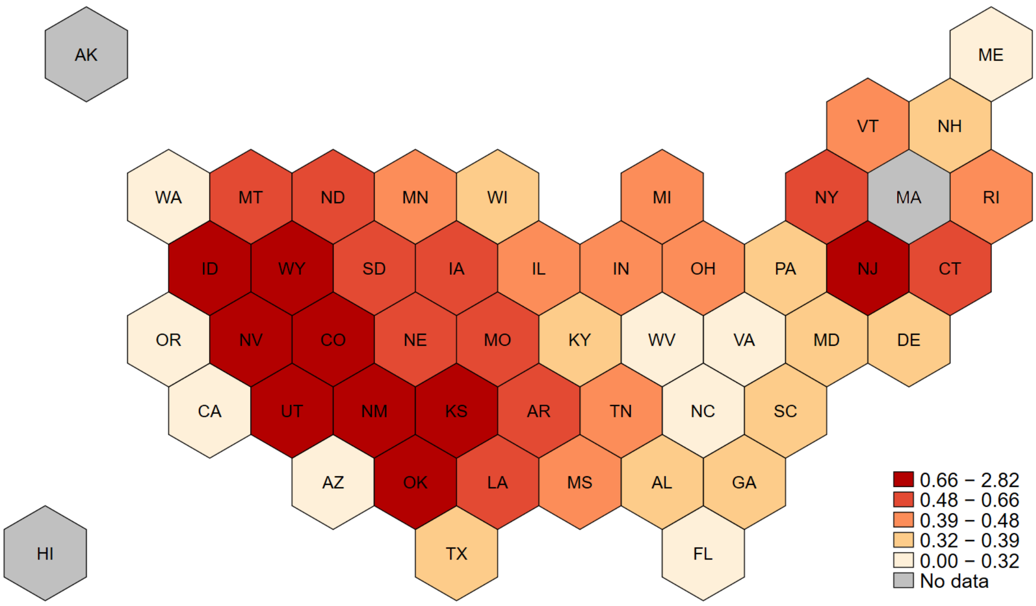

Figure 9: Average Increase in Annual State Mortality Rates Per 10,000 Attributable to NTS Atmospheric Testing, 1952-1973. Source: Author's calculations.

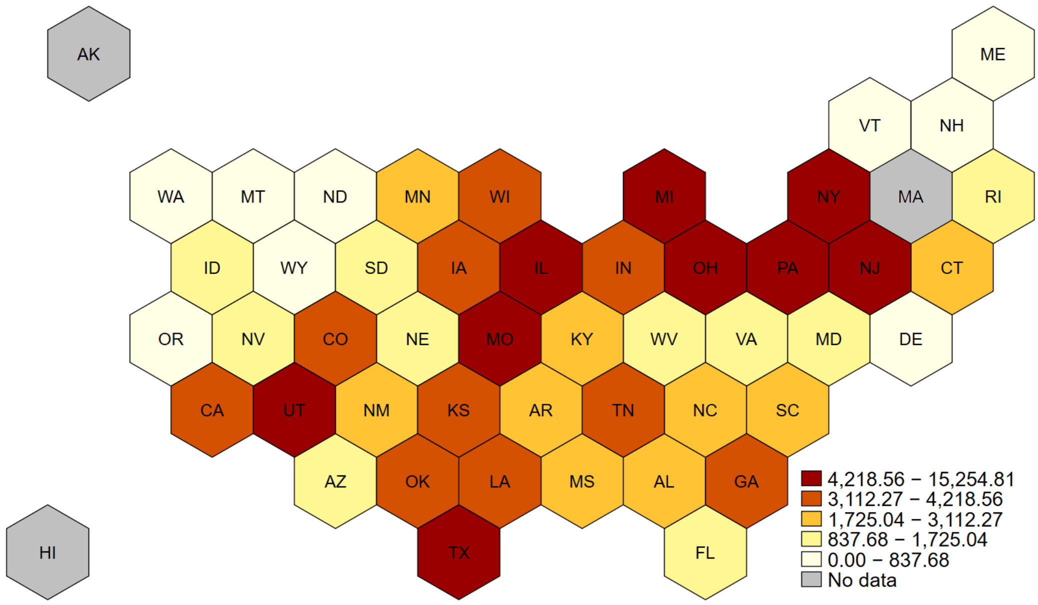

Figure 10: Cumulative Deaths Attributable to NTS Atmospheric Testing by State, 1952-1973. Source: Author's calculations.

