Investigating the Economic Consequences of Atmospheric Nuclear Testing

by

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As members of the Dissertation Committee, we certify that we have read the dissertation prepared by Keith Andrew Meyers, titled "Investigating the Economic Consequences of Atmospheric Nuclear Testing" and recommend that it be accepted as fulfilling the dissertation requirement for the Degree of Doctor of Philosophy.

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Dedication

I dedicate this manuscript to those who have helped me, my family, and supportive friends. I am especially grateful to my sister, Alison Meyers, who has patiently listened to my long winded digressions into economic jargon and who has helped me through many stressful points in my academic career. You are the best sister I could ever ask for.

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Abstract

During the Cold War the United States detonated hundreds of atomic weapons at the Nevada Test Site (NTS). Many of these nuclear tests were conducted above ground and released tremendous amounts of radioactive pollution into the environment. The primary aim of this dissertation research is to answer empirical questions regarding the social costs of atmospheric nuclear testing. My research focuses on two broad areas: 1) how do economic agents respond to the adverse effects of environmental shocks, and 2) how does policy shape responses to said shocks. My studies combine data from a myriad of agricultural, environmental, and public health sources and rely upon clearly identified reduced-form models to estimate the social costs of NTS activities.

The United States' nuclear weapons testing program had much larger effects than previously known. I find that radioactive iodine generated from nuclear testing contributed to hundreds of thousands of excess deaths from 1951 to 1978. Increases in mortality rates due to fallout occurred throughout the entire country and that substantial damage occurred in places far from the region typically considered to be "Downwind" of the NTS. This radioactive material also harmed agricultural production and led to billions of dollars of lost output (2016$). Expanding upon these results, I use fallout measures to instrument for agricultural productivity and study how policy shapes agricultural producers' responses to adverse productivity shocks. Fallout shocks allow me to measure how farmers respond to adverse productivity shocks when the cause of the shock is unobserved and unanticipated from the perspective of the agent.

Chapter 1

Introduction: Atmospheric Nuclear Testing on the North American Continent

One of the legacies of the Cold War is nuclear weapons technology and the risks associated with them. While the specter of Mutually Assured Destruction and atomic Armageddon have mostly disappeared from public consciousness, contemporary society has inherited this nuclear legacy and the dangers associated with it. Nuclear proliferation, increasing friction in geopolitics among nuclear powers, and accidents from our aging nuclear infrastructure all pose nontrivial risks. Mistakes and accidents could result in the catastrophic release of radioactive pollutants into the environment. There is little empirical knowledge about the potential economic risks posed by such accidents. In this dissertation, I quantify some of the social costs of radioactive pollution and America's nuclear weapons program by using historical releases of radioactive fallout from nuclear testing.

Recent economic research has started to explore the economic effects of radioactive pollutants on human capital and wellbeing in Europe and Japan using uncontrolled releases of radioactive material in the environment due to nuclear testing and accidents at nuclear power plants (Almond et al., 2009; Lehmann and Wadsworth, 2011; Black et al., 2013; Danzer and Danzer, 2016; Ito and Kuriyama, 2017). I contribute to and expand upon this literature by examining episodes of nuclear weapons testing in the United States. I measure how these activities adversely affected public health and the economy.

From 1951 to 1958, the United States government detonated scores of nuclear weapons in the Nevada desert. These events irradiated tremendous quantities of earth, drew radioactive materials high into the atmosphere, and spread harmful radioactive fallout throughout much of the continental United States. Policymakers during the period of testing generally thought that radioactive fallout from atmospheric testing posed little threat to public health or the economy. In fact the individual tasked with identifying potential sites for continental nuclear testing in 1949, Navy Captain Howard B. Hutchinson, stated that continental atmospheric nuclear tests would not cause "physical or economic detriment to the population, the economy nor the industry of the nation" (Fehner and Gosling, 2000, 2006). With the benefit of hindsight, it is clear that this assertion is inaccurate.

During the Cold War governments around the world detonated over 2,000 nuclear weapons. Of these tests, the United States government was responsible for 1,054 nuclear tests. From 1945 to 1992, the U.S. conducted 210 atmospheric tests, 5 underwater tests, and 839 underground atomic tests. There were three periods to America's nuclear testing program. The atmospheric testing period transpired from 1945 to 1958. From 1958 to 1961 there was a nuclear testing moratorium between the U.S. and U.S.S.R. that suspended atmospheric testing. A brief period of atmospheric testing occurred after the U.S.S.R. broke the moratorium in 1961, and the Partial Nuclear Test Ban Treaty passed in 1963 ended atmospheric nuclear testing. All subsequent U.S. nuclear tests from 1963 to 1992 were conducted underground with the vast majority, 839, occurring at the Nevada Test Site (NTS) just northwest of Las Vegas, Nevada (US Department of Energy, 2000; Fehner and Gosling, 2006).

