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

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Abstract

The United States' atmospheric nuclear weapons testing program resulted in the tremendous release of radioactive material into the environment. This paper analyzes the consequences of the Truman Administration's decision to conduct nuclear tests in Nevada. For each test conducted in Nevada from 1951 to 1958, I construct a novel county-level panel of radioactive fallout for the continental United States. This paper use differences in county-level measures of radioactive fallout resulting from nuclear tests to study the mortality effects of sudden increases in ambient levels of ionizing radiation. I find the decision to conduct atmospheric nuclear tests in the Nevada desert resulted in hundreds of thousands of premature deaths. I then compare the Nevada Test Site (NTS) to alternative testing locations and evaluate the social saving attributable to the Partial Nuclear Test Ban Treaty.

JEL Codes: I15, N32, Q53. Keywords: Nuclear Testing, Public Health, Radioactive Fallout, Defense Policy

Introduction

The United States' rapid development of nuclear weapons allowed it to become the preeminent player of the Cold War. In 1951 the U.S. began a program of atmospheric nuclear testing at the Nevada Test Site (NTS) that resulted in substantial and sudden increases in human exposure to potentially harmful ionizing radiation. In this paper I assess the public health effects of these activities for the continental United States. I then analyze the consequences of the Truman Administration's decision to conduct tests in Nevada relative to other locations and measure the value of transitioning nuclear tests underground. By measuring the human cost of the NTS testing paper adds to an economics and human capital literature studying the adverse effects of nuclear accidents and prenatal radiation exposure in European populations (Almond et al., 2009; Lehmann and Wadsworth, 2011; Danzer and Danzer, 2016; Elsner and Wozny, 2018; Black et al., 2019). The development of nuclear weapons is an example of how government policy and the adoption of specific technologies can impose substantial public health externalities. Like previous advancements and innovations in technology, such as the decision to adopt lead water piping or the adoption of fossil fuels (Troesken, 2008; Hanlon, 2016; Clay et al., 2016; Beach and Hanlon, 2016), the advancement of nuclear technologies created substantial unintended social consequences for areas even thousands of miles from the NTS.

To explore how NTS activities affected mortality patterns in U.S. Vital Statistics I construct a county by year panel of radiation deposition for atmospheric tests conducted from 1951 to 1958. Using a difference in differences strategy I assess the average effect of a sudden increase in ambient radiation on mortality, the temporal extent to which mortality increases persist, and the geographic extent to which NTS testing affects public health. In contrast to the clinical literature focusing on thyroid cancer and leukemia risks from NTS testing, I find that atmospheric nuclear testing in Nevada increased all-cause mortality at levels greater than what can be explained by increases in cancer mortality alone (Kerber et al., 1993; Stevens et al., 1990; Gilbert et al., 2010; Simon et al., 2006; Simon and Bouville, 2015). I argue that most of the impact of NTS testing occurs in regions beyond the scope of the U.S.'s compensation program, that the Radiation Exposure Compensation Act, and that nuclear non-proliferation efforts are substantially undervalued. Using a model of air particulate flow, I compare the NTS to alternative locations and show that most alternatives considered would have greatly increased human exposure to ionizing radiation.

By exploring the U.S.'s experience with radiation exposure from nuclear testing this paper extends the literature on the human capital effects of sudden increases low levels of ionizing radiation (National Research Council, 2006). I establish that low levels of ionizing radiation contributed to increases in both all-cause and cancer mortality at least ten years following the arrival of fallout. Studies analyzing the effects of prenatal exposure to low levels of ionizing radiation by Almond et al. (2009) and Black et al. (2019) reveal substantial reductions in both education and income from increased radiation exposure but find little direct evidence of adverse health effects. Lehmann and Wadsworth (2011) find that increased exposure to Chernobyl radiation adversely affects self-reported measures of health and economic well-being. Danzer and Danzer (2016) reveal that uncertainty surrounding personal radiation exposure imposes a substantial psychological burden. Elsner and Wozny (2018) show persons residing in more irradiated areas during the Chernobyl disaster experience more rapid cognitive decline later in life. Other research has shown that sudden increases in ionizing radiation can directly affect economic activity. Meyers (2019) finds that sudden increases in ambient radiation resulting from NTS testing reduced agricultural productivity in the United States. Ito and Kuriyama (2017) and Kawaguchi and Yukutake (2017) show that the Fukushima disaster affected consumer behaviors and land values.

The epidemiological literature measuring the public health effects of NTS activities focus on small populations that resided in Nevada, Arizona, or Utah during the period of testing and focus primarily on leukemia and thyroid cancer as outcomes (Kerber et al., 1993; Stevens et al., 1990; Gilbert et al., 2010; Simon et al., 2006; Simon and Bouville, 2015). Rather than extrapolating out disease risks from a small sample to the general population, I expand the geographic scope of the analysis to the continental

U.S. and measure connections between mortality in U.S. Vital Statistics and radiation deposition.

The remainder of this manuscript is organized as follows. Section I describes the history behind the U.S.'s nuclear testing program and the health effects of ionizing radiation according to the clinical literature. Section II describes data used on ambient radiation and health used in the analysis. Section III presents the main results from the differences and differences event study used to study the effect of a sudden radiation shock. In Section IV I analyze the cumulative effect of ionizing radiation resulting from atmospheric testing and discuss the implications for the LNTM. In Section V I evaluate the insufficiency of the Radiation Exposure Compensation Act (RECA), consequences of choosing to locate the nuclear test site in Nevada, and the decision to cease atmospheric testing and move testing underground under the PTBT. Section VI discusses the implications of my results for other sources of ionizing radiation and the undervaluation of nuclear non-proliferation efforts.

I Historical and medical background

The decision to begin atmospheric nuclear testing was driven by the Atomic Energy Commission (AEC) and U.S. government's desire to hasten the development of its nuclear weapons arsenal. A continental test site had logistical advantages of being close to U.S. laboratories and nuclear weapons production infrastructure. Prior to 1951 all postwar nuclear tests occurred in the Pacific at Bikini and Enewetak Atolls. In 1947 the Armed Forces Special Weapons Project (AFSWP) created "Project Nutmeg" to study the feasibility of conducting continental testing. They selected Navy Captain Howard Hutchison, a meteorologist, to conduct the initial feasibility study regarding continental nuclear testing. Hutchinson asserted that with proper precautions continental testing would "result in no harm to the population, economy, or industry." Hutchinson recommended potential test sites either off the Atlantic Coast or in the arid Southwest (Fehner and Gosling, 2000). Project Nutmeg ended with the

AEC tabling the proposal barring a "National Emergency." The first successful Soviet nuclear weapons test in 1949 pushed the Truman administration to accelerate the U.S.'s nuclear weapons program. It took the advent of Korean War to give the AEC its "National Emergency." The war caused a reallocation of naval logistical and air transport resources that created bottlenecks and delays for Pacific testing. In the AFSWP's reevaluation of continental testing, test sites off the coasts of Texas and North Carolina were considered, as were the Dugway Proving Ground-Wendover Bombing Range in Utah and the Alamogordo testing range (the site of the first nuclear detonation called Trinity) Executive Office of The President (1950). The Las Vegas Bombing and Gunnery Range eventually became the site of the NTS.

From its earliest stages, the U.S. Military and Atomic Energy Commission downplayed the public health and economic risks associated with the decision to perform nuclear testing in Nevada. Sociologist James Rice (2015) argues that this was part of an "organized production of denial." On January 11, 1951, on the eve of the first test series named Ranger, a flyer circulated around the NTS stating "Health and safety authority have determined that no danger from or as a result of AEC test activities may be expected outside the limits of the Las Vegas Bombing and Gunnery Range." Figure 1 presents this poster (U.S. Atomic Energy Commission, 1951).

In 1955, following substantial amounts of fallout exposure in communities in Utah during the 1953 Upshot Knothole test series, the AEC circulated a pamphlet discussing the risks atmospheric testing posed. In the document risks from visible light and sound were highlighted while radiological risks were minimized. The AEC repeatedly stated that public exposure to NTS fallout was comparable to background radiation and that radiation from NTS testing "does not constitute a serious hazard to any living thing outside the test site." The AEC also reported that "no persons in the nearby region has been exposed to hazardous amounts of radiation, even from the heavier fall-out" (U.S. Office of Test Information, 1955). Similar assertions are made with regards to the 1957 Plumbbob test series. "For the United States as a whole, average exposure will be small in comparison with the radiation dosage normally received from background radiation" (U.S. Office of Test Information, 1957).

The public was largely unaware of the dangers that the NTS posed to public health during the testing period. The Public Health Service (PHS) and Atomic Energy Commission (AEC) sought to downplay concerns regarding the atomic testing (Rice, 2015; Ball, 1986; Fradkin, 2004; LeBaron, 1998).[1] In some cases, government officials sought to suppress or classify research suggesting radiation from these tests posed substantial health risks. In the 1960s the Public Health Service and Centers for Disease Control studied clusters of leukemia and cancer appearing in Nevada and Utah but avoided linking leukemia to fallout from nuclear testing (Lyon, 1999). The U.S. Congress opened a series of hearings in the late 1970s regarding the consequences of radioactive fallout resulting from U.S. nuclear testing (United States House of Representatives, 1980). Subsequent Freedom of Information Act requests later revealed that the test officials knew that NTS activities posed a public health risk and that the AEC sought to suppress medical studies highlighting the health dangers (Fradkin, 2004).[2]

Testing in Nevada and fallout

Located mostly in Nye County, Nevada, this military zone became the epicenter of the American nuclear weapons program and hosted 928 of the 1,054 nuclear tests conducted by the United States (U.S. Department of Energy, 2000; Fehner and Gosling, 2006). From 1951 to 1958 the U.S. conducted most of its atmospheric nuclear tests at the NTS. A moratorum between the U.S. and USSR led to a suspension of testing from 1958 to 1962. With the signing of the Partial Nuclear Test Ban Treaty in 1963 all atmospheric nuclear tests conducted by the U.S. ceased and testing went underground. Figure 2 describes the number, explosive magnitude (measured in kilotons of TNT), and estimated radioactive release from these NTS nuclear tests by year. One estimate places the total atmospheric release of radioactive material from the NTS at over 12

[1] Unlike more recent nuclear disasters where governments sought to limit and mitigate public exposure to potentially harmful ionizing radiation, there was no concerted national effort to inform the public on the potential risks NTS testing posed.

[2] Knapp (1963) identifies the threat radioactive iodine-131 in dairy posed to the public and is an example of research the AEC sought to suppress.

billion Curies between 1951 and 1963. In comparison, Chernobyl released an estimated 81 million Curies of radioactive material (LeBaron, 1998).

When atmospheric tests were performed near the surface of the ear, the denotations would vaporize and irradiate the surrounding soil. The resulting mushroom plume would draw much of the irradiated material high into the atmosphere where it would be carried by high altitude winds. In the days following the detonation, the fallout cloud would intersect with rain systems and rainfall would scavenge the irradiated material to the earth. Figure 3 presents a map constructed from the National Cancer Institute (NCI) estimates of cumulative radioactive iodine-131 deposition by county 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 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.

Exposure to harmful radioactive fallout can occur either through direct channels such as landing on the skin or inhalation of irradiated dust, or through indirect channels such as the consumption of irradiated food products. Research by the National Cancer Institute (1997) and Center for Disease Control (2006) establishes that the diary supply served as the main vector of exposure for NTS fallout.[3] The short lived isotope of radioactive iodine-131 has unique characteristics that results in it concentrating in fresh dairy. Dairy cows would inadvertently 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. The structure of the dairy industry during the 1950s involved local production and often

[3]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; Wolff, 1957).

daily deliveries of milk to households. In this way irradiated dairy tended to be produced and consumed locally (Dreicer et al., 1990; National Cancer Institute, 1997; Manchester and Blayney, 1997).[4] 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.[5] 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. Through this dairy channel, local deposition of fallout is connected with human exposure to fallout. The NCI estimates the majority of the 160 million U.S. residents alive during the period of testing experienced some level of exposure to fallout resulting from NTS activities.

Dosimetry and the Linear No Threshold Model of Radiation Exposure

Studies of atomic bomb survivors and persons exposed during pregnancy demonstrate increased cancer risks, and 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 iodine-131 poisoning in exposed populations (Shibata et al., 2001; Williams, 2002). Researchers studying American populations living near the NTS have also found evidence of increased thyroid cancer and leukemia risks (Kerber et al., 1993; Stevens et al., 1990; Gilbert et al., 2010; Simon et al., 2006; Simon and Bouville, 2015). The clinical and medical literature studying human exposure to NTS fallout has focused

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

[5] 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).

primarily on thyroid cancer and leukemia as endpoints.[6] Exposure to such radiation can damage tissue and DNA in ways that are difficult for the body to repair and beyond cancer there is evidence that exposure to ionizing radiation can increase the risk of developing cardiovascular disease and metabolic diseases (National Research Council, 2006; Tapio et al., 2021). 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).

II Data

Radiation deposition data

The radiation deposition and exposure data used in this research is provided by the National Cancer Institute (NCI). These records are the most complete estimates of radioactive fallout resulting from nuclear testing conducted in Nevada from 1951 to 1958. The NCI derived estimates from raw gummed film radiation monitors for total radiation, the position of radiation clouds in the days following tests, and meteorological data. Estimates for radioactive iodine-131 is derived from estimates for total fallout deposition.[7]

In 1983, Congress authorized the Secretary of Health and Human Services to investigate and measure thyroid cancers 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. The NCI undertook the task of gathering and reconstructing records monitoring radioactive fallout deposition across the United

[6]Increased incidences of leukemia generally emerge relatively soon after exposure to ionizing radiation while other health effects can be more latent (National Research Council, 2006).

[7]Specific details on how the NCI constructed the data is available in the appendix. The iodine-131 estimates are proportional to total fallout deposition due since heavier and lighter fallout would not have separated much during the few days following the tests.