Table 1: Summary Statistics

Table 11: Summary Statistics, Overall Mortality Sample

Variable	Mean	(Std. Dev.)	Min.	Max.	N
Overall Mortality, per 10,000	100.110	(25.173)	0	564.871	128,570
Standardized Mortality Ratio	0.975	(0.158)	0	7.313	128,570
I-131 Dep., 1,000s nCi per m^2	0.052	(0.247)	0	25.330	128,570
I-131 Milk, 1,000s nCi	0.032	(0.136)	0	4.600	128,570
Avg I-131 Dep., t-1/t-5 1,000s nCi	0.052	(0.139)	0	6.608	128,570
Avg I-131 Milk, t-1/t-5 1,000s nCi	0.032	(0.078)	0	1.857	128,570
Population, interpolated	58,018	(204,273	73	8,586,032	128,570

Table 1B: Summary Statistics, Cancer Mortality Sample

Variable	Mean	(Std. Dev.)	Min.	Max.	N
Cancer Deaths, per 10,000	16.041	(6.385)	0	121.465	127,581
I-131 Dep., 1,000s nCi per m^2	0.052	(0.246)	0	25.330	127,581
I-131 Milk, 1,000s nCi	0.032	(0.136)	0	4.600	127,581
Avg I-131 Dep., t-1/t-5 1,000s nCi	0.052	(0.139)	0	6.608	127,581
Avg I-131 Milk, t-1/t-5 1,000s nCi	0.032	(0.078)	0	1.857	127,581
Population, interpolated	58,426	(205,010)	241	8,586,032	127,581

Table 2: Relationship between Pre-Nuclear Testing Mortality Rates of Cumulative Fallout Deposition, 1946-1950

	Overall Mortality Rate			Cancer Death Rate		
	(1)	(2)	(3)	(4)	(5)	(6)
Total I-131 Dep., 1,000s nCi	-0.131	0.013	0.164	0.069**	-0.003	0.011
	(0.140)	(0.179)	(0.176)	(0.028)	(0.041)	(0.041)
State FE	No	Yes	Yes	No	Yes	Yes
Age Cohort Controls	No	No	Yes	No	No	Yes
N	14,950	14,950	14,950	14,835	14,835	14,835
adj. R^2	0	0.250	0.286	0	0.324	0.342

Robust standard errors in parentheses. All mortality rates are per 10,000 residents. Age Cohort Controls are variables denoting the share of the population in the following age groups: 0/4, 5/14, 15/24, 25/34, 35/44, 45/54, 55/64, 65/74, 75+.
* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Table 3: Short-Run Overall Mortality Effect of I-131 Deposition, 1946-1988

	Overall Deaths per 10,000			
	(1)	(2)	(3)	(4)
I-131 Dep, 1,000s nCi t	0.452	-0.386	-0.426	-0.159
	(0.296)	(0.276)	(0.274)	(0.233)
I-131 Dep., 1,000s nCi t-1	1.137***	0.336	0.369	0.172
	(0.305)	(0.235)	(0.240)	(0.177)
I-131 Dep., 1,000s nCi t-2	1.147***	0.482*	0.532**	0.376**
	(0.310)	(0.265)	(0.265)	(0.187)
I-131 Dep., 1,000s nCi t-3	0.741***	0.075	0.049	0.160
	(0.286)	(0.224)	(0.225)	(0.207)
I-131 Dep., 1,000s nCi t-4	1.209***	0.421	0.322	0.155
	(0.323)	(0.260)	(0.259)	(0.184)
I-131 Dep., 1,000s nCi t-5	0.991***	0.181	0.254	0.503***
	(0.260)	(0.242)	(0.242)	(0.180)
Year FE	Yes	Yes	Yes	Yes
County FE	Yes	Yes	Yes	Yes
Weather Controls	No	No	Yes	Yes
Age Cohort Controls	No	Yes	Yes	Yes
Economic Controls	No	No	No	Yes
N	128,570	128,570	128,570	11,5941
adj. R^2	0.627	0.769	0.770	0.800
Joint Significance Test, F-stat.	5.179	1.610	1.841	2.224
Joint Significance Test, P-value	0.000	0.140	0.087	0.038