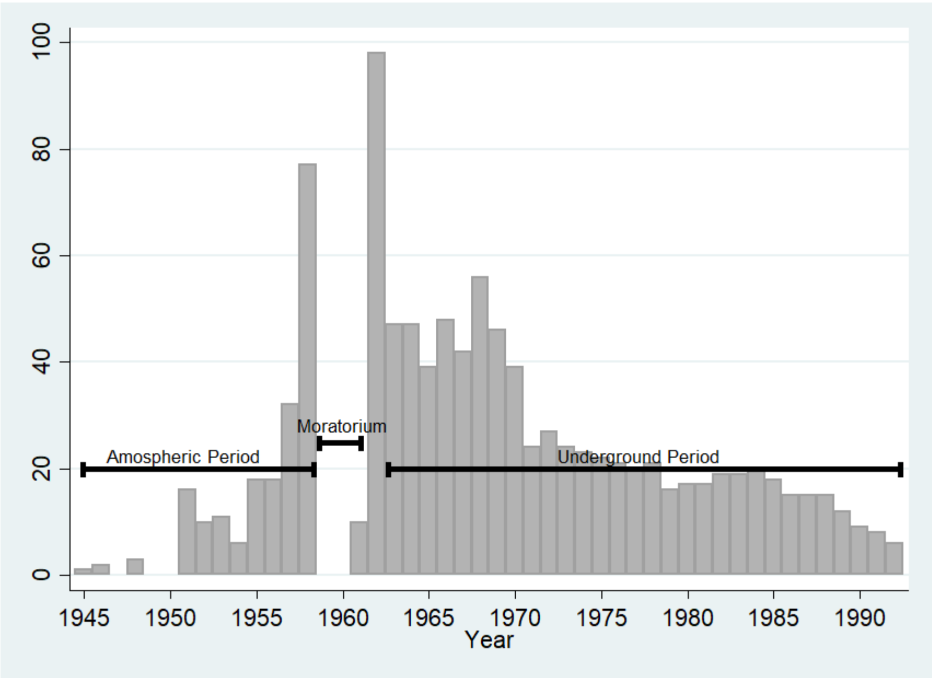


Figure 1.1: Number of U.S. Nuclear Tests. Source: U.S. Department of Energy (2000)

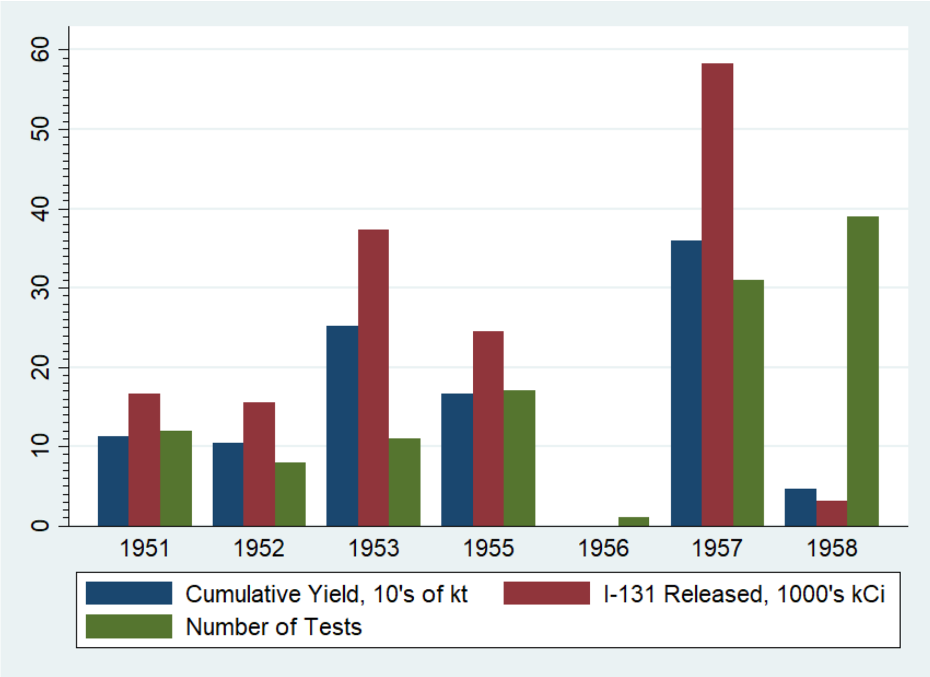


Figure 1.2: Annual Cumulative Yields, Atmospheric I-131 Releases, and # of Tests for NTS, 1951 - 1958. Source: Created from National Cancer Institute (1997)

Figure 1.1 denotes the number of U.S. nuclear tests conducted in a given year the three major time periods. The papers in this dissertation focus on the testing window from 1951 to 1958 when 100 atmospheric nuclear tests were conducted at the NTS.

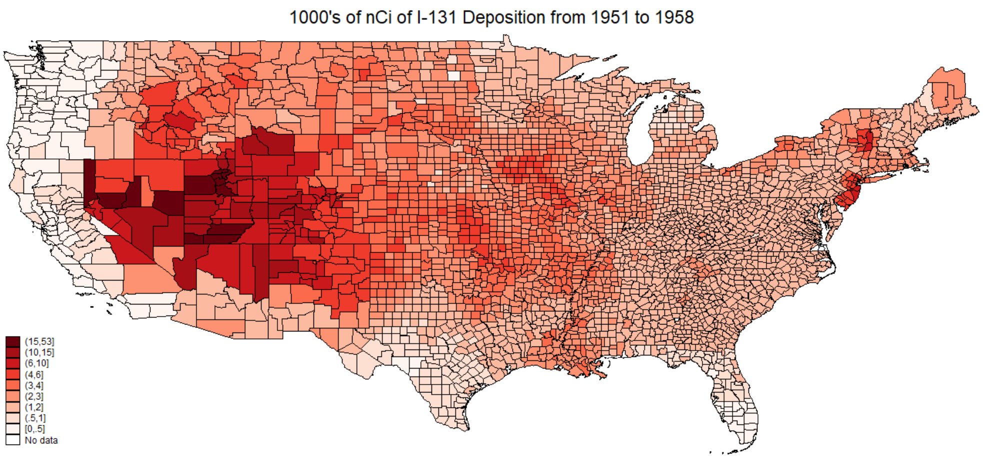


Figure 1.3: Total I-131 Fallout Deposition by County, 1951-1958.
Source: Created from National Cancer Institute (1997)

While smaller in magnitude than the tests in the Pacific, atmospheric tests performed in Nevada created enormous quantities of radioactive fallout. Figure 1.2 describes these Nevada tests, their size, and relative "dirtiness." Much of this irradiated material generated by desert testing was carried high into the atmosphere and precipitated down across the eastern United States. Figure 1.3 reports the cumulative amount of iodine 1-131, a radioactive pollutant harmful to public health, that deposited across U.S. counties from these NTS tests. The decision to carry out nuclear testing in the Nevada desert had substantial unintended environmental consequences and harmful radioactive material from these tests deposited all across the United States. Fallout landed on agricultural fields and pastures. Livestock grazed irradiated pasture and radioactive pollutants readily entered the food supply.

Prior to NTS testing, all nuclear tests (with the exception of the 1945 Trinity Test at White Sands, New Mexico) were carried out in the Pacific. These Pacific tests were logistically complicated, had unattractive weather conditions, and were strategically vulnerable to Soviet submarines. In 1948, an internal study codenamed Project Nutmeg assessed the feasibility of continental nuclear testing. Policy makers were initially hesitant about the prospects of testing nuclear weapons on the American continent, but a number of global events transpired that changed the leaders' political calculus. On August 29th, 1949 the Soviet Union shocked the world by detonating its first nuclear weapon and threatened American atomic hegemony. This caused military and civilian leaders to expand America's nuclear weapons program. Then the onset of the Korean War during the summer of 1950 disrupted planned Pacific tests, Operation Greenhouse, as naval resources were diverted to the war effort (Fehner and Gosling, 2000, 2006). These two forces led leaders to conclude that continental testing was necessary for national defense and the Las Vegas Gunnery and Bombing Range was expanded and converted into the NTS.

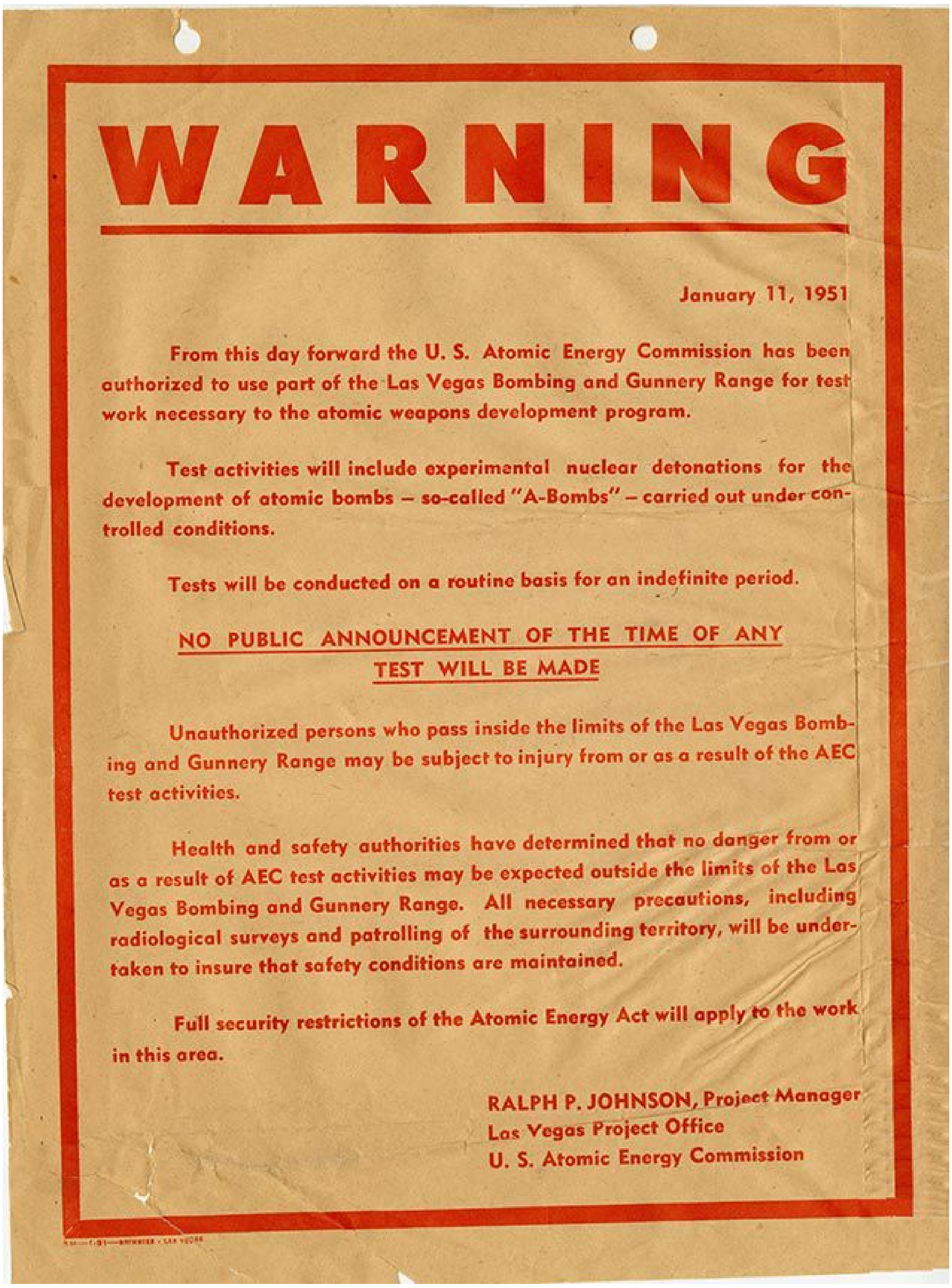


Figure 1.4: 1951 Testing Announcement Flyer. Source: U.S. Department of Energy, NNSA-Nevada Site Office.

Initially, the position of the Atomic Energy Commission (AEC), Public Health Service (PHS), and U.S. Federal Government was that nuclear testing posed no threat to public health and radioactive material would be contained within the boundaries of the NTS. Figure 1.4 is a flyer posted prior to 1951 Ranger test series and conveys these positions. As testing continued it became apparent that radioactive material was depositing in regions far from the test site and posed a public health risk. Most of these dangers were downplayed, denied, or hidden from public knowledge until Congressional inquiries and Freedom of Information Act requests in 1978 led to the release of AEC and PHS documents detailing the risks posed by atmospheric testing (Ball, 1986). This revelation prompted additional Congressional investigations (US Government Printing Office, 1980), public health studies (Bouville et al., 1990; National Cancer Institute, 1997; Simon and Bouville, 2015), and eventually compensation efforts for victims (US Department of Justice, 2016). Nevertheless, most of the research studying the adverse effects of NTS activities has focused on persons living in the regions surrounding the NTS and their health outcomes. This dissertation expands the geographic and empirical scope of this research to include the entire continental United States. In three chapters of this dissertation, I employ radioactive fallout exposure measures, provided from the National Cancer Institute, to study how atmospheric nuclear testing negatively affected public health, human capital, and the agricultural production in the United States.

This dissertation consists of three empirical research papers quantifying the social costs of atmospheric nuclear testing in Nevada. The first paper, titled “Some Unintended Fallout from Defense Policy: Measuring the Effect of Atmospheric Nuclear Testing on American Mortality Patterns," matches annual radioactive county level fallout exposure measures with an annual county panel of crude death rates from U.S. Vital Statistics. Through a series of reduced form panel regressions, I analyze how nuclear testing affected county level mortality rates throughout the continental United States, measure the temporal extent of the harm, and provide evidence that nuclear testing had broad adverse effects for public health. In the subsequent two chapters, I study how radioactive fallout precipitating down on agricultural land damaged crops, harmed livestock, and interacted with USDA regulatory controls that tied incentives to farmers' past production histories. In the second paper, “In the Shadow of the Mushroom Cloud: Nuclear Testing, Radioactive Fallout and Damage to U.S. Agriculture," I find that nuclear testing had sizable and direct effects on U.S. agricultural output in areas of the Midwest and Great Plains. In the third paper, titled “Measuring

Policy's Role in Mediating Responses to Agricultural Productivity Shocks," I study how government policy can fundamentally shape producer responses to agricultural productivity shocks. I use radioactive fallout from NTS testing as an instrument for agricultural productivity and use variation in USDA policies between crops to study how policy can affect both the magnitude and direction of a response to a productivity shock.

Chapter 2

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

During the Cold War the United States detonated hundreds of atomic weapons at the Nevada Test Site. Many of these nuclear tests were conducted above ground and released tremendous amounts of radioactive pollution into the environment. This paper combines a novel dataset measuring annual county level fallout patterns for the continental U.S. with vital statistics records. I find that fallout from nuclear testing led to persistent and substantial increases in overall mortality for large portions of the country. The cumulative number of excess deaths attributable to these tests is comparable to the bombings of Hiroshima and Nagasaki. *JEL Codes: I10; N32; Q50. Keywords: Nuclear Testing, Public Health, Radioactive Fallout, Defense Policy*

2.1 Introduction

Pollution is often the byproduct of human activity and imposes significant costs upon the public. In many settings, the government attempts to address the external costs associated with polluting activities, but there are cases where government policy is the direct cause of harmful pollution. During the Cold War the United States detonated hundreds of nuclear weapons just northwest of Las Vegas at the Nevada Test Site (NTS). Prior to 1963 many of these tests were conducted above ground and released tremendous quantities of radioactive material into the environment. One estimate places the total atmospheric release of radioactive material from the NTS as over 12 Billion Curies between 1951 and 1963. In comparison, Chernobyl released an estimated 81 Million Curies of radioactive material (LeBaron, 1998). These nuclear tests exposed millions of Americans to harmful radioactive material and many people are still living with the consequences of this pollution today. This paper measures the effect of domestic atmospheric nuclear testing on the crude death rate for the entire continental United States. I present evidence that nuclear testing had broad and adverse effects on human capital in the extreme and contributed to at least as many deaths as the bombings of Hiroshima and Nagasaki.

The medical and scientific literature studying the health effects of nuclear testing has focused primarily upon small samples of populations who lived in the areas surrounding the Nevada Test Site.[1] These studies examine the health effects of fallout exposure in these populations and extrapolate the potential health consequences for the nation. Simon and Bouville (2015) of the National Cancer Institute (NCI) note that there is great uncertainly underlying these estimates. They estimate that fallout from domestic nuclear testing caused 49,000 thyroid cancer deaths.[2] One of the major drawbacks of these medical and scientific studies is that they fail to capture the temporal and geographic scope of these health effects.

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

[2]The 95 percent confidence interval for this estimate is 11,300 and 220,000 deaths. Simon and Bouville (2015) suggest testing contributed up to 11,1000 additional of other cancer deaths. Without nuclear testing they estimated that 400,000 cases of thyroid cancer would arise naturally in the same population.

Using an alternative empirical approach, this paper provides substantial evidence that nuclear testing had profound effects on American health. I combine measures of radioactive fallout exposure from the National Cancer Institute (1997) and mortality data for the continental U.S. to analyze the mortality effects of atmospheric nuclear testing. By using within county variation in fallout deposition across years, this paper measures both the geographic and temporal extent of the harm caused by nuclear testing. The results from the empirical analysis reveal that nuclear testing led to prolonged increases in the crude death rate in many regions of the country. Contrary to the assumptions made in the medical literature, the largest mortality effects occurred in the Great Plains and Central Northwest U.S., far outside of the areas studied by the current literature. Back-of-the-envelope estimates suggest that fallout from nuclear testing contributed between 340,000 to 460,000 excess deaths from 1951 to 1973.

Economists have extensively studied the effects of air pollution, lead contamination, and other pollutants upon mortality and public health, but little economic research has studied the public health consequences of atmospheric nuclear testing.[3] The economic research studying the social costs and consequences of radioactive pollution has focused primarily on Scandinavian and Ukrainian populations. Danzer and Danzer (2016) and Lehmann and Wadsworth (2011) study the cost of the Chernobyl disaster to Ukrainian populations using cross sectional variation in exposure. Another body of research has successfully used variation in multiple sources of air pollution as a shock to test the fetal origins hypothesis (Almond et al., 2009; Almond and Currie, 2011; Currie, 2013; Currie et al., 2015; Isen et al., 2017). With respect to radioactive pollution, both Almond et al. (2009) and Black et al. (2013) use radioactive pollution to test the fetal origins hypothesis in Scandinavia. Almond et al. (2009) use radioactive fallout from the Chernobyl disaster and associate negative educational outcomes with in-utero exposure to fallout in Swedish cohorts. Black et al. (2013) use data from 14 radiation monitoring stations in Norway to study exposure in cohorts born between 1956 and 1966. They discover persistent and statistically reductions in educational attainment, earnings, and IQ scores among cohorts exposed during months three and

[3] Work by Hanlon (2015) has shown that coal consumption in 19th Century England had substantial effects on mortality rates and that coal utilization. Barreca et al. (2014) and Clay et al. (2016) study the long-term health consequences of using coal for heating and electricity generation for the United States. Troesken (2008) and Clay et al. (2014) study how historic municipal decisions relating to the adoption of lead water pipes had long run effects on public health.

four of gestation.

The results of this paper corroborate the negative effects found in previous research and improves upon the identification by exploiting the specific biological mechanisms through which American populations were exposed to harmful radioactive toxins. Radioactive fallout deposition can be an imprecise measure of human exposure to harmful ionizing radiation. Humans only metabolize specific radioactive isotopes created through fission. The primary mechanism through which people were exposed to concentrated doses of radiation was through the ingestion of irradiated food products. Fallout deposition may approximate the presence of fallout in the local food supply, but radiation exposure proxied through deposition becomes more inaccurate if local deposition fails to enter the local food supply. The National Cancer Institute (1997) finds that the consumption of irradiated dairy products served as the primary vector through which Americans consumed large concentrations of radioactive material. During the 1950's most milk was consumed in the local area it was produced. It is through this channel where local fallout deposition would enter the local food supply (National Cancer Institute, 1997). This paper leverages estimates of I-131 concentrations in locally produced milk to provide a more precise estimate of human exposure to fallout than previous studies.

2.2 Medical, Scientific, and Historical Background

2.2.1 History of NTS

In the 1950's, millions of Americans were unknowingly exposed to radioactive fallout through both the environment and the food supply. With respect to economic and demographic activities, exposure to radioactive matter from atmospheric nuclear testing can generally be considered as a plausibly exogenous event. Radioactive pollution is often an invisible and imperceptible threat to human health. National security concerns in the 1950's motivated atomic testing at the NTS. While the location of the base was not random, the base was not chosen due to surrounding characteristics of the residing population.[4]

Atmospheric atomic testing on U.S. soil was a deliberate policy decision made by domestic political leaders. In 1949 the Soviet Union detonated its first nuclear bomb Joe-1. Provoked and surprised by this sudden event, U.S. political and military leaders sought to accelerate America's own nuclear weapons program. Prior to this event, nuclear testing occurred in the Pacific.[5] The Pacific tests proved logistically costly, slow to implement, and expensive. American leaders sought a convenient testing location and settled on the Nevada Test Site due to its proximity to U.S. government labs, low levels of precipitation, and relatively secluded location (Center for Disease Control, 2006; National Cancer Institute, 1997). Located in Nye County, Nevada, this military zone became the epicenter of the American nuclear weapons program. Nuclear testing occurred from 1951 until 1992. The period of atmospheric nuclear testing occurring between 1951 and 1963. During this period, the U.S. detonated 100 atmospheric bombs at the NTS (US Department of Energy, 2000).

During the 1950's, the public was largely unaware of the dangers that the NTS posed to public health. Often, the Public Health Service (PHS) and Atomic Energy Commission (AEC) sought to dismiss fears regarding the atomic testing. Official government statements made during the testing period asserted that all dangerous radioactive material remained within the confines of the NTS.[6] At best, these organizations failed to adequately warn civilians living around the test site of the health risks associated with these atomic tests (Ball, 1986; Fradkin, 2004; LeBaron, 1998). In 1978, the plight of populations living near the NTS received national media attention. Subsequent Congressional inquries and Freedom of Information Act requests later revealed that the government knew of these dangers to public health the NTS tests posed and that the AEC had suppressed medical studies highlighting the health dangers (Fradkin, 2004).

[4]The base was chosen over more environmentally friendly locations due to its proximity to government labs, access to public land, and rapid ease of establishment (Schwartz, 2011).

[5]The three Trinity test in 1945 were conducted in White Plains New Mexico. All other tests conducted prior to the opening of the NTS occurred in the Pacific.

[6]In the Appendix is an example of a 1951 AEC flyer explicitly iterating this official claim. The website for the Official Department of Energy Nuclear Testing Archive where this flyer is from is https://www.nnss.gov/pages/resources/NuclearTestingArchive.html. The government circulated flyers such as these in the areas surrounding the NTS, all while the AEC and PHS detected substantial quantities of fallout depositing in populated areas far beyond the confines of the atomic test range.

2.2.2 The Health Consequences of Radiation Exposure

Radioactivity generally refers to dangerous particles given off by radioactive decay of matter. The weakest forms of ionizing radiation are alpha particles, and these particles generally cannot penetrate most thin physical barriers. Beta radiation is more dangerous and can penetrate deep into flesh and cause damage. Gamma radiation is the most dangerous form of radioactivity and consists of highly energetic photons. Gamma radiation can travel easily through the body and causes immense damage to biological tissues.

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

The medical and scientific knowledge regarding the effects of human exposure to ionizing radiation comes from many sources. Studies of Japanese atomic bomb survivors and persons living downwind of nuclear test sites provide much of this knowledge. In human population studies of radiation exposure, researchers have measured a variety of negative health and developmental consequences from exposure to ionizing radiation.

Studies of atomic bomb survivors and persons exposed during pregnancy demonstrate increased cancer risks, negative developmental and cognitive effects due to radiation exposure (Lee, 1999; Otake et al., 1993; Otake, 1996; Schull, 1997). Researchers studying Chernobyl have found greater incidences of thyroid cancers, and lesions indicative of I-131 poisoning in exposed population (Shibata et al., 2001; Williams, 2002). Researchers studying downwind American populations have also found evidence of increased thyroid cancer and leukemia risks in domestic downwind cohorts (Gilbert et al., 2010; Kerber et al., 1993; Stevens et al., 1990). Together, the medical and scientific literature suggest that exposure to ionizing radiation increases the risks of various types of cancer and can have detrimental effects upon human growth and development. An additional effect of fallout exposure is that it could degrade health, inhibit immune responses, and cause people to die from other non-cancer related causes.

2.2.3 Exposure Mechanisms

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

The NCI establishes the dairy channel as a primary vector through which Americans were exposed to significant quantities of radioactive material. Most Americans would not be exposed to radioactive dust carried by low altitude winds. Instead, high altitude winds would carry the material far from the test site and the material would only deposit on the ground if it happened to be precipitating while the radiation cloud was overhead. In the few days following the nuclear test, this radioactive material would deposit on crops and pasture. Some radioactive material would enter wheat and other plant products, but consumption of these products would not necessarily be in the same region where they were produced. Dairy, however, during the 1950s and 1960s was generally produced and consumed locally (National Cancer Institute, 1997). During the 1950s most milk was produced near population centers and delivered daily. In the late 1950s refrigerated truck adoption spread and deliveries switched to every few days (Dreicer et al., 1990). The dairy channel is unique in that cows would consume large quantities of irradiated pasture and concentrate radioactive material, specifically I-131, in milk.

People living in the region where deposition occurred would then be more likely to consume this irradiated food product containing a potent radioactive poison in the days following the atomic test. Pasturing practices would affect the quantities of fallout entering the dairy supply. The areas surrounding the NTS experienced the greatest quantities of radioactive fallout deposition, but often had very little I-131 entering the dairy supply. Dairy farming practices in much of AZ, NV, and UT in the 1950s relied on importing hay from outside regions and as such very little radioactive matter would enter the food supply. This in turn makes deposition itself a less accurate proxy for human exposure to fallout in these areas.

2.3 Empirical Strategy: Measuring Mortality Effects

2.3.1 Empirical Model

The empirical analysis of this paper focuses on two different panel regression models to ascertain the geographic and temporal extent of the health cost of atomic testing. The first set of regressions test whether within county variation in radioactive fallout exposure across years had an immediate effect upon crude death rates using a distributed lag framework. Short run changes in the crude death rate from fallout exposure are potentially less vulnerable to measurement error in treatment and migration bias than regressions measuring the long run effects of fallout. These regressions, however do not fully capture the temporal extent of these increases in mortality rates. The negative health effects of radiation poisoning often materialize long after the damage has occurred. A set of long run regressions employ a distributed lagged framework and pool exposure into five year averages. Estimation of this model measures how persistent the effects of fallout were on crude death rates, accounts for the cumulative effect of fallout exposure over multiple years, and whether exposure to fallout led to harvesting. If exposure to radioactive fallout shortened lifespans and exposed populations who died tended to die at younger ages than if they were not exposed, then these people would not appear in subsequent years in the county panel. This harvesting effect would decrease estimated mortality rates many years following the initial exposure event, because people who would have died in these periods died earlier in the sample.

$$y_{it} = \Sigma_{k=0}^{5} \beta_k * X_{it-k} + \alpha_i + \gamma_{st} + \epsilon_{it} \quad (2.3.1)$$

Equation (2.3.1) describes the full model specification of this paper. This model tests whether radioactive fallout in locally produced milk or in the environment had a statistically significant effect upon mortality in the years directly following the test. The outcome denoted by y_{it} measures the number of total deaths per 10,000 people in a given county i and year t. X_{it-k} denotes the exposure variable used to proxy for fallout exposure. There are two different measures of radiation exposure used in the analysis. These measures are ground deposition of I-131 and I-131 concentrations on locally produced milk. The variable $Deposition\ Exposure_{it}$ denotes the cumulative measure of total radioactive iodine deposited per square meter in each county year.[7]

The variable $Milk\ Exposure_{it}$ denotes the measure of radioactive iodine in locally produced milk in each county year in thousands of nCi per day/Liter. The NCI created daily integrated estimates of secreted iodine per liter of milk for each nuclear test. They then summed up these secretions over the entire test series. If a cow in a county produced one liter of milk each day, this would measure the amount of radioactive iodine secreted in all those liters of milk in each year. Furthermore, the milk variable accounts for grazing practices across regions. Cows in upstate New York would not have been exposed to much radiation from February tests as they would have been inside barns consuming fodder while cows in Georgia or Texas would have been exposed.

The variables α_i and γ_{st} denote county and state-by-year fixed effects. These county fixed effects control for time invariant county characteristics. The state-by-year fixed effects account for unobserved annual shocks shared across counties within the same state and year. One drawback of state-by-year fixed effects is that they might control for much of the effect of radioactive fallout exposure. Only variation in fallout exposure between counties within the same state provide identification.[8] Alternative specifications replace these state-by-year fixed effects with year fixed effects and state specific time trends to control for possible underlying trends in the data that might be correlated with the exogenous variable of interest. The variable ϵ_{it} denotes the heteroskedastic error term and is clustered at the county level.[9]

[7] Alternative functional forms find similar results. These alternative specifications are reported in the online appendix.

[8] Only variation in county level exposure above or below the state year average for exposure provides identification. It is quite likely that the effect of fallout exposure will be underestimated when using state-by-year fixed effects, since the identifying variation is narrower.

[9] Multiple yearly lag structures were tried and the results are generally robust with respect to the number of lags. A specification with five lags was selected since the long run specifications use five year averages. Using five year lags identifies the mortality effect of fallout exposure that is being averaged in the long run panel.

$$y_{it} = \Sigma_{j=0}^{5} \theta_j * Avg\_X_{it,j} + \alpha_i + \gamma_{st} + \epsilon_{it} \quad (2.3.2)$$

Equation (2.3.2) describes the distributed lag specification for the long run panel regressions. This model uses a similar framework to that of Equation 1, but the exposure of interest consists of lagged five year averages of the I-131 exposure measures. The variable $Avg\_X_{it,j}$ denotes the average exposure term with j lags. This distributed lag structure measures the dynamic mortality response to county level radiation exposure over a longer time horizon. Fallout in the current year is excluded from the regression and only past deposition patterns provide variation. This model uses variation in average fallout exposure one to five years prior, six to ten years prior, eleven to fifteen years prior, sixteen to twenty years prior, and twenty-one to twenty-five years prior to identify the temporal extent to which fallout affected mortality patterns.

2.3.2 Identification and Sample

The source of identifying variation in the empirical analysis comes from within county variation in radiation exposure across years after controlling for state specific annual shocks. There are two main assumptions that allow for measurement of the causal effect of fallout upon mortality. The first assumption is that the exposure variable is orthogonal to the unobserved error term. The second assumption is that most people who were exposed to radioactive fallout eventually die in the county where they were exposed.

Fallout exposure from nuclear testing is a plausibly exogenous event. First, the public generally cannot observe whether they are exposed to radioactive pollution. Radioactive threats generally are imperceptible. Second, the public generally did not know about the polluting effects of the NTS until long after atmospheric testing was suspended. The imprecise public knowledge regarding the effects of fallout exposure prior to 1978 suggests such behavior would be unlikely for much of the country. One challenge to the orthogonality assumption is that people living in the counties surrounding the NTS could observe radioactive dust blows from atomic tests and might have engaged in avoidance behaviors. In order to avoid these potential endogeneity issues, I exclude the counties surrounding the NTS and those counties listed as Downwind by the US Department of Justice (2016) from the empirical analysis.[10] Outside of these counties, people would have been exposed to fallout through the irradiated food supply and not by visible radioactive dust blows.

The second assumption is necessary to measure the treatment effect of fallout upon mortality patterns. Since exposure is at the county level rather than individual level, identification relies on people dying in the counties where exposure is reported. In and out migration would introduce measurement error in the treatment variable. If migration decisions are not systematically correlated with radiation exposure, then migration bias should attenuate the effect of radiation exposure on mortality as the time between the exposure event and reported deaths widen.

2.3.3 Public Health Data

The empirical analysis uses a county-level annual panel constructed by Bailey et al. (2016) of crude deaths from 1915 to 2007 from Annual Reports of the U.S. Vital Statistics. A subsample from 1940 to 1988 forms the panel for the bulk of the empirical analysis and is selected for its completeness of county level coverage. This panel is used to measure the geographic and temporal extent to which radioactive pollution from the NTS harmed human health. The crude death rate per 10,000 individuals approximates the total mortality effect associated with fallout exposure. Exposure to ionizing radiation can increase cancer risks, but exposure might also make persons less healthy overall and increase non-cancer related mortality rates.

2.3.4 Fallout Exposure Data

In 1983, Congress authorized the Secretary of Health and Human Services to investigate and measure thyroid doses from I-131 in American citizens. The NCI undertook

[10] A total of 26 counties are excluded from the analysis. These counties are all located in AZ, CA, NV, and UT. Relatively speaking, very few individuals resided in these counties during the testing period and these areas experienced large quantities of fallout deposition. Including these counties into the sample does not substantially affect the estimates using milk exposure but substantially affects the precision of the deposition measures. Including an interaction term for these counties or taking the log of the treatment variable corrects for the imprecision these counties introduce for the deposition measure.

the task of gathering radiation monitoring station data from historical records. With these records and weather station data the NCI could track the position of the radiation cloud, determine how much radiation would deposit with precipitation, and employ kriging techniques to estimate fallout deposition in counties without monitoring stations. Much of the raw data came from national monitoring stations whose number varied across time, but never exceeded 100 stations. The military also engaged in air monitoring and used city-county stations around the NTS to track the radiation cloud National Cancer Institute (1997).[11] These are the most complete and comprehensive measures for fallout deposition from nuclear tests for the United States.

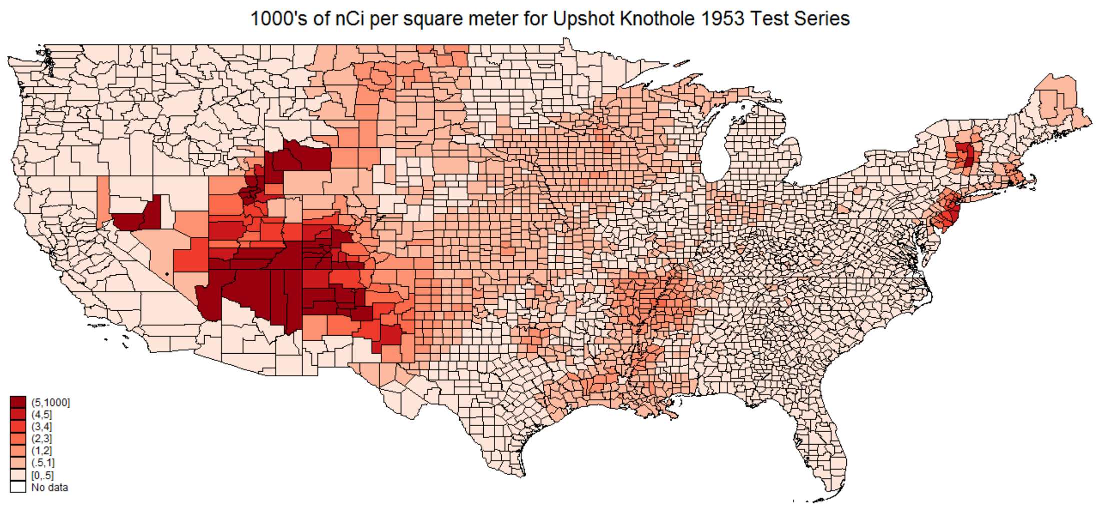


Figure 2.1: Cumulative I-131 Deposition Measures from Upshot Knothole Series. Source: Created from National Cancer Institute (1997)

The data employed in this paper are derived from the NCI estimates. The NCI provides estimate for I-131 deposition for each nuclear test conducted from 1951 to 1958, except for three tests in the Ranger 1951 series.[12] The depositions are measured as nanoCuries (nCi) per meter squared and are reported for each day following a nuclear test until the next subsequent test in the series. Figure 2.1 provides a map of my deposition data for the Upshot Knothole test series. This map show how geographically extensive and heterogeneous fallout patterns are across the country. Notice how states such as Vermont and New Jersey experienced large depositions in 1953.

[11]The locations of monitoring stations is not available through National Cancer Institute records.

[12]The National Cancer Institute is currently trying to create estimates for deposition using simulation methods since monitoring station data is missing for the first three Ranger tests. These tests are not included in this paper's analysis.

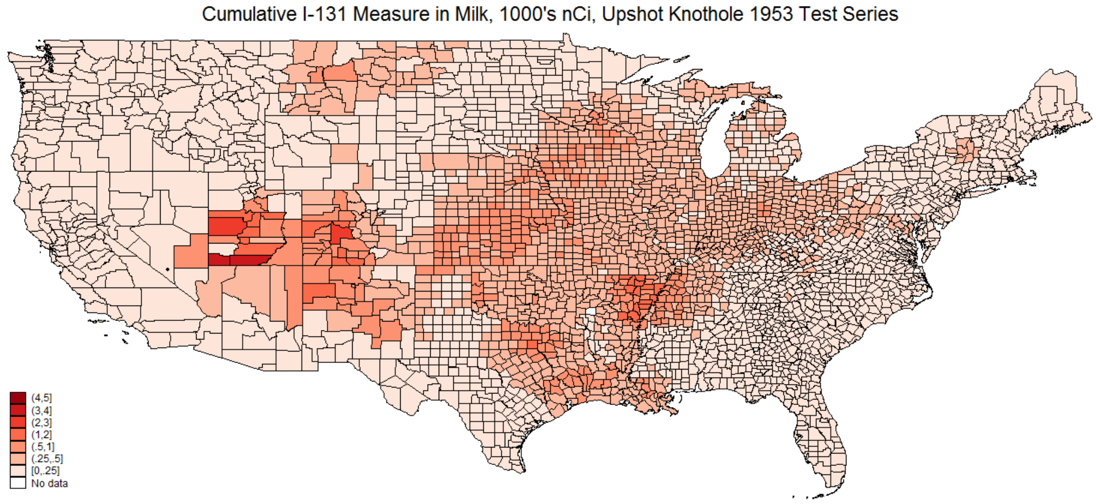


Figure 2.2: Cumulative I-131 Milk Measures from Upshot Knothole Series.
Source: Created from National Cancer Institute (1997)

The NCI also provides daily integrated estimates for I-131 secreted in locally produced milk. These measures are a function of how cows metabolize and secrete iodine at different levels of exposure, grazing practices during the testing window, and the levels of radiation deposition estimated in the kriging model. This methodology can cause substantial differences between radiation presence in milk estimated at the county level and deposition. During the 1950's, many households consumed locally produced dairy, and I-131's short eight-day half-life means that persons would consume it before the radioactive I-131 would decay. Children would be especially vulnerable to this radiation exposure channel because they tended to drink more milk than adults, had smaller thyroids, and were still growing during this period (National Cancer Institute, 1997). Since a child's thyroid is smaller than an adult's, the same quantity of I-131 would cause greater damage because it would be concentrated into a smaller area. Furthermore, the thyroid regulates growth and development. Harm to this organ might lead to unanticipated long term health problems. Figure 2.2 provides a map of my milk exposure data for the Upshot Knothole test series.[13] Notice how milk measures vary from the deposition measures. Areas with the highest levels of ground deposition around the NTS have relatively low levels of I-131 present in the local milk supply.

[13] A small number of counties in both the deposition and milk measures consistent of sub county units. I created weighted averages of exposure at the county level from these subcounty units. In the analysis, these counties are excluded from the main sample. Other counties and Virginia Independent Cities are omitted from the sample due to data limitations.

The counties downwind of the NTS experienced fallout mostly as dry precipitate, and according to the agronomic data provided by the NCI, dairy cows in these areas consumed very little local pasture. This can create a substantial difference in the estimated exposure via milk versus estimated exposure via deposition.

$$ICM_{pij} = \int_0^{\infty} C_p(ijt) * P(ijt) * f_m dt \tag{2.3.3}$$

Equation (2.3.3) refers to the NCI's methodology for estimating daily I-131 concentrations in milk from deposition data. ICM_{pij} denotes the Integrated I-131 concentration in milk produced in pasture p in county i on day j and is measured in daily nCI per liter of milk. $C_p(ijt)$ denotes average daily concentration after deposition day. It is a function of deposition of I-131 and the fraction of this I-131 intercepted by plants. $P(ijt)$ denotes the average pasture consumption rate by cows and was constructed from agronomic studies relating to pasturing behavior of dairy farmers during the 1950's. The value f_m denotes I-131 intake to milk transfer coefficient. This value was constructed from milk secretion studies where cows were fed radioactive iodine. These adjustments are made at the state level and should not be systematically correlated with any unobserved underlying economic or environmental conditions that would affect county mortality. The quantity of pasture a cow consumes on an average day and how long pastures are available to farmers during the year do not have any apparent relationship with crude death rates. These factors affect annual mortality rates only by altering the amount of I-131 entering the local food supply.

2.4 Empirical Results

2.4.1 Panel Regression Results

The empirical results suggest that fallout exposure due to NTS atomic testing led to persistent and sizable increases in mortality for large areas of the continental United States. The measured effect is generally larger for specifications using the milk exposure measure than the raw deposition measure. In the short run panel regressions, exposure to fallout through milk leads to immediate and sustained increases in the crude death rate. In the long run panel regressions, both deposition and the milk exposure regressions are associated with large increases in mortality following fallout exposure events. Finally, human exposure to fallout measured by I-131 in milk continues to have positive and statistically significant effects after the inclusion of state-by-year fixed effects, while the coefficients of the deposition measures attenuate towards zero.

Table 2.1: Fallout and mortality summary statistics

	mean	sd	count	min	max
Crude Death Rate (CDR) per 10,000	100.977	25.075	124,260	8.597	564.871
I-131 Dep., 1,000's nCi	0.047	0.229	124,260	0	7.837
Avg Dep. 1 to 5 years prior, 1,000's nCi	0.052	0.141	124,260	0	6.608
I-131 in Milk, 1,000's nCi	0.030	0.136	124,260	0	4.600
Avg Milk 