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.[8] The primary measurement for radiation exposure by county used in this analysis is cumulative annual average iodine-131 deposition per m^2.[9]

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 of 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. Most of the irradiated material 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. In areas outside of the "Downwind" region, high altitude winds

[8] In 1962 some atmospheric nuclear testing occurred when a nuclear testing moratorium between the U.S. and USSR 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 location of 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.

carried radioactive material and would be scavenged by precipitation. Many areas of the U.S. experienced fallout if it rainfall happened to coincide with the travel path of the fallout cloud.

Aggregate public health and mortality data

Annual overall mortality, commonly referred to as all-cause mortality, 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. Furthermore, cancer might not be attributed as a cause of death on death certificates if it is only a contributing cause.

In addition to this overall death measure, I also collect and use information on annual cancer, motor vehicle, influenza/pneumonia, diabetes, and tuberculosis deaths by county. Cancer has historically been the outcome focus of radiation health studies. Deaths from motor vehicle and influenza/pneumonia come from behaviors and infectious diseases that should be unrelated with fallout exposure and are used for falsification tests. For 1946 to 1958, these records were constructed from cause of death tables in the Vital Statistics of the United States (National Center for Health Statistics, 1958). Cancer and motor vehicle deaths from 1959 to 1967 were aggregated from the National Center for Health Statistics' Multiple Cause of Death Files (National Center for Health Statistics, 1967).[12] Cancer and motor vehicle deaths from 1968 to 1988 were compiled at the county year level from the National Center for Health Statistics' Compressed Mortality File (National Center for Health Statistics, 1988). The main sample used in the event study is from 1946 to 1970. This window is selected since as the as fallout deposition events become more temporally distant other factors may affect patterns of mortality in a given region.

[11] Deaths by age and thus age adjusted mortality is not available at the county level until 1959. This is when individual level death certificates containing age information become available.

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

Demographic and weather data

Demographic characteristics of an area can proxy for relevant factors that affect mortality (Chay et al., 2003). Therefore, I include additional demographic information such as race, education, income, and population from decennial censuses come from (Haines, 2010). Since weather events such as temperature can affect mortality (Barreca et al., 2016), estimated fallout from nuclear testing is in part derived from meteorological records: some specifications include monthly temperature averages and precipitation controls derived from the National Oceanic and Atmospheric Administration's Global Historic Climatology Network (Lawrimore et al., 2011).

III Empirical Effects of NTS Fallout

Event study of initial radiation deposition event

In this section I study how the initial and sudden arrival of a large amount of fallout in a county affects patterns in mortality in subsequent years. First I present the results for a simple differences and differences model with a pre and post treatment period. I then flexibly compare the evolution in mortality across single years in an event study. I define the threshold event as the first year a county in the sample experiences NTS fallout exceeding the median deposition amount across all testing years. This threshold is defined as 303 nCi of i-131 per m^2.[13] Figure 4 presents the average cumulative sum of i-131 deposition across years. It is plotted against the timing of when the median deposition threshold is first exceeded. There is a discrete jump in average cumulative deposition in counties after the threshold event is first exceeded. The initial fallout deposition events are on average 702 nCi per m^2. The cumulative deposition from

[13] Fallout occurred over multiple years during the 1950s and the NCI estimates that most counties in the U.S. experienced non-negligible levels of iodine-131 deposition. Some locations, primarily west of the NTS, received little deposition while many areas east of the NTS experienced multiple deposition events. Most counties in the sample eventually exceed this threshold. In total 2,801 counties in the sample exceed the threshold. Only 148 counties, mostly in states on the west and gulf coasts, do not exceed the deposition event threshold. In 1951 170 counties first exceeded the threshold, 1276 counties in 1952, 760 in 1953, 85 in 1955, and 510 in 1957.

previous years ranges from zero to 1001 nCi.[14]

$$y_{it} = \Sigma_{r=-5,r\neq-1}^{10}\phi_r * DE_{ir} + \lambda * P_{it} + \theta * A_{it} + X_{it}\beta + W_{it}\omega + \alpha_i + \gamma_t + \epsilon_{st} \quad (1)$$

Equation 1 describes the full specification of the event study regression. y_{it} denotes mortality per 1,000 people in a given county i and year t for a specific cause of death. I explore the relationship between the initial arrival of a large quantity of fallout and mortality from all-causes and cancer.[15] I use deaths from motor vehicle accidents and influenza/pneumonia as a falsification exercise to address since radiation exposure is plausibility not associated with vehicular accident or increased incidences of infectious disease.

DE_{ir} denotes a set of indicator variables that take the value one if year t is r years relative to the threshold fallout deposition event.[16] The excluded reference year is the year prior, t-1, to the threshold event. There are four indicator variables for the years leading up to the event and eleven indicator variables for years after fallout has exceeded the threshold event. Identification of the ϕ coefficients comes from differences in the timing of initial fallout deposition between counties that have and have not yet exceeded the threshold. Some counties experience threshold exceeding fallout events earlier that others.

To isolate the pure effect of the threshold deposition event from prior and subsequent fallout deposition events, I control for cumulative fallout deposition in the years leading up to the threshold event, P_{it}, and cumulative fallout deposition years after

[14]The 25th, 50th, and 75th percentiles for these initial threshold events are 395 nCi, 549 nCi, and 1501 nCi. The cumulative deposition from previous tests is on average 202 nCi. The 25th, 50th, and 75th percentiles are 10 nCi, 106 nCi, and 307 nCi.

[15]For each event timing group for I fit a pretrend adjustment according to methodology described in Goodman-Bacon (2021) for all-cause mortality and cancer mortality variables used in the event study. In the appendix I present results from the Goodman-Bacon decomposition to show there the identifying variation for the differences in differences coefficient comes from. The majority of the identifying variation comes from comparisons between fallout deposition events in 1951 and 1952 with counties that exceed the threshold later in the decade.

[16]I pool event study years t-6 and earlier into a single variable and event study years t+11 and later into a single coefficient.

the threshold event, A_{it}.[17] X_{it} is a vector of interpolated demographic and economic controls. These include the share of county population that is white, share of the population with high school degrees or higher, share of the population in an urban area, and the log of the median household income.[18] 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.[19] The year fixed effects account for unobserved annual shocks shared across counties. The variable ϵ_{st} denotes the heteroskedastic error term. To address potential effects in spatial correlation in fallout deposition, I cluster the standard errors at the state level.[20]

Table 2 presents the results of a simple differences in difference model where years t-1 and earlier are pooled into a pre-period and years t+0 and later are pooled into a single post-period. Specification (1) reports the effect of crossing the threshold on all-cause mortality. Specification (2) presents the effect for cancer mortality. Specifications (3) and (4) present the results for deaths from motor vehicle a and influenza/pneumonia. The initial crossing of the fallout deposition threshold is associated with an increase in all-cause mortality of 0.293 deaths per 1,000 residents and is statistically significant at the 1% level. Cancer mortality increases by 0.037 deaths per 1,000 residents and is also statistically significant at the 1% level. The coefficients for deaths from automobile accidents, 0.013, and influenza/pneumonia, 0.002, are small in comparison and statistically insignificant.

Figures 5 and 6 present regression coefficient plots for the threshold event study for all-cause mortality and cancer mortality. The dashed lines denote the 95% confi-

[17] The empirical results are robust to the inclusion and exclusion of these controls.

[18] Household income is first reported in 1950. Values for 1946-1949 are extrapolated from the 1950 to 1960 trend

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

[20] The agriculture and climate change literature commonly uses state clustering to account for spatial correlation in weather data and the results are generally equivalent to standard error adjustments done according to Conley (1999) (Deschênes and Greenstone, 2007). In the appendix I present standard errors correcting for special correlation.

dence interval for each of the event study coefficients. Tables reporting the regression coefficients and standard errors and differences in specification are provided in the appendix. All the coefficients for all-cause mortality and cancer mortality are jointly significant. Relative to the year prior to crossing the fallout deposition threshold, mortality rates increase year after year until four or five years after testing and then proceed to decline. The coefficients for cancer mortality range from 0.027 to 0.078 additional cancer deaths per 1,000 residents with an average coefficient size of 0.058. The increase in all cause mortality ranges from 0.120 to 0.345 additional deaths per 1,000 with an average coefficient size of 0.257. The associated increase in all-cause mortality for exceeding the fallout threshold is approximately 4.4 times greater than the increase in cancer mortality alone. Back of the envelope calculations suggest that the arrival of the first large fallout shock resulted in approximately 80,900 additional cancer deaths and additional 359,600 deaths from all-cause.[21]

In contrast to the patterns observed for cancer and all-cause mortality, deaths from motor vehicle accidents and influenza/pneumonia do not show a significant change in mortality following the initial arrival of a large radiation shock. Figures 7 and 8 present no discernible relationship between crossing the i-131 threshold and mortality from auto accident or influenza/pneumonia. This result suggests that mortality associated with causes such as automobile usage or infectious disease are not causing the increase in all-cause mortality and that the observed increases in mortality resulting from nuclear testing is not driven by an underlying trend in mortality.

IV Effects of Cumulative Radiation Exposure

The purpose of the event study is to test if areas that experienced substantial deviations in fallout experienced statistically significant deviations in mortality. The deposition threshold event does not necessarily account for the health effects of previous deposition events below the threshold. To account for the marginal effect of fallout

[21]This calculation multiplied each statistically significant coefficient by the shock indicator and by population and sums up the total number of deaths.

deposition across time, I use pooled averages of historical deposition in a difference in differences framework with a continuous treatment. This allows me to first measure if fallout events below the threshold are associated with changes in mortality. Second, this model lets me measure the temporal persistence of these changes in mortality.[22] I expand the sample to 1980 so that all nuclear tests in the data contribute to the estimation of the lagged coefficients.

$$y_{it} = \Sigma_{j=0}^{4} \theta_j Avg\_E_{it,j} + X_{it}\phi + W_{it}\omega + \alpha_i + \gamma_t + \epsilon_{it} \tag{2}$$

Equation (2) describes the distributed lag specification for the long-run panel regressions. This model uses the same variables that are in Equation 1, but the measure of interest consists of lagged five year averages of the iodine-131 deposition measure.[23] 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. Using lagged five year averages measures the temporal extent to which fallout affects mortality. This model uses variation in average fallout deposition one to five years prior, six to ten years prior, eleven to fifteen years prior, and sixteen to twenty years prior prior to identify the temporal extent to which fallout affected mortality patterns. Identification comes from comparisons in annual mortality between counties more exposed to fallout relative to counties less exposed to fallout. The hypothesis being that areas with greater amounts of fallout during a five year lag would experience greater deviations in mortality than areas that experienced less fallout deposition.[24]

[22] I pool the lagged deposition measures to limit the profusion of coefficients in the regression model and address potential serial correlation in fallout deposition events in counties.

[23] y_{it} mortality per 1,000 people in a given county i and year t. X_{it} is a vector of interpolated demographic and economic controls measuring the share of county population in 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. A vector of twelve monthly precipitation total and twelve average monthly temperatures controls represented by W_{it}. The variables α_i and γ_t denote county and year fixed effects.The variable ϵ_{it} denotes the heteroskedastic error term and is clustered at the state level. The sample is expanded until 1980 so that all of the atmospheric nuclear tests in the sample provide identifying variation for each of the lags.

[24] One caveat, 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. There is no strong a priori reason to believe that fallout deposition is system-

The results for all-cause rates and cancer death rates are presented in Table 3. Both the all-cause rate and cancer death rate increase in counties with more deposition relative to those with less deposition and that these increases in mortality may persist up to fifteen years after the fallout occurs. Specifications (1) and (5) presents the results only using year and county fixed effects for all-cause and cancer mortality respectively. Specifications (2) and (6) present present the specifications using monthly weather controls and demographic controls from decennial censuses. Specifications (3) and (7) exclude counties that are defined as "Downwind" by the U.S. Justice Department for the purposes of the Radiation Exposure Compensation Act (RECA). These are the areas that experienced radioactive dust blows, flashes of light, and sonic booms that could destroy windows. It is plausible that people in these areas might have migrated or engaged in avoidance behaviors in response to NTS activities. Figure 9 presents a map of this region.[25] Specifications (4) and (8) include quadratic terms from the measures of fallout deposition. The primary model used to estimate cancer risks from ionizing radiation is called the linear-no-threshold model (LNTM) (National Research Council, 2006; Brenner et al., 2003). The LNTM states that risk of cancer death increases linearly with radiation exposure.

In all specifications increases in average fallout deposition 1 to 5 years prior is associated with increases all-cause and cancer mortality that are statistically significant at the 5% level. The coefficients for all-cause mortality range from 0.272 to 0.566 deaths per 1,000 nCi. The coefficients for cancer mortality range from 0.060 to 0.122 deaths per 1,000 nCi. The exclusion of RECA Downwind counties increase the magnitude of the of the implied mortality effect. The inclusion of a quadratic term suggests that the mortality response to i-131 deposition is non-linear. This evidence is in opposition to

atically correlated with underlying migration patterns in such a way that it would affect underlying patterns in county mortality. In the appendix I test whether or not migration prior to nuclear testing or measures of population are correlated with fallout deposition and find little evidence suggesting that fallout is correlated with underlying trends in population or migration. I also examine if fallout is systemically correlated with population characteristics and test if differences in average state level radiation deposition is correlated with migrant characteristics.

[25]According to RECA, only persons living in twenty-two counties during the periods of testing can be considered living "Downwind" of the NTS.See `https://www.justice.gov/civil/common/reca` for more details on RECA.

the LNTM and suggests that low-levels of ionizing radiation exhibit a convex shape. Fallout deposition 6 to 10 years prior has a statistically significant effect on all-cause mortality in specification (4) and cancer mortality in specifications (5) and (6) at the 10% level. Including a quadratic term increases the size of the effect fallout has on cancer deaths 1 to 10 years after deposition occurs.[26] When clustering at the county level there is not a strong statistically significant relationship between mortality 11 to 15 years after deposition in the sample. For years 16 to 20 after deposition there appears to be statistically significant and negative relationship between average deposition and cancer mortality in specifications (5) and (6). The exclusion of downwind counties, accounting for non-linearity in dose response, or weighting the regressions by county population removes this relationship. The number of deaths resulting from one to ten years after deposition using the statistically significant coefficients range from 90,700 to 279,900 for all cause mortality and 21,100 to 58,400 for cancer mortality.

Table 3 presents alternative specifications for both all-cause and cancer mortality. Alternative specifications accounting for spatial correlation in the standard errors with a 200 kilometer cut off, (1) and (5), show that clustering at the state level provides more conservative estimates of standard errors. Weighting by population, (2) and (6), increases the size of the reported coefficients. Using the natural log of mortality rates suggests that a one standard deviation increase in i-131 deposition, 175 nCi, increases all-cause and cancer mortality approximately by 0.560 and 0.577 percent 1 to 5 years after fallout deposited. Controlling for the underlying age structure of the counties, specifications (4) and (8) does not substantially alter the estimates.

Table 5 presents results for other causes of mortality that should be unrelated to i-131 deposition. These causes in death are the results of lifestyle behaviors or infectious diseases that should be uncorrelated with deaths due to radiation exposure. These include deaths from motor vehicle accidents, deaths from infections diseases, and deaths would be associated with diet or lifestyle. The table shows there is no

[26]The specification (4) coefficients suggest the all-cause mortality increases until the average reaches 3,800 nCi for t-1/t-5 and 2,600 nCi for t-6/t-10. Only 26 counties have an five year average that exceeds 2,600 nCi and are all in Nevada and Utah. For cancer mortality, mortality risk is increasing until 3,800 nCi for t-1/t-5 and 3,300 nCi for t-6/t-10.

discernible statistically significant relationship between deaths from motor vehicle accidents, tuberculosis, or diabetes an fallout. Influenza and pneumonia deaths are negatively associated with radiation deposition t-6 to t-20 years after fallout appears, but this result disappears when weighing counties by population.[27] Selective migration of people with worse underlying health characteristics and risks into more irradiated county could pose a challenge to the identifying assumptions of the model. I find little evidence that people with greater risks of dying from diabetes or respiratory illnesses is correlated with fallout deposition.

V Policy Implications of NTS Activities

Social Costs of the Nevada 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 1990s 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 1950s. 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.[28]

The results from the long-run panel regressions suggest that fallout resulting from atmospheric tests conducted in Nevada from 1951 to 1958 led to statistically significant increases in both overall mortality and cancer mortality. These increases in mortality persist at least ten years after fallout landed in a region. Since small amounts of fallout were broadly distributed in the United States during the period of testing, the

[27] Alternative specifications tests using weights and sample restrictions are in the appendix

[28] See https://www.justice.gov/civil/common/reca for more details on RECA.

empirical results suggest that the public health effects of atmospheric nuclear testing are broader than that suggested by researchers focusing on populations surrounding the testing locations.

The number of excess deaths attributable to the initial large i-131 deposition event is approximately 359,600 over a ten year period. The number of cancer deaths associated with the initial fallout shock is approximately 80,900 over a ten year period. Using a continuous lagged measures of i-131 deposition over five year windows suggest a lower mortality burden. The models that account for non-linearity in the mortality response to i-131, I find that nuclear testing contributed towards an additional 279,900 all-cause and 58,600 cancer deaths over a ten year window.[29] In comparison, estimates from Simon and Bouville (2015) suggest that nuclear testing at the NTS resulted in approximately 49,000 additional cases of thyroid cancer and up to 12,000 deaths from other cancers.[30] If we assumed all the thyroid cancer cases resulted in death, then the implied increase in all-cause (cancer) mortality from the event study is 5.89 (1.33) times greater than what the National Cancer Institute's values. For the model using pooled averages of fallout deposition the values are 4.59 (0.96) times that for all-cause (cancer) mortality. 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\$. Using their values, I estimate the value of total life lost from ground deposition between \$447.8 billion and \$3,308 billion. For cancer specific deaths, the values range from \$93.8 billion to \$744.3 billion.

While fallout attributable deaths are substantial in magnitude, deaths attributable to outdoor air pollution (e.g. PM2.5 and ozone) far exceed that which can be attributed to NTS fallout. Recent estimates on the mortality burden of outdoor air pollution in

[29] This calculation uses coefficients specification (4) and (8) in Table 3. I multiplied statistically significant coefficients by iodine-131 deposition values and population.

[30] The authors estimate that 400,000 cases of thyroid cancer would emerge naturally in the decades after nuclear testing. Thyroid cancer has a low mortality rate relative to other forms of cancer. They stress there are large uncertainties with these estimates.

the U.S. by Dedoussi et al. (2020) suggest that air pollution contributes to tens of thousands of deaths a year. The authors find that outdoor air pollution contributed towards 96,600 deaths in 2005, 83,000 in 2011, and 66,100 in 2018. Other estimates on the annual number of deaths attributable to air pollution in the U.S. range between 90,000 to 360,000 per year.

Alternative Testing Locations

The decision to commence continental nuclear testing came as a result of a "national emergency" brought about by political events during the early Cold War. Both the AFSWP and AEC concluded in 1950 that the United States needed to accelerate and expand the scale of its testing program. Project Nutmeg suggested test sites either in the Southwestern U.S. or off the mid-Atlantic coast to minimize the risk fallout would disperse into populated areas. To assess the relative pollution exposure risks associated with alternative test sites, I use Nicholas Muller's AP2 model. Using this model I estimate the cumulative effect a one unit increase in air particulate emissions, PM2.5, from a single source county has on ambient air particulate levels in all other counties in the U.S.. For all counties other than the source county, I weight weight the marginal increase in air particulate exposure by county population in 1950 and sum the cumulative effect for all of the 3,100 potential source counties.

Table 6 presents the list of potential counterfactual counties and counties that would have the least air particulate spillovers according to AP2. I normalize the are particulate spillovers relative to the NTS/Nye County, NV. If policy makers sought to minimize human exposure to fallout, then the location of the NTS is quite fortunate. According to AP2, the NTS ranks 39th out of 3,100 counties. The next contender for continental nuclear testing is the Alamogordo/White Sands Proving grounds. This is the location of the 1945 Trinity atomic test. This location was rejected due to the proximity of Albuquerque, NM (Fehner and Gosling, 2000). According to AP2, this location choice would have roughly resulted in 2.232 times the level of human exposure to fallout. Dugway Proving Grounds in Toole County, UT was another contender and was not selected because it was too proximate to Salt Lake City, UT. Alternative test locations in North Carolina and Texas were also inferior alternatives to the NTS. A few counties in the Pacific Northwest, the Florida Keys, and Upstate Maine are locations that AP2 suggests would have been cleaner locations for testing than Nye, County. These results reveal that atmospheric testing in the continental U.S. could have plausibly been much worse for American populations and public health. It also suggests that policy makers at the time sought to minimize human exposure to potential radiological harms.[31]

The Partial Nuclear Test Ban Treaty

The cessation of atmospheric nuclear testing drastically reduced the release of harmful radioactive material into the air and likely saved many American 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. 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).[32]

Assuming that the domestic mortality effect of atmospheric testing is proportional to the tonnage of the weapons tests, one might estimate approximately how many American lives were saved by the moratorium period and the Partial Nuclear Test Ban

[31] One caveat, however, is that AP2 estimates the effects an increase in air particulate in one source county on ambient levels of suspended air particulate in other counties. This model does not fully account for the radioactive iodine that was scavenged due to precipitation. It was not after the cessation of atmospheric nuclear testing that the dangers of radioactive iodine scavenged by rainfall and thus entering local dairy supplies posed.

[32] 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.

Treaty. Multiplying the smallest and largest cumulative mortality effects by the ratio of the moratorium tonnage to atmospheric tonnage suggests that the moratorium possibly saved between 54,900 and 175,300 lives. Employing the same back of the envelope calculation, the Partial Nuclear Test Ban Treaty might have saved between 3 and 9.7 million American lives. These calculations have some caveats. First, it is likely that the transition to underground testing increased the size of the weapons tested. This likely would overestimate the potential effect of shifting underground testing above ground. Second, even without the moratorium and treaty, there was an increasing body of independent scientific and medical evidence suggesting that NTS activity were harmful to public safety. It is likely that atmospheric testing at the NTS would have become politically untenable as more of the negative health effects associated with atmospheric testing became realized. Finally, continuation of atmospheric testing likely would have increased repeated public exposure to radioactive fallout. This increase in average frequency of exposure might alter the point estimates identified in the panel regressions. Therefore, using the realized estimates might underestimate the potential effect of continued atmospheric testing upon mortality patterns.

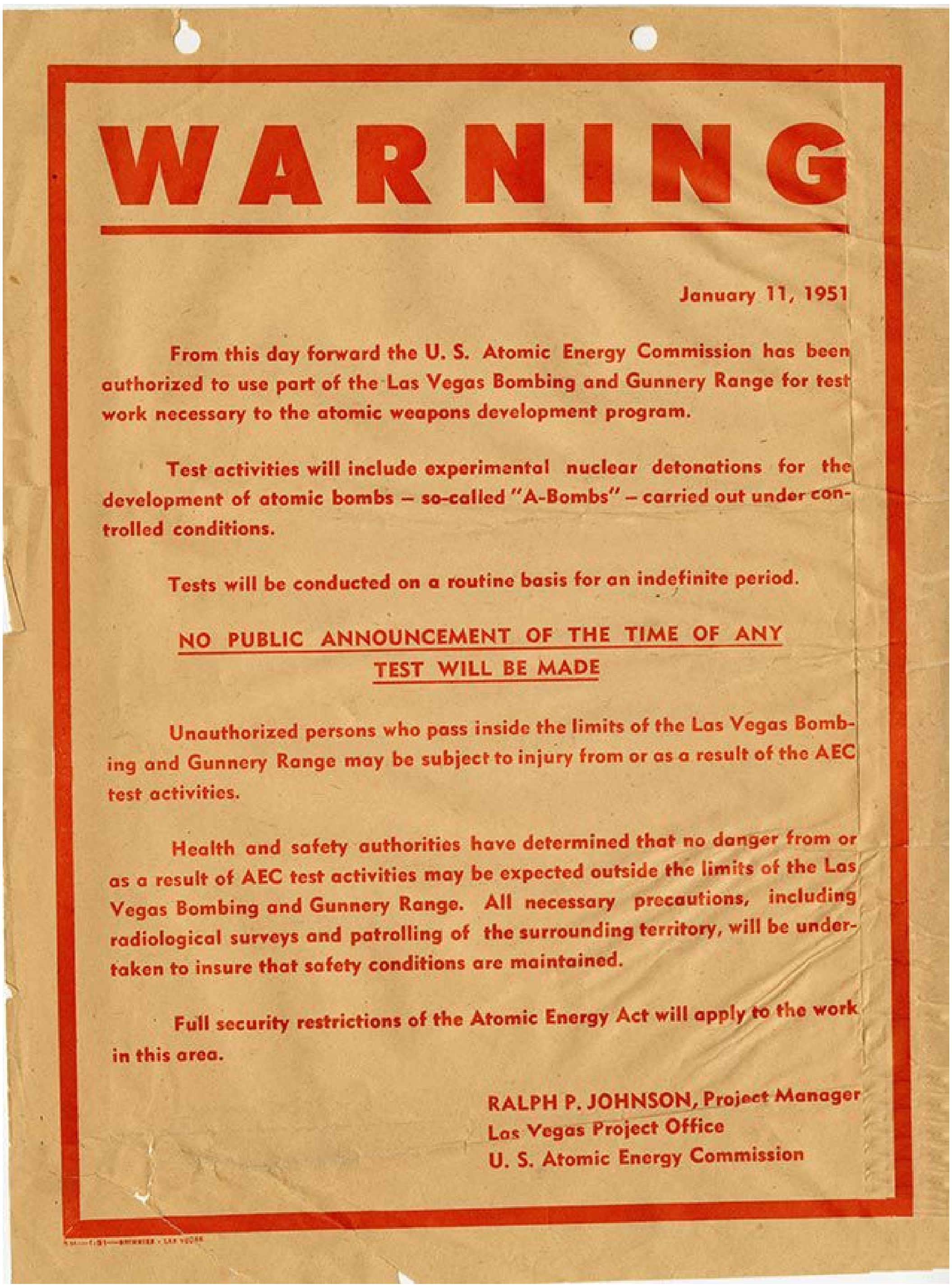
VI Conclusion

The Truman Administration's decision to perform atmospheric nuclear tests in Nevada was consequential not only for person residing near the test site but for the entire United States. The public was unknowingly and inadvertently exposed to radioactive material resulting from these tests and there was little effort to inform the public regarding these risks. At a minimum, atmospheric nuclear testing conducted from 1951-1958 at the NTS resulted in tens of thousands of premature cancer deaths. Nevertheless the adverse impact of this policy could have been much worse. Test organizers were fortunate in their choice of the NTS over Alamogordo or another alternative sites.

The suspension of atmospheric nuclear testing and signing of the Partial Nuclear Test Ban Treaty greatly reduced human exposure to radioactive pollutants. Humans are still regularly exposed to low levels of ionizing radiation through medical treatments and radon accumulation in households. An aging nuclear energy infrastructure and uncertain risk with nuclear power plant accidents as present a potential risk for human exposure to ionizing radiation. As the effects of climate change become more acute there is a renewed interest in civilian nuclear power generation as a means of reducing greenhouse gas emissions. Disasters such as Three Mile Island, Chernobyl, and Fukashima-Daiichi show that the risks of unintentional releases of radioactive pollutants are non-zero.

Finally, large stockpiles of nuclear weapons and nuclear proliferation present ever present existential risks and nontrivial threats of potential radiation exposure. During the 20th Century many of the agreements regulating the development and deployment of nuclear weapons have lapsed. The trend started with the George W. Bush Administration's withdrawal from the Anti-Ballistic Missile Treaty in 2002. Efforts reduce nuclear stockpiles and combat nuclear weapons proliferation through the New START treaty and the Joint Comprehensive Plan of Action with Iran under the Obama Administration were threatened or reversed under the subsequent Presidential administration. The expiration of the Intermediate-Range Nuclear Forces Treaty in 2019 signifies a further degradation of the arms control infrastructure.

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. The U.S.'s historic experience with nuclear weapons testing highlights how policy decisions made in haste can have tremendous unintended consequences. Approximately 160 million Americans lived through the period of atmospheric nuclear testing and were exposed to nontrivial quantities of radioactive pollutants (Simon and Bouville, 2015). This paper finds that fallout resulting from nuclear testing in Nevada affects an extreme measure of human capital. It is plausible that the consequences of this weapons testing program had and continues to have persistent consequences for health, wealth, and human welfare.



WARNING

January 11, 1951

From this day forward the U. S. Atomic Energy Commission has been authorized to use part of the Las Vegas Bombing and Gunnery Range for test work necessary to the atomic weapons development program.

Test activities will include experimental nuclear detonations for the development of atomic bombs – so-called "A-Bombs" – carried out under controlled conditions.

Tests will be conducted on a routine basis for an indefinite period.

NO PUBLIC ANNOUNCEMENT OF THE TIME OF ANY TEST WILL BE MADE

Unauthorized persons who pass inside the limits of the Las Vegas Bombing and Gunnery Range may be subject to injury from or as a result of the AEC test activities.

Health and safety authorities have determined that no danger from or as a result of AEC test activities may be expected outside the limits of the Las Vegas Bombing and Gunnery Range. All necessary precautions, including radiological surveys and patrolling of the surrounding territory, will be undertaken to insure that safety conditions are maintained.

Full security restrictions of the Atomic Energy Act will apply to the work in this area.

RALPH P. JOHNSON, Project Manager
Las Vegas Project Office
U. S. Atomic Energy Commission

Figure 1: 1951 AEC Flyer Source: Nevada National Security Site Nuclear Testing Archive

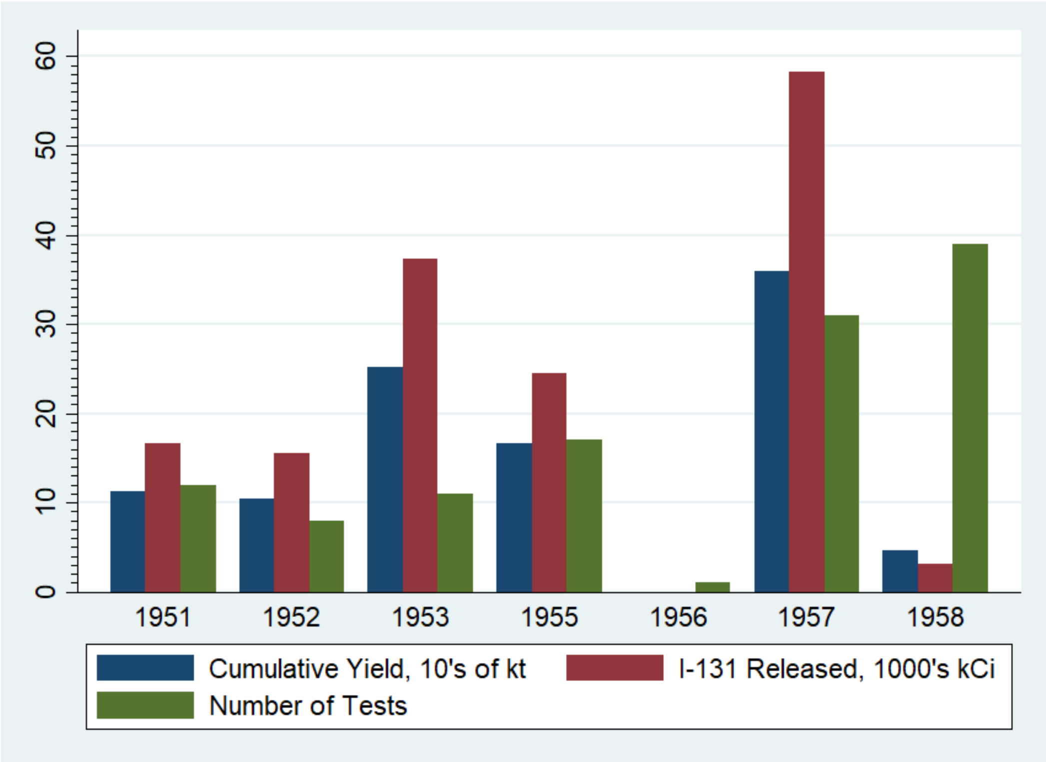


Figure 2: Annual Cumulative Atmospheric Yields, Atmospheric iodine-131 Releases, and Number of Tests for the NTS, 1951-1958. Source: Created from National Cancer Institute (1997) records.

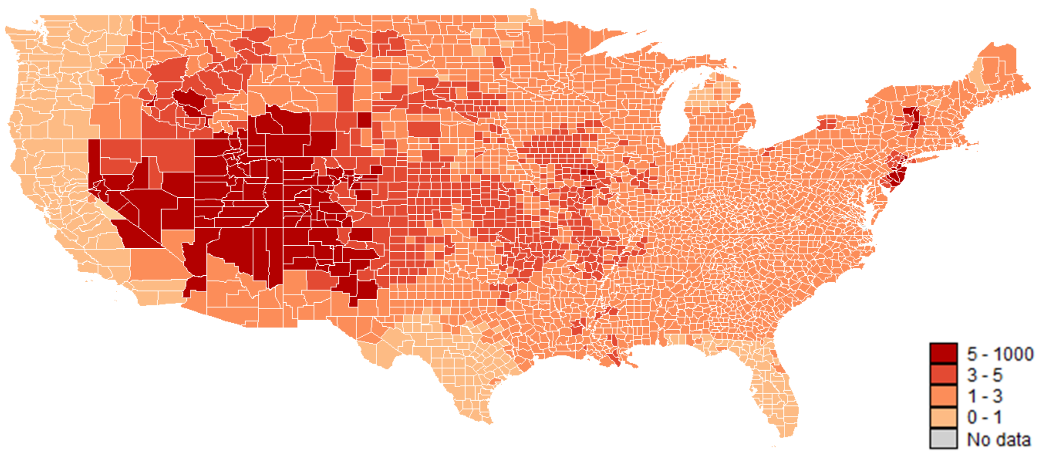


Figure 3: Cumulative Radioactive iodine-131 Deposition per m^2 for NTS Atmospheric Tests conducted from 1951-1958. Source: Created from National Cancer Institute (1997) records.

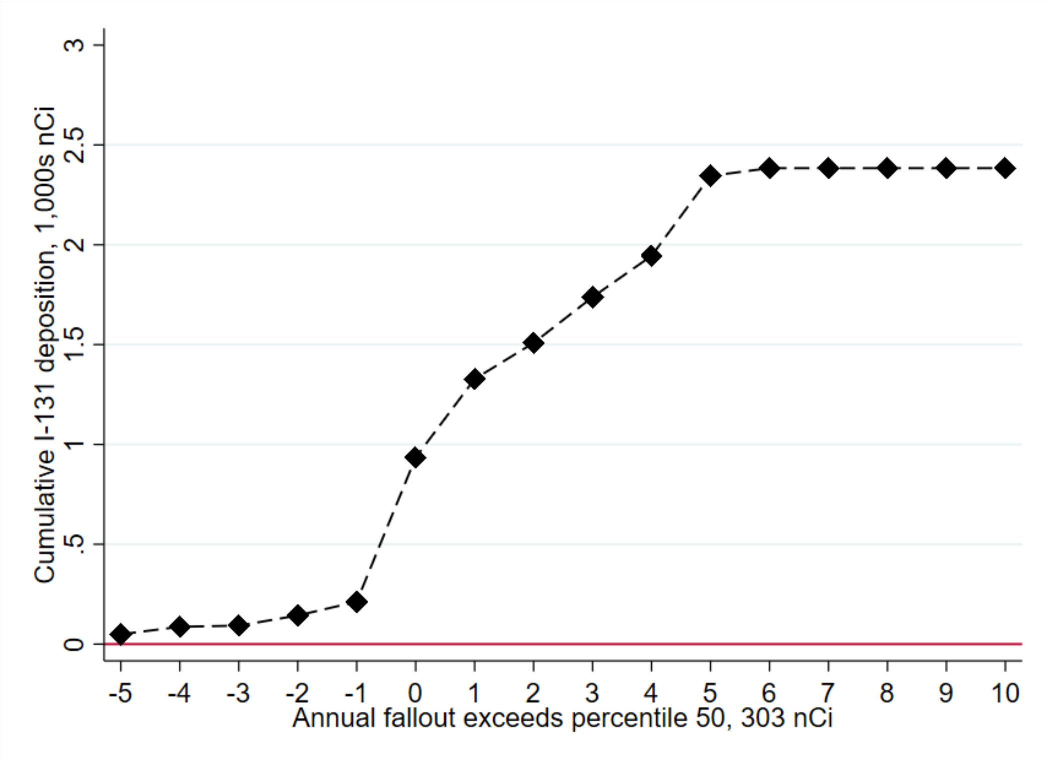


Figure 4: Average cumulative iodine-131 deposition relative to the time median deposition threshold is first exceeded Source: Author's calculation

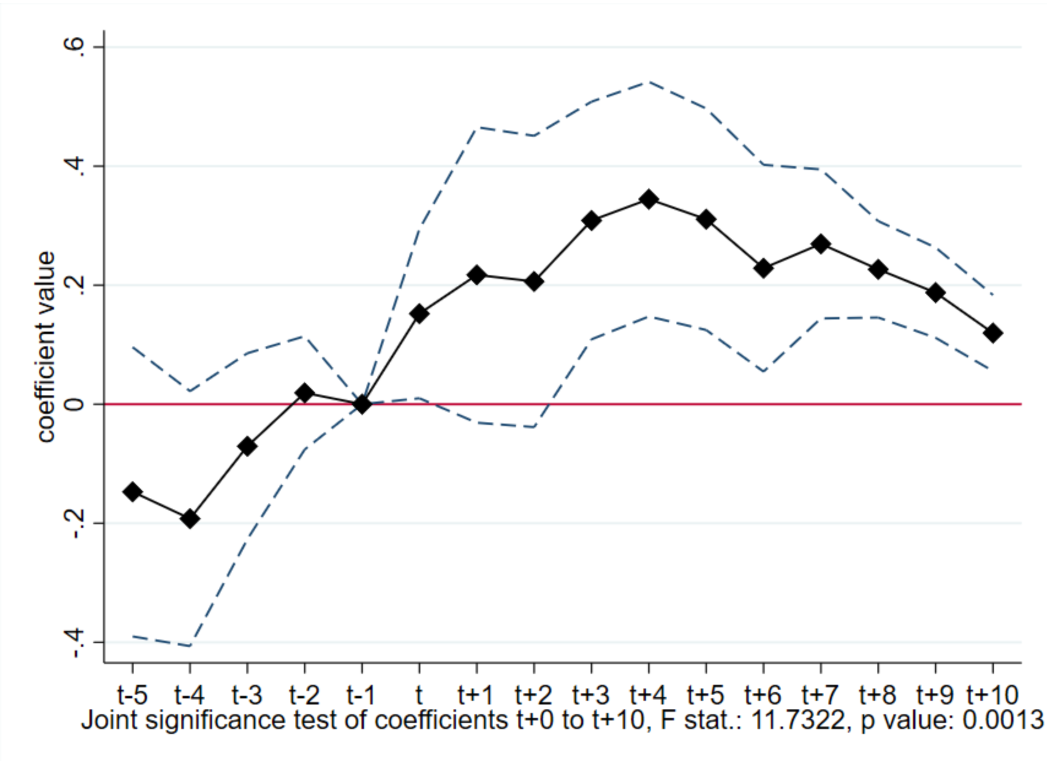


Figure 5: Fallout threshold coefficients and 95%CI , all-cause death rate per 1,000. Source: Author's calculation.

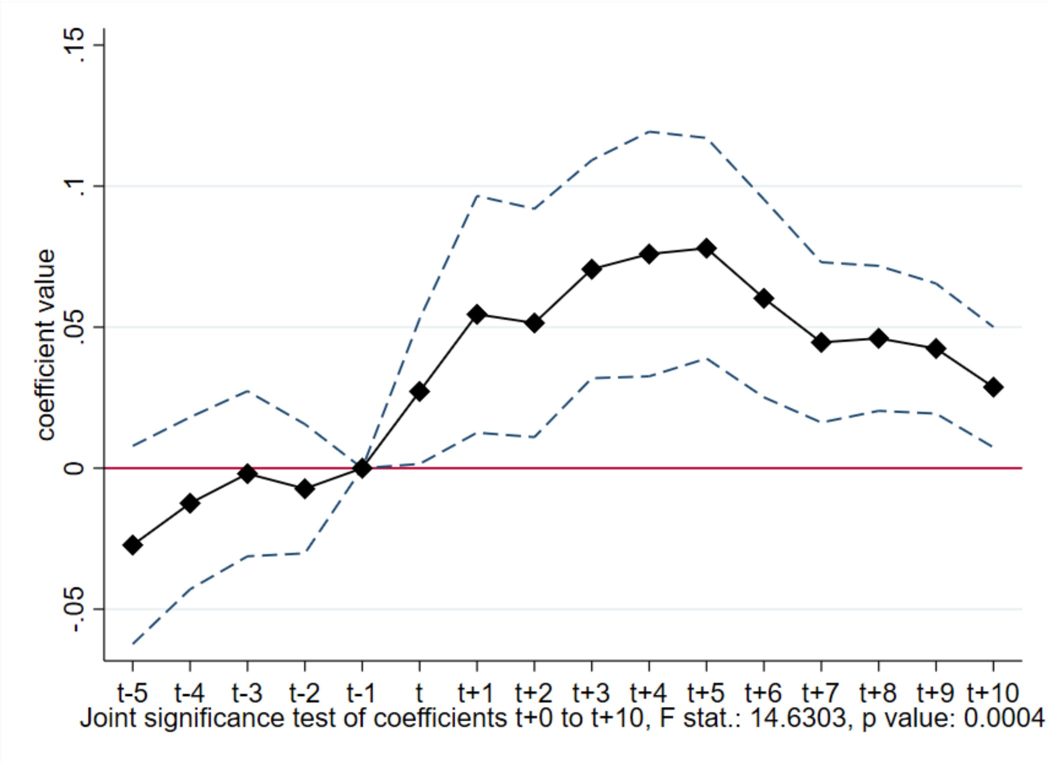


Figure 6: Fallout threshold coefficients and 95%CI , cancer death rate per 1,000. Source: Author's calculation.

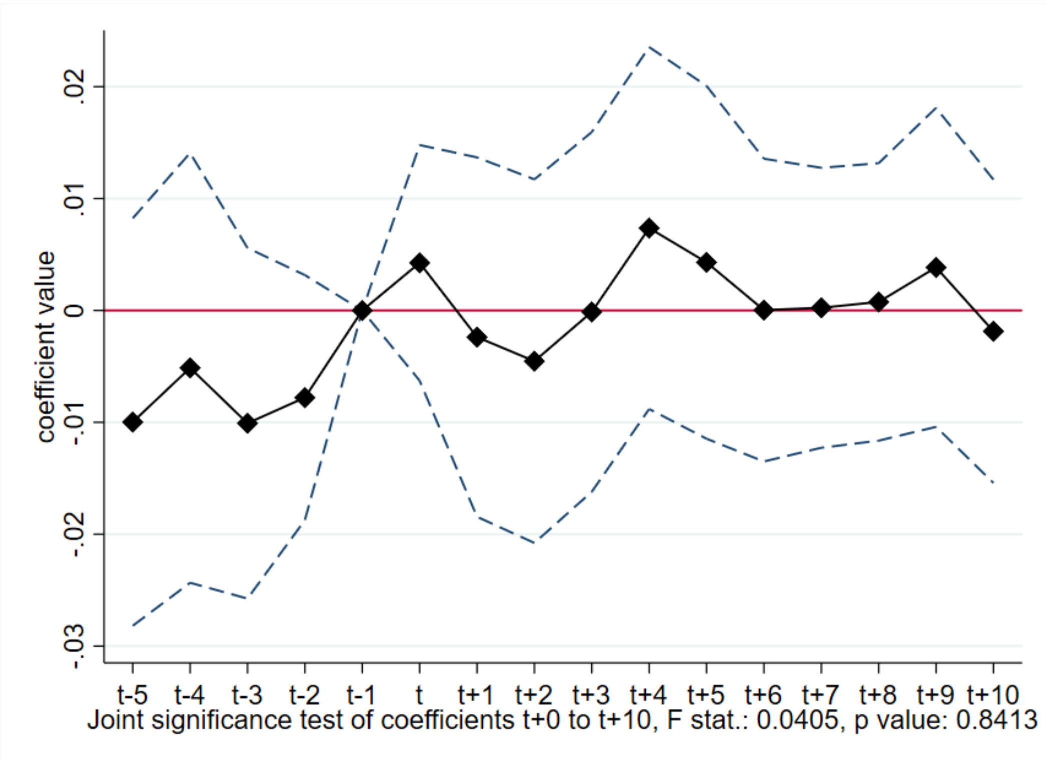


Figure 7: Fallout threshold coefficients and 95%CI , motor vehicle death rate per 1,000. Source: Author's calculation.

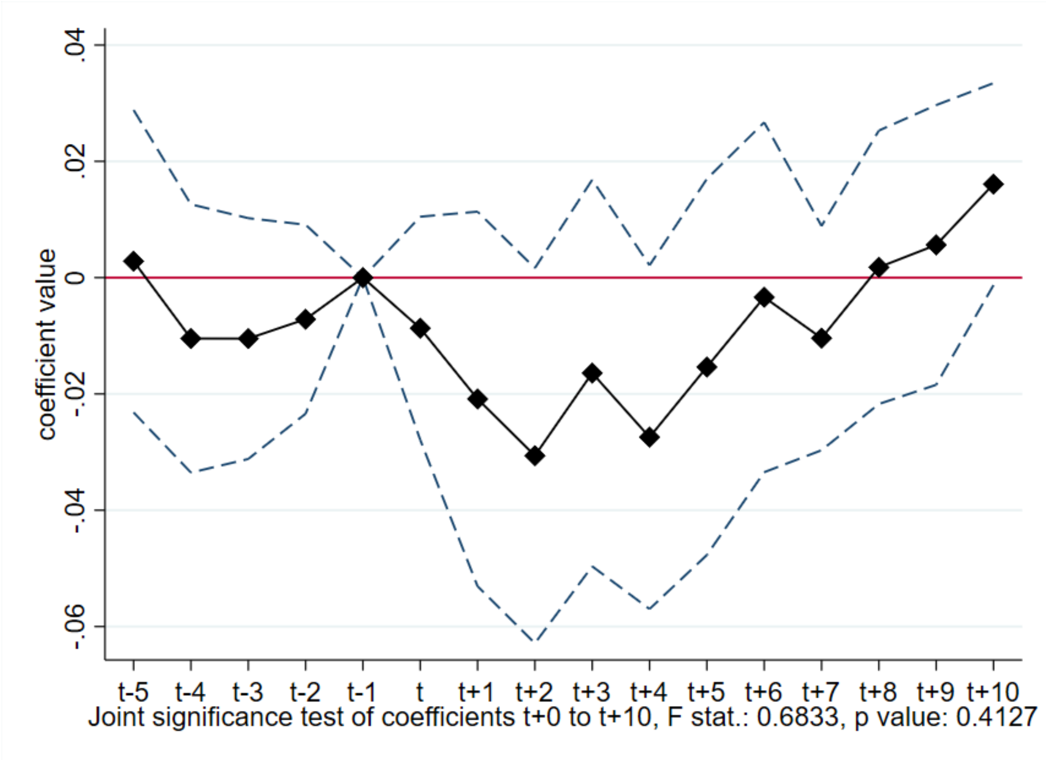


Figure 8: Fallout threshold coefficients and 95%CI , influenza/pneumonia death rate per 1,000. Source: Author's calculation.

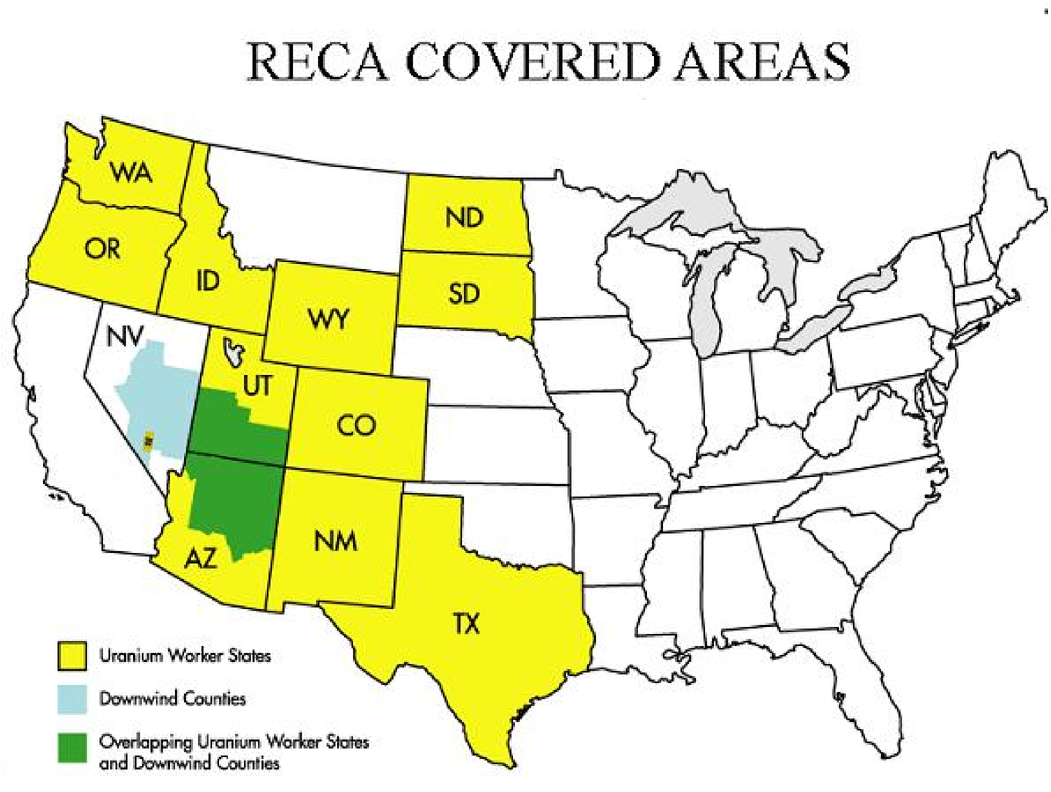


Figure 9: Radiation Exposure Compensation Act regions. Source: U.S. Department of Justice.

Table 1: Summary statistics

Variable	**Mean**	**Std. Dev.**	**Min.**	**Max.**	**N**
all-cause mortality per 1,000	10.04	2.449	0.88	56.487	103215
cancer mortality per 1,000	1.502	0.578	0	8.586	103215
motor vehicle mortality per 1,000	0.329	0.22	0	3.072	103215
tuberculosis mortality per 1,000	0.076	0.146	0	5.534	103196
influenza/pneumonia mortality per 1,000	0.357	0.242	0	15.537	103196
diabetes mortality per 1,000	0.18	0.15	0	12.77	103196
i-131 deposition, 1000s nCi per m^2	0.065	0.323	0	43.916	103215
avg. five year i-131 dep., 1000s nCi per m^2	0.065	0.175	0	10.583	103215
population	55911.413	196180.436	1090	7477503	103215
percent population white	0.638	0.32	0.002	1	103215
percent population with high school degree	38.863	15.279	3.7	90.400	103215
percent population in urban area	0.321	0.274	0	1	103215
ln(median household income)	8.478	0.73	3.109	10.275	103215

Table 2: Effect of initial fallout threshold event on mortality rates per 1,000 residents, 1946-1970

	(1) All-Cause	(2) Cancer	(3) Motor Vehicle	(4) Flu/Pneumonia
post threshold	0.293***	0.037***	0.013	0.002
	(0.082)	(0.013)	(0.009)	(0.009)
year FE	Yes	Yes	Yes	Yes
county FE	Yes	Yes	Yes	Yes
weather controls	Yes	Yes	Yes	Yes
U.S. Census controls	Yes	Yes	Yes	Yes
N	73725	73725	73725	73706
adjusted $r2$	0.813	0.745	0.187	0.255

1. Standard errors in parentheses clustered by the state level. Sample is fully balanced panel of 2,949 county equivalent units. Weather controls include monthly precipitation totals and temperature averages for each county and year. U.S. census controls include linearly interpolated measures from decennial censuses. These include share of population white, share of population with high school degree, and median household income. Median household income for 1946 to 1949 is extrapolated from the 1950 to 1960 trend since the 1940 census only reports wage income.
2. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Table 3: Long-run relationship between all-cause and cancer mortality per 1,000 residents and iodine-131 deposition, 1946-1980

	All-Cause Mortality				Cancer Mortality			
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	Base	Full	No-DW	Squared	Base	Full	No-DW	Squared
Avg. dep, t-1/t-5	0.282**	0.272**	0.430***	0.566***	0.066***	0.060***	0.088***	0.122***
	(0.138)	(0.112)	(0.148)	(0.133)	(0.023)	(0.019)	(0.032)	(0.027)
Avg. dep, t-6/t-10	0.158	0.112	0.254	0.341*	0.039*	0.033*	0.040	0.067**
	(0.156)	(0.120)	(0.171)	(0.189)	(0.022)	(0.019)	(0.030)	(0.029)
Avg. dep, t-11/t-15	0.053	0.086	0.269	0.344	0.009	0.020	0.026	0.044
	(0.161)	(0.138)	(0.204)	(0.228)	(0.023)	(0.021)	(0.032)	(0.036)
Avg. dep, t-16/t-20	-0.144	-0.026	0.092	0.159	-0.072**	-0.042*	-0.031	-0.045
	(0.199)	(0.185)	(0.293)	(0.343)	(0.029)	(0.023)	(0.038)	(0.047)
Avg. dep sq., t-1/t-5				-0.074***				-0.016***
				(0.021)				(0.003)
Avg. dep sq., t-6/t-10				-0.064**				-0.010**
				(0.030)				(0.004)
Avg. dep sq., t-11/t-15				-0.069*				-0.007
				(0.037)				(0.005)
Avg. dep sq., t-16/t-20				-0.051				0.000
				(0.051)				(0.006)
weather controls	No	Yes	Yes	Yes	No	Yes	Yes	Yes
U.S. Census controls	No	Yes	Yes	Yes	No	Yes	Yes	Yes
N	103215	103215	102410	103215	103215	103215	102410	103215
adjusted $r2$	0.651	0.681	0.681	0.681	0.533	0.548	0.546	0.548
Implied # deaths	90700	87700	137100	279900	21100	31000	39200	58648

[1] Standard errors in parentheses clustered by state. All regressions include year and county fixed effects. Sample is fully balanced with 2,949 counties per year from 1946 to 1980. Weather controls include monthly precipitation totals and temperature averages. U.S. census controls include linearly interpolated share of population white, share of population with high school degree, share of population in urban areas, and median household income. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Table 4: Alternative specifications for all-cause and cancer mortality per 1,000 residents and iodine-131 deposition, 1946-1980

	All-Cause Mortality				Cancer Mortality			
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	Spatial SE	Pop. weights	ln(mortality)	Age controls	Spatial SE	Pop. weights	ln(mortality)	Age controls
Avg dep., t-1/t-5	0.272***	0.343**	0.032**	0.243**	0.060***	0.079***	0.033**	0.055***
	(0.063)	(0.130)	(0.013)	(0.103)	(0.015)	(0.027)	(0.015)	(0.017)
Avg dep., t-6/t-10	0.112**	0.201	0.015	0.094	0.033***	0.049**	0.015	0.030*
	(0.052)	(0.123)	(0.013)	(0.111)	(0.012)	(0.021)	(0.015)	(0.017)
Avg dep., t-11/t-15	0.086	0.192	0.013	0.062	0.020	0.033	0.013	0.016
	(0.058)	(0.149)	(0.014)	(0.127)	(0.013)	(0.026)	(0.016)	(0.021)
Avg dep., t-16/t-20	-0.026	0.107	0.001	-0.047	-0.042***	-0.012	-0.023	-0.044**
	(0.067)	(0.199)	(0.018)	(0.176)	(0.014)	(0.031)	(0.015)	(0.022)
weather controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
U.S. Census controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
N	103215	102410	103215	103215	103215	102410	103215	103215
adjusted $r2$	0.681	0.807	0.700	0.691	0.548	0.744	0.557	0.554

[1] Standard errors in parentheses, unless otherwise noted, are clustered by state. All regressions include year and county fixed effects. Sample is fully balanced with 2,949 counties per year from 1946 to 1980. Weather controls include monthly precipitation totals and temperature averages. U.S. census controls include linearly interpolated share of population white, share of population with high school degree, share of population in urban areas, and median household income. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

[2] Specifications (1) and (5) included standard errors correlated for spatial correlation with a cut off of 200km. Specifications (2) and (6) weight the regression by county population. Specifications (3) and (7) use the natural log of all-cause and cancer mortality as outcomes respectively. Specifications (4) and (8) controls for shares of the population in different age categories, 0/4, 5/14, 15/24, 35/44, 45/54, 55/64, 65/74, and 75+.

Table 5: Long-run relationship between other-causes mortality per 1,000 residents and iodine-131 deposition, 1946-1980

	(1) Motor Vehicle Mortality	(2) Flu/Pneumonia Mortality	(3) Tuberculosis Mortality	(4) Diabetes Mortality
Avg. dep, t-1/t-5	0.012	-0.004	0.011	0.001
	(0.010)	(0.013)	(0.010)	(0.005)
Avg. dep, t-6/t-10	0.013	-0.019**	0.006	-0.008
	(0.010)	(0.007)	(0.011)	(0.005)
Avg. dep, t-11/t-15	0.000	-0.028**	0.005	0.001
	(0.010)	(0.012)	(0.012)	(0.006)
Avg. dep, t-16/t-20	0.004	-0.029**	0.004	-0.003
	(0.013)	(0.012)	(0.015)	(0.005)
year FE	Yes	Yes	Yes	Yes
county FE	Yes	Yes	Yes	Yes
weather controls	Yes	Yes	Yes	Yes
U.S. Census controls	Yes	Yes	Yes	Yes
N	103215	103196	103196	103196
adjusted $r2$	0.184	0.234	0.444	0.180

[1] Standard errors in parentheses clustered by state. All regressions include year and county fixed effects. Sample is fully balanced with 2,949 counties per year from 1946 to 1980. Weather controls include monthly precipitation totals and temperature averages. U.S. census controls include linearly interpolated share of population white, share of population with high school degree, share of population in urban areas, and median household income. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Table 6: Ranking of alternative continental nuclear test sites using AP2 air particulate flows.

Location	**Pollution Intensity**	**Rank**
Alternative testing locations considering by AFSWP		
Nevada Test Site (Nye County), NV	1	39
Alamogordo/White Sands (Socorro County), NM	2.232	489
Dugway Proving Grounds (Tooele County), UT	4.067	1207
Camp Lejeune (Onslow County), NC	2.953	775
Cape Hatteras (Dare County), NC	2.25	495
Cape Fear (Brunswick County), NC	5.466	1686
Texas Gulf Coast (Kenedy County), TX	1.637	204
Top five lowest ranked counties		
Modoc County, CA	0.261	1
Lake County, OR	0.315	2
Monroe County FL	0.315	3
Klamath County, OR	0.409	4
Del Norte County, CA	0.409	5

1. Parameters for the AP2 model were graciously provided by Nicholas Muller (Carnegie Mellon University). Ranking was done by multiplying all county to county flows of air particulate, PM2.5, in the AP2 model with population in 1950 and summing up the cumulative values. Rank denotes order of least polluting counties 1 to 3,100. Pollution intensity denotes population weighted PM2.5 exposure for all recipient counties relative to the effect of increased PM2.5 emissions from Nye County/NTS. The location of the alternative test site is excluded from the calculation.

2. Locations for alternative test sites were taken from Fehner and Gosling (2000) and the memorandum authorizing continental nuclear testing signed by President Harry Truman on December 18, 1950 (Executive Office of The President, 1950). I selected the least populated Texas Gulf County since no specific location was given in the text.

3. The worst ranked locations were all in the vicinity/boroughs of New York City, the most populated location in the United States.

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A1 Robustness and alternative specifications

1 Threshold event study coefficients and alternative specifications

Table A1: Event study coefficients all-cause deaths per 1,000, 1946-1970

	(1) Base	(2) Weather	(3) Full	(4) No Downwind	(5) NoPrePost
$t \leq -6$	0.030	-0.053	-0.243	-0.227	-0.100
	(0.184)	(0.178)	(0.181)	(0.181)	(0.175)
t-5	0.009	-0.047	-0.147	-0.139	-0.024
	(0.132)	(0.118)	(0.121)	(0.121)	(0.123)
t-4	-0.058	-0.113	-0.192^{*}	-0.181^{*}	-0.072
	(0.112)	(0.103)	(0.106)	(0.108)	(0.116)
t-3	-0.032	-0.023	-0.071	-0.066	0.039
	(0.086)	(0.078)	(0.078)	(0.078)	(0.091)
t-2	-0.035	0.038	0.019	0.029	0.118^{**}
	(0.052)	(0.054)	(0.047)	(0.048)	(0.055)
t-1	0.000	0.000	0.000	0.000	0.000
	(.)	(.)	(.)	(.)	(.)
t=0	0.001	0.112^{*}	0.152^{**}	0.167^{**}	0.188^{***}
	(0.066)	(0.066)	(0.071)	(0.078)	(0.060)
t+1	0.040	0.133	0.217^{*}	0.226^{*}	0.158^{**}
	(0.113)	(0.106)	(0.123)	(0.130)	(0.060)
t+2	0.068	0.103	0.206^{*}	0.212	0.128^{**}
	(0.109)	(0.108)	(0.122)	(0.126)	(0.057)
t+3	0.178^{*}	0.210^{**}	0.309^{***}	0.310^{***}	0.215^{***}
	(0.104)	(0.091)	(0.099)	(0.100)	(0.057)
t+4	0.170^{*}	0.260^{***}	0.345^{***}	0.338^{***}	0.241^{***}
	(0.094)	(0.085)	(0.098)	(0.099)	(0.061)
t+5	0.186^{**}	0.229^{**}	0.311^{***}	0.294^{***}	0.219^{***}
	(0.090)	(0.086)	(0.092)	(0.092)	(0.056)
t+6	0.072	0.171^{**}	0.229^{**}	0.211^{**}	0.157^{**}
	(0.072)	(0.076)	(0.086)	(0.085)	(0.062)
t+7	0.135^{**}	0.249^{***}	0.269^{***}	0.256^{***}	0.202^{***}
	(0.064)	(0.059)	(0.062)	(0.062)	(0.043)
t+8	0.138^{***}	0.210^{***}	0.227^{***}	0.210^{***}	0.157^{***}
	(0.047)	(0.045)	(0.040)	(0.039)	(0.039)
t+9	0.147^{***}	0.181^{***}	0.187^{***}	0.173^{***}	0.115^{**}
	(0.035)	(0.041)	(0.038)	(0.037)	(0.046)
t+10	0.100^{***}	0.119^{***}	0.120^{***}	0.107^{***}	0.065^{*}
	(0.032)	(0.034)	(0.032)	(0.031)	(0.036)
$t \geq +11$	-0.070	-0.113	-0.129	-0.116	-0.170^{*}
	(0.094)	(0.091)	(0.091)	(0.090)	(0.097)
pre thresh. dep.	-0.206	-0.327^{*}	-0.125	-0.129	
	(0.186)	(0.187)	(0.232)	(0.236)	
post thresh. dep.	0.010	0.009	0.003	0.035	
	(0.050)	(0.046)	(0.045)	(0.065)	
year FE	Yes	Yes	Yes	Yes	Yes
county FE	Yes	Yes	Yes	Yes	Yes
Weather Ctrls.	No	Yes	Yes	Yes	Yes
Census Ctrls.	No	No	No	Yes	Yes
N	73725	73725	73725	73150	73725
$adj.r^2$	0.660	0.660	0.814	0.816	0.803

Table A2: Event study coefficients cancer deaths per 1,000, 1946-1970

	(1) Base	(2) Weather	(3) Full	(4) No Downwind	(5) NoPrePost
t ≤ -6	-0.016	-0.015	-0.037*	-0.032	-0.014
	(0.026)	(0.026)	(0.022)	(0.021)	(0.022)
t-5	-0.014	-0.017	-0.027	-0.024	-0.004
	(0.021)	(0.019)	(0.017)	(0.017)	(0.019)
t-4	-0.005	-0.006	-0.012	-0.010	0.013
	(0.017)	(0.017)	(0.015)	(0.015)	(0.018)
t-3	-0.005	0.001	-0.002	-0.001	0.022
	(0.015)	(0.016)	(0.015)	(0.015)	(0.019)
t-2	-0.018	-0.008	-0.007	-0.007	0.015
	(0.011)	(0.013)	(0.011)	(0.012)	(0.014)
t-1	0.000	0.000	0.000	0.000	0.000
	(.)	(.)	(.)	(.)	(.)
t=0	0.007	0.018	0.027**	0.029**	0.035**
	(0.012)	(0.014)	(0.013)	(0.013)	(0.013)
t+1	0.031	0.036	0.055**	0.055**	0.032**
	(0.024)	(0.023)	(0.021)	(0.021)	(0.012)
t+2	0.037	0.032	0.051**	0.052**	0.024*
	(0.025)	(0.024)	(0.020)	(0.020)	(0.013)
t+3	0.053**	0.050**	0.071***	0.071***	0.040***
	(0.026)	(0.023)	(0.019)	(0.019)	(0.011)
t+4	0.053**	0.061**	0.076***	0.076***	0.044***
	(0.025)	(0.024)	(0.022)	(0.021)	(0.013)
t+5	0.063***	0.063***	0.078***	0.077***	0.049***
	(0.023)	(0.023)	(0.019)	(0.019)	(0.013)
t+6	0.043**	0.050**	0.060***	0.058***	0.038***
	(0.019)	(0.019)	(0.017)	(0.017)	(0.013)
t+7	0.032*	0.041**	0.045***	0.043***	0.024**
	(0.017)	(0.016)	(0.014)	(0.014)	(0.011)
t+8	0.041***	0.045***	0.046***	0.044***	0.026**
	(0.014)	(0.015)	(0.013)	(0.013)	(0.010)
t+9	0.039***	0.044***	0.042***	0.043***	0.023**
	(0.012)	(0.012)	(0.011)	(0.012)	(0.011)
t+10	0.025**	0.028**	0.029***	0.027**	0.014
	(0.011)	(0.012)	(0.011)	(0.011)	(0.009)
t $\geq +11$	-0.033*	-0.031*	-0.027*	-0.026*	-0.036*
	(0.018)	(0.018)	(0.015)	(0.015)	(0.018)
pre thresh. dep.	0.026	-0.001	0.035	0.035	
	(0.050)	(0.046)	(0.038)	(0.038)	
post thresh. dep.	-0.002	-0.000	-0.000	0.001	
	(0.007)	(0.006)	(0.006)	(0.009)	
year FE	Yes	Yes	Yes	Yes	Yes
county FE	Yes	Yes	Yes	Yes	Yes
Weather Ctrls.	No	Yes	Yes	Yes	Yes
Census Ctrls.	No	No	No	Yes	Yes
N	73725	73725	73725	73150	73725
$adj.r^2$	0.518	0.507	0.745	0.746	0.734

Table A3: Event study coefficients influenza/pneumonia deaths per 1,000, 1946-1970

	(1) Base	(2) Weather	(3) Full	(4) No Downwind	(5) NoPrePost
t ≤ -6	0.015	0.002	-0.009	-0.011	-0.019
	(0.019)	(0.019)	(0.018)	(0.018)	(0.021)
t-5	0.019	0.008	0.003	0.003	-0.006
	(0.013)	(0.014)	(0.013)	(0.013)	(0.017)
t-4	0.004	-0.005	-0.010	-0.009	-0.019
	(0.012)	(0.012)	(0.011)	(0.011)	(0.016)
t-3	0.003	-0.008	-0.010	-0.011	-0.018
	(0.011)	(0.010)	(0.010)	(0.010)	(0.015)
t-2	0.001	-0.005	-0.007	-0.007	-0.016
	(0.008)	(0.008)	(0.008)	(0.008)	(0.013)
t-1	0.000	0.000	0.000	0.000	0.000
	(.)	(.)	(.)	(.)	(.)
t=0	-0.003	-0.008	-0.009	-0.006	-0.003
	(0.009)	(0.009)	(0.010)	(0.010)	(0.011)
t+1	-0.012	-0.018	-0.021	-0.023	0.007
	(0.016)	(0.016)	(0.016)	(0.016)	(0.011)
t+2	-0.028*	-0.031*	-0.031*	-0.028*	-0.001
	(0.015)	(0.015)	(0.016)	(0.016)	(0.009)
t+3	-0.011	-0.014	-0.016	-0.015	0.013
	(0.017)	(0.016)	(0.017)	(0.017)	(0.009)
t+4	-0.020	-0.028*	-0.027*	-0.027*	0.001
	(0.015)	(0.014)	(0.015)	(0.015)	(0.009)
t+5	-0.010	-0.015	-0.015	-0.015	0.009
	(0.016)	(0.015)	(0.016)	(0.016)	(0.010)
t+6	-0.004	-0.004	-0.003	-0.004	0.015
	(0.015)	(0.014)	(0.015)	(0.015)	(0.011)
t+7	-0.010	-0.010	-0.010	-0.011	0.005
	(0.009)	(0.009)	(0.010)	(0.010)	(0.007)
t+8	-0.001	0.001	0.002	0.001	0.015*
	(0.012)	(0.011)	(0.012)	(0.012)	(0.008)
t+9	0.007	0.004	0.006	0.005	0.017**
	(0.013)	(0.012)	(0.012)	(0.012)	(0.008)
t+10	0.014	0.016*	0.016*	0.016*	0.023***
	(0.009)	(0.008)	(0.009)	(0.009)	(0.006)
t $\geq +11$	0.008	0.012	0.008	0.007	0.005
	(0.009)	(0.009)	(0.009)	(0.009)	(0.011)
pre thresh. dep.	-0.070*	-0.077**	-0.083**	-0.080**	
	(0.036)	(0.034)	(0.035)	(0.035)	
post thresh. dep.	-0.007*	-0.009**	-0.009***	-0.006	
	(0.003)	(0.003)	(0.003)	(0.004)	
year FE	Yes	Yes	Yes	Yes	Yes
county FE	Yes	Yes	Yes	Yes	Yes
Weather Ctrls.	No	Yes	Yes	Yes	Yes
Census Ctrls.	No	No	No	Yes	Yes
N	73706	73706	73706	73131	73706
$adj.r^2$	0.250	0.252	0.256	0.269	0.254

Table A4: Event study coefficients motor vehicle deaths per 1,000, 1946-1970

	(1) Base	(2) Weather	(3) Full	(4) No Downwind	(5) NoPrePost
$t \leq -6$	-0.031*	-0.034**	-0.020	-0.021	-0.017
	(0.016)	(0.015)	(0.013)	(0.014)	(0.013)
t-5	-0.012	-0.016	-0.010	-0.009	-0.010
	(0.011)	(0.010)	(0.009)	(0.009)	(0.009)
t-4	-0.008	-0.011	-0.005	-0.005	-0.007
	(0.010)	(0.010)	(0.010)	(0.010)	(0.010)
t-3	-0.012	-0.013	-0.010	-0.010	-0.012
	(0.010)	(0.008)	(0.008)	(0.008)	(0.007)
t-2	-0.011*	-0.011*	-0.008	-0.007	-0.010*
	(0.006)	(0.006)	(0.005)	(0.005)	(0.006)
t-1	0.000	0.000	0.000	0.000	0.000
	(.)	(.)	(.)	(.)	(.)
t=0	0.000	0.002	0.004	0.005	0.000
	(0.006)	(0.005)	(0.005)	(0.005)	(0.005)
t+1	-0.010	-0.009	-0.002	-0.002	-0.003
	(0.009)	(0.008)	(0.008)	(0.008)	(0.006)
t+2	-0.010	-0.009	-0.005	-0.005	-0.005
	(0.009)	(0.008)	(0.008)	(0.008)	(0.006)
t+3	-0.008	-0.006	-0.000	0.000	0.001
	(0.009)	(0.008)	(0.008)	(0.008)	(0.006)
t+4	0.001	0.005	0.007	0.007	0.009
	(0.009)	(0.007)	(0.008)	(0.008)	(0.006)
t+5	-0.002	0.002	0.004	0.005	0.006
	(0.008)	(0.007)	(0.008)	(0.008)	(0.007)
t+6	-0.002	0.000	0.000	-0.000	0.001
	(0.006)	(0.007)	(0.007)	(0.007)	(0.006)
t+7	-0.003	0.000	0.000	-0.000	0.002
	(0.006)	(0.006)	(0.006)	(0.006)	(0.005)
t+8	0.000	0.003	0.001	-0.000	0.003
	(0.006)	(0.006)	(0.006)	(0.006)	(0.006)
t+9	0.004	0.007	0.004	0.002	0.006
	(0.007)	(0.007)	(0.007)	(0.006)	(0.007)
t+10	0.002	-0.001	-0.002	-0.002	0.000
	(0.006)	(0.006)	(0.007)	(0.007)	(0.007)
$t \geq +11$	0.004	0.003	0.009	0.010	0.012*
	(0.008)	(0.007)	(0.006)	(0.006)	(0.007)
pre thresh. dep.	-0.028	-0.026*	-0.010	-0.011	
	(0.018)	(0.015)	(0.015)	(0.015)	
post thresh. dep.	0.003	0.003	0.005	0.005	
	(0.003)	(0.003)	(0.003)	(0.004)	
year FE	Yes	Yes	Yes	Yes	Yes
county FE	Yes	Yes	Yes	Yes	Yes
Weather Ctrls.	No	Yes	Yes	Yes	Yes
Census Ctrls.	No	No	No	Yes	Yes
N	73725	73725	73725	73150	73725
$adj.r^2$	0.182	0.183	0.187	0.182	0.187

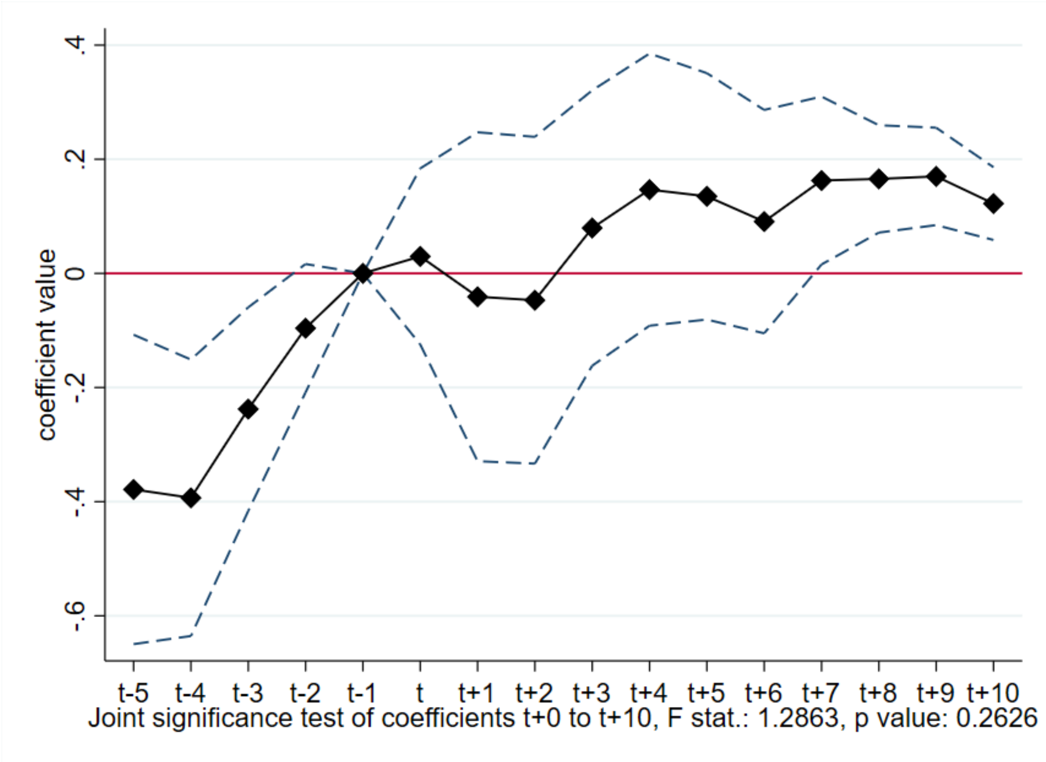

Figure A10: Fallout threshold coefficients and 95%CI , all-cause death rate per 1,000. No pre-trend adjustment. Source: Author's calculation.

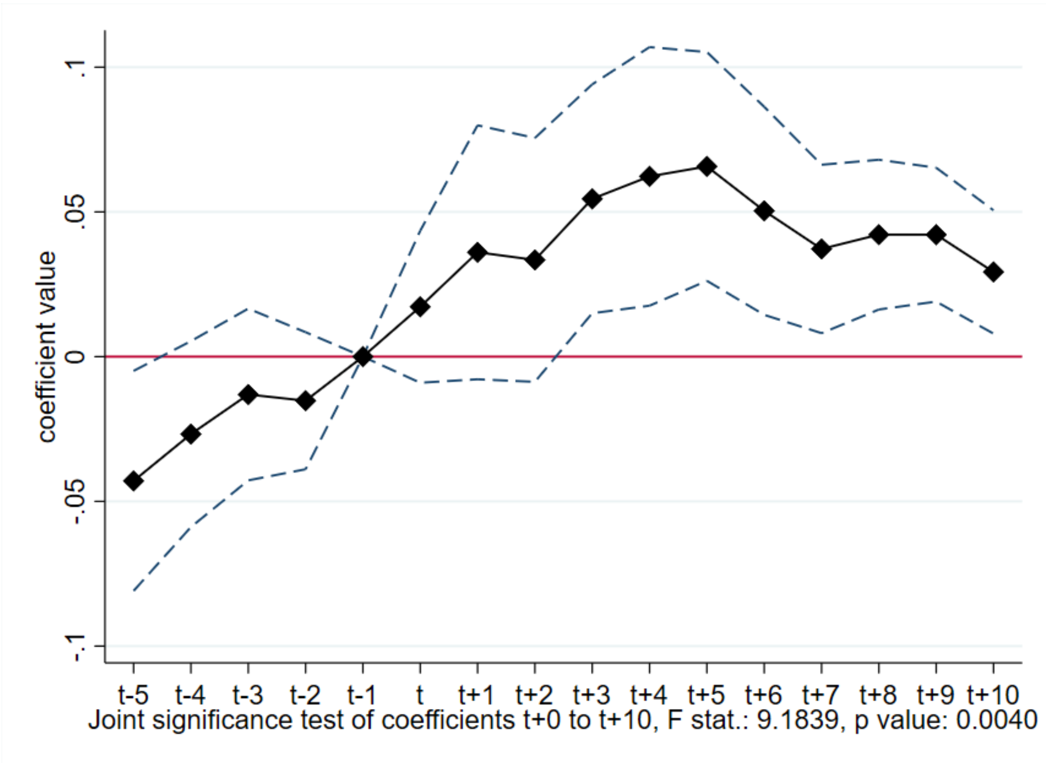

Figure A11: Fallout threshold coefficients and 95%CI, cancer death rate per 1,000. No pre-trend adjustment. Source: Author's calculation.

2 Migration and population change

Selective migration over a long period could introduce bias if systemically correlated with the variable of interest. If migration is not correlated with fallout deposition, then the migration of individuals exposed to fallout different from their place of death would introduce measurement error in the treatment variable and bias coefficients towards zero. Demographers and historians tend to use net migration measures, defined as the change of population between Censuses plus deaths and minus births, to study migration for the relevant period. This measure of migration is unsuitable since is it constructed from one of the outcome variables used in the mortality analysis. To the author's knowledge, there is no consistent measures of county to county migration in the U.S. for the periods prior, during, or immediately after nuclear testing that could be used to weight the fallout measures.[33]

The 1940 complete count U.S. Census has measures of migration by county. Using the complete count 1940 IPUMS sample (Ruggles et al., 2017), I construct shares of the population that do not migrate, move state to state, move within state, and move from abroad within the past five years. I then regress these values against cumulative fallout deposition estimates in U.S. counties from 1951 to 1958 while controlling for state fixed effects. The results are presented in table A5 and show no relationship between cumulative fallout deposition and migration prior to nuclear testing. Since changes in population are in part caused by migration and since population is the denominator of the mortality rates of empirical interest, I regress decennial population from 1940 to 1980 against cumulative deposition and find no statistically significant relationship between population and deposition. These two results suggest that migration prior to nuclear testing and underlying changes in population before and after testing are uncorrelated with the fallout.

[33]The IRS provides county to county migration estimates from U.S. tax filings starting in 1978, form more details see ICPSR record 2937 https://doi.org/10.3886/ICPSR02937.v1.

Table A5: Relationship between migration status five years prior in 1940 Census and iodine-131 deposition

	(1)	(2)	(3)	(4)
	% non-movers	% within state	% cross state	% abroad
cum. dep.	0.073	0.040	-0.022	-0.003
	(0.106)	(0.079)	(0.067)	(0.003)
N	3059	3059	3059	3059
adjusted $r2$	0.426	0.362	0.511	0.302

Robust standard errors in parentheses and include state fixed effects.
* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

3 Relationship between deposition and decennial Census observables

To test if there is any correlation between a counties racial composition, education, urban status, income, or population, I follow the example of Hornbeck (2012) and regress the variable of interest against observable county characteristics from decennial censuses. I regress decennial Census variables on cumulative deposition of I-131. There is only a relationship between high school educational attainment prior to and after the period of testing. The stated relationship suggests that a 1,000 nCi increase in deposition is associated with a third to half of a percent higher level of high school degree holding in the population.

Table A6: Relationship between 1940 Census controls and cumulative I-131 deposition

	(1) share white	(2) share hs grad	(3) share urban	(4) population
cum. dep.	-0.002	0.326***	0.004	1802.361
	(0.001)	(0.126)	(0.003)	(1197.059)
N	3016	3016	3016	3016
adjusted $r2$	0.589	0.504	0.141	0.056

Robust standard errors in parentheses. All regressions control for state FE.

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

Table A7: Relationship between 1950 Census controls and cumulative I-131 deposition

	(1) share white	(2) share hs grad	(3) share urban	(4) log median income	(5) population
cum. dep.	-0.002	0.431***	0.003	14.653	2201.391
	(0.002)	(0.154)	(0.003)	(11.738)	(1454.087)
N	3016	3016	3016	2961.000	3016
adjusted $r2$	0.572	0.580	0.126	0.550	0.056

Robust standard errors in parentheses. All regressions control for state FE.

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

Table A8: Relationship between 1960 Census controls and cumulative I-131 deposition

	(1) share white	(2) share hs grad	(3) share urban	(4) log median income	(5) population
cum. dep.	-0.002	0.364**	0.004	19.728	2617.012
	(0.002)	(0.161)	(0.003)	(16.452)	(1808.329)
N	3016	3016	3016	3004.000	3016
adjusted $r2$	0.554	0.556	0.120	0.496	0.061

Robust standard errors in parentheses. All regressions control for state FE.

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

Table A9: Relationship between 1970 Census controls and cumulative I-131 deposition

	(1) share white	(2) share hs grad	(3) share urban	(4) log median income	(5) population
cum. dep.	-0.000	0.484**	0.003	40.129	2603.128
	(0.000)	(0.189)	(0.003)	(27.658)	(2035.185)
N	3016	3016	3016	3016	3016
adjusted $r2$	0.529	0.577	0.109	0.436	0.070

Robust standard errors in parentheses. All regressions control for state FE.

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

Table A10: Relationship between 1980 Census controls and cumulative I-131 deposition

	(1) share white	(2) share hs grad	(3) share urban	(4) log median income	(5) population
cum. dep.	-0.001	0.506***	0.005	99.106	2236.212
	(0.002)	(0.164)	(0.003)	(62.110)	(2212.159)
N	3016	3016	3016	3016	3016
adjusted $r2$	0.488	0.585	0.113	0.292	0.080

Robust standard errors in parentheses. All regressions control for state FE.

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

Table A11: Effect of initial fallout threshold event on mortality rates per 1,000 residents, 1946-1970

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
	p25	p50	p75	any	hilo	p25	p50	p75	any	hilo
post threshold	0.197	0.293***	0.227**	-0.048		0.049**	0.037***	-0.011	0.077*	
	(0.134)	(0.082)	(0.111)	(0.197)		(0.022)	(0.013)	(0.013)	(0.040)	
post threshold, low					0.267***					0.029*
					(0.096)					(0.016)
post threshold, high					0.334**					0.050**
					(0.126)					(0.019)
N	73725	73725	73725	73725	73725	73725	73725	73725	73725	73725
$adj.r^2$	0.887	0.813	0.818	0.922	0.813	0.785	0.745	0.736	0.699	0.745

4 State to state migration characteristics

One potential threat to identification is that people with worse underlying heath characteristics selectively migrate into more irradiated regions or that healthy people move away from more irradiated regions. To tests if this is a potential concern I take Census samples from the 1960, 1970, and 1980 Censuses from IPUMS (Ruggles et al., 2017). Using location five year prior to determine migration status, I test if differences in average levels of radiation deposition from 1951 to 1958 between destination and source states has any relationship to migrant characteristics.

$$y_{d,s} = \alpha_d + \beta_1 Migrant[0,1] + \beta_2 DepDiff_{d,s} + \epsilon_d \tag{3}$$

Equation 3 describes the regression specification where I compare the characteristics of migrants to non-migrants. For each Census year, I test if differences in fallout deposition in destination and source states, $DepDiff_{d,s}$, is associated with differences in average age, sex, race, education, employment, and income. It is plausible that mortality risks increase with age, that women have lower mortality risks than men, that whites have lower mortality risks than nonwhites, and that mortality risks decrease with income and education. I include a dummy indicating if a group is a migrant group, $Migrant[0,1]$, a fixed effect to control for destination characteristics (state of residence during the Census enumeration year), α_d, and standard errors clustered by destination state, ϵ_d. In the tables below I find little evidence to suggest differences in radiation deposition between the states migrants came from and migrated to is associated with characteristics that could affect mortality in 1960 and 1970. These include age, gender, income, education, and employment. There is evidence that migrants are more likely to be white if they are migrating into more irradiated states.

Table A12: Relationship between differences in fallout between destination and source state for migrants and migrant demographics

	(1)	(2)	(3)
	1960	1970	1980
migrant group (0,1)	-10.66933***	-11.08394***	-10.74522***
	(0.31695)	(0.32048)	(0.28678)
effect on average age	-0.04644	-0.03133	-0.03947
	(0.03353)	(0.05917)	(0.04562)
	1960	1970	1980
migrant group (0,1)	-0.07149***	-0.07220***	-0.05468***
	(0.00556)	(0.00710)	(0.00355)
effect on share female	0.00046	-0.00249*	0.00031
	(0.00090)	(0.00146)	(0.00118)
	1960	1970	1980
migrant group (0,1)	-0.03660**	-0.02818**	-0.01858**
	(0.01402)	(0.01174)	(0.00879)
effect on share nonwhite	0.00466***	0.00385***	0.00362***
	(0.00065)	(0.00089)	(0.00066)

Standard errors in parentheses

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

Table A13: Relationship between differences in fallout between destination and source state for migrants and migrant demographics cont.

	(1)	(2)	(3)
	1960	1970	1980
	Migration status (0,1)		
migrant group (0,1)	0.26245***	0.26436***	0.19051***
	(0.01175)	(0.00996)	(0.00808)
effect on share high school grad.	-0.00156	-0.00306	-0.00061
	(0.00148)	(0.00195)	(0.00110)
	1960	1970	1980
migrant group (0,1)	0.09781***	0.12557***	0.13816***
	(0.00583)	(0.00714)	(0.00818)
effect on share college grad.	-0.00106	-0.00377**	0.00095
	(0.00108)	(0.00177)	(0.00135)
	1960	1970	1980
migrant group (0,1)	-0.07546***	-0.08422***	-0.09581***
	(0.00540)	(0.00709)	(0.00458)
effect on share employed	-0.00090	-0.00195	-0.00350***
	(0.00101)	(0.00200)	(0.00112)
	1960	1970	1980
migrant group (0,1)	0.17653***	0.05545*	0.09438***
	(0.03496)	(0.03240)	(0.01846)
effect on average ln(wage income)	-0.00180	0.01598	0.00251
	(0.00946)	(0.01228)	(0.00253)
N	2277	2180	2284

Standard errors clustered by state of residence in census year.

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

5 Goodman-Bacon Decomposition

Never treated counties make up a small portion of the sample and consist of counties primarily off the Gulf Coast or in California, Washington, and Oregon. The positive mortality effects observed come primarily from comparisons between counties that cross the fallout threshold in 1951 and 1952 and those that cross later. For all cause mortality comparisons between counties that cross the threshold in 1953 or 1955 and those that cross in 1957 are negative. For cancer mortality the coefficients for comparisons between 1953 and 1952, and 1955 and 1957 are negative. Very few counties exceed the threshold in 1955 since 1955 patterns of fallout overlapped much with 1952 and 1953 patterns.

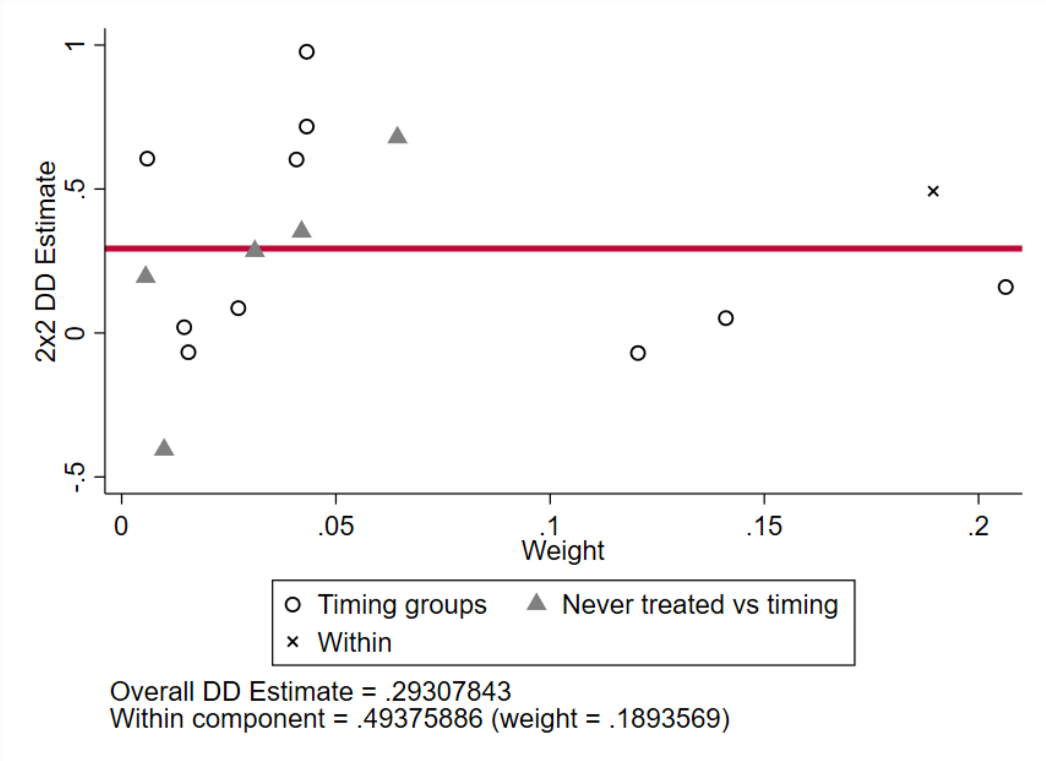

Figure A12: Plot of Goodman-Bacon decomposition coefficients, all-cause mortality

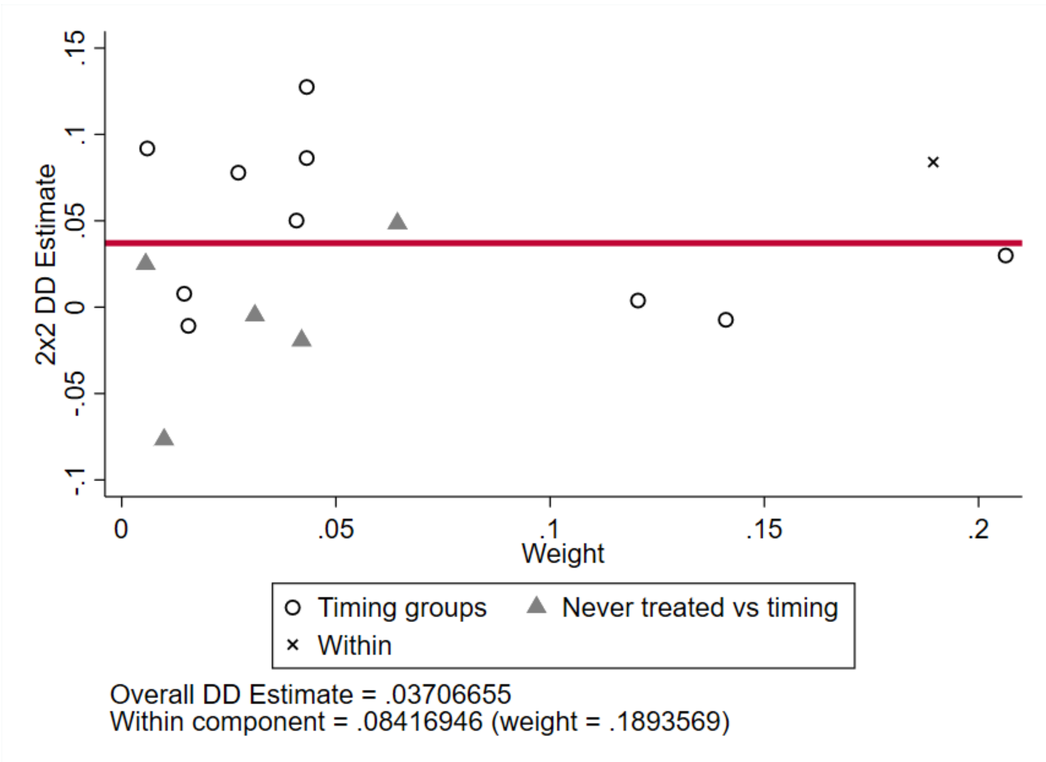

Figure A13: Plot of Goodman-Bacon decomposition coefficients, cancer mortality

Table A14: Goodman-Bacon decomposition, all-cause mortality

Coefficients from timing groups: Average DiD Coefficient: 0.293

52_51	53_51	53_52	55_51	55_52	55_53	57_51	57_52	57_53	57_55
0.978	0.604	0.053	0.607	0.087	0.021	0.718	0.161	-0.069	-0.066

Never_51	Never_52	Never_53	Never_55	Never_57	Within
-0.405	0.679	0.351	0.5	0.284	0.494

Weights

52_51	53_51	53_52	55_51	55_52	55_53	57_51	57_52	57_53	57_55
0.043	0.041	0.141	0.006	0.027	0.015	0.043	0.206	0.120	0.015

Never_51	Never_52	Never_53	Never_55	Never_57	Within
0.010	0.064	0.042	0.006	0.031	0.189

Average beta coefficient from timing groups comparisons is 0.206 with a weight of 0.658. For comparisons between timing and never threshold crossing the beta coefficient is 0.421 with a weight of 0.153. Census and weather controls contribute positively to the estimate mortality effect.

Table A15: Goodman-Bacon decomposition, cancer mortality

Coefficients from timing groups: Average DiD Coefficient: 0.037

52_51	53_51	53_52	55_51	55_52	55_53	57_51	57_52	57_53	57_55
0.128	0.050	-0.007	0.092	0.078	0.008	0.087	0.030	0.004	-0.011
Never_51	Never_52	Never_53	Never_55	Never_57	Within				
-0.077	0.049	-0.019	0.025	-0.005	0.084				

Weights

52_51	53_51	53_52	55_51	55_52	55_53	57_51	57_52	57_53	57_55
0.043	0.041	0.141	0.006	0.027	0.015	0.043	0.206	0.120	0.015
Never_51	Never_52	Never_53	Never_1955	Never_1957	Within				
0.010	0.064	0.042	0.006	0.031	0.189				

Average beta coefficient from timing groups comparisons is 0.0298 with a weight of 0.010. For comparisons between timing and never threshold crossing the beta coefficient is 0.421 with a weight of 0.153. Census and weather controls contribute positively to the estimate mortality effect.