Standard errors clustered by county in parentheses. All mortality rates are per 10,000 residents and the sample consists of counties/county equivalents continuously reporting mortality data from 1946 to 1988. Weather Controls denote monthly county level precipitation totals and average temperatures for each year. Age Cohort Controls are variables denoting the share of the population in the following age groups: 0/4, 5/14, 15/24, 25/34, 35/44, 45/54, 55/64, 65/74, 75+. Economic Controls consist of share of the population with a high school degree, share of the population that is white, and log median household income. Median household income is reported in Haines (2010) starting in 1950 and its inclusion reduces the size of the empirical sample.

* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Table 4: Short-Run Cancer Mortality Effect of I-131 Deposition, 1946-1988

	Total Cancer Deaths per 10,000			
	(1)	(2)	(3)	(4)
I-131 Dep, 1,000s nCi t	0.325***	0.153**	0.133*	0.169***
	(0.082)	(0.077)	(0.077)	(0.053)
I-131 Dep., 1,000s nCi t-1	0.339***	0.178*	0.184*	0.127
	(0.109)	(0.096)	(0.096)	(0.094)
I-131 Dep., 1,000s nCi t-2	0.265***	0.136*	0.139*	0.129*
	(0.081)	(0.071)	(0.072)	(0.067)
I-131 Dep., 1,000s nCi t-3	0.252***	0.126*	0.127*	0.137**
	(0.078)	(0.066)	(0.067)	(0.062)
I-131 Dep., 1,000s nCi t-4	0.447***	0.301***	0.302***	0.190***
	(0.121)	(0.110)	(0.110)	(0.060)
I-131 Dep., 1,000s nCi t-5	0.235***	0.089	0.083	0.152***
	(0.070)	(0.070)	(0.071)	(0.055)
Year FE	Yes	Yes	Yes	Yes
County FE	Yes	Yes	Yes	Yes
Weather Controls	No	No	Yes	Yes
Age Cohort Controls	No	Yes	Yes	Yes
Economic Controls	No	No	No	Yes
N	127,581	127,581	127,581	115,144
adj. R^2	0.543	0.604	0.605	0.592
Joint Significance Test, F-stat.	6.906	4.117	3.970	5.306
Joint Significance Test, P-value	0.000	0.000	0.000	0.000

Standard errors clustered by county in parentheses. All mortality rates are per 10,000 residents and the sample consists of counties/county equivalents continuously reporting mortality data from 1946 to 1988. Weather Controls denote monthly county level precipitation totals and average temperatures for each year. Age Cohort Controls are variables denoting the share of the population in the following age groups: 0/4, 5/14, 15/24, 25/34, 35/44, 45/54, 55/64, 65/74, 75+. Economic Controls consist of share of the population with a high school degree, share of the population that is white, and log median household income. Median household income is reported in Haines (2010) starting in 1950 and its inclusion reduces the size of the empirical sample.

* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Table 5: Long-Run Overall Mortality Effect of I-131 Deposition, 1946-1988

	Total Deaths per 10,000			
	(1)	(2)	(3)	(4)
Avg. Dep. 1-5 yrs ago	5.602***	1.648***	1.658***	1.573***
	(1.177)	(0.635)	(0.635)	(0.503)
Avg. Dep. 6-10 yrs ago	4.160***	1.514**	1.715**	1.524***
	(1.093)	(0.671)	(0.676)	(0.552)
Avg. Dep. 11-15 yrs ago	2.939***	1.454**	1.194**	1.170**
	(1.092)	(0.600)	(0.586)	(0.484)
Avg. Dep. 16-20 yrs ago	-0.356	-0.418	-0.651	-0.606
	(0.986)	(0.585)	(0.567)	(0.461)
Avg. Dep. 21-25 yrs ago	-1.051	0.085	0.441	0.289
	(0.813)	(0.513)	(0.534)	(0.400)
County FE	Yes	Yes	Yes	Yes
Weather Controls	No	No	Yes	Yes
Age Cohort Controls	No	Yes	Yes	Yes
Economic Controls	No	No	No	Yes
N	128,570	128,570	128,570	115,941
adj. R^2	0.628	0.769	0.770	0.800
Joint Significance Test, F-stat.	9.225	3.958	4.665	5.068
Joint Significance Test, P-value	0.000	0.001	0.000	0.000
Estimated Additional Deaths	429,433	157,834	155,578	145,383

Standard errors clustered by county in parentheses. All mortality rates are per 10,000 residents and the sample consists of counties/county equivalents continuously reporting mortality data from 1946 to 1988. Weather Controls denote monthly county level precipitation totals and average temperatures for each year. Age Cohort Controls are variables denoting the share of the population in the following age groups: 0/4, 5/14, 15/24, 25/34, 35/44, 45/54, 55/64, 65/74, 75+. Economic Controls consist of share of the population with a high school degree, share of the population that is white, and log median household income. Median household income is reported in Haines (2010) starting in 1950 and its inclusion reduces the size of the empirical sample. Estimated Additional Deaths are calculated using statistically significant coefficients.
* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Table 6: Long-Run Cancer Mortality Effect of I-131 Deposition, 1946-1988

	Total Cancer Deaths per 10,000			
	(1)	(2)	(3)	(4)
Avg. Dep. 1-5 yrs ago	1.542***	0.833***	0.822***	0.845***
	(0.313)	(0.206)	(0.207)	(0.231)
Avg. Dep. 6-10 yrs ago	0.938***	0.497***	0.545***	0.682***
	(0.254)	(0.172)	(0.178)	(0.214)
Avg. Dep. 11-15 yrs ago	0.554**	0.291*	0.254	0.362**
	(0.224)	(0.157)	(0.156)	(0.161)
Avg. Dep. 16-20 yrs ago	-0.101	-0.062	-0.112	0.080
	(0.190)	(0.185)	(0.186)	(0.159)
Avg. Dep. 21-25 yrs ago	-0.780***	-0.396***	-0.399***	-0.139
	(0.172)	(0.134)	(0.135)	(0.138)
County FE	Yes	Yes	Yes	Yes
Weather Controls	No	No	Yes	Yes
Age Cohort Controls	No	Yes	Yes	Yes
Economic Controls	No	No	No	Yes
N	127,581	127,581	127,581	115,144
adj. R^2	0.544	0.604	0.605	0.592
Joint Significance Test, F-stat.	6.592	4.322	4.328	3.353
Joint Significance Test, P-value	0.000	0.001	0.001	0.005
Estimated Additional Deaths	69,823	38,092	28,656	50,384

Standard errors clustered by county in parentheses. All mortality rates are per 10,000 residents and the sample consists of counties/county equivalents continuously reporting mortality data from 1946 to 1988. Weather Controls denote monthly county level precipitation totals and average temperatures for each year. Age Cohort Controls are variables denoting the share of the population in the following age groups: 0/4, 5/14, 15/24, 25/34, 35/44, 45/54, 55/64, 65/74, 75+. Economic Controls consist of share of the population with a high school degree, share of the population that is white, and log median household income. Median household income is reported in Haines (2010) starting in 1950 and its inclusion reduces the size of the empirical sample. Estimated Additional Deaths are calculated using statistically significant coefficients.
* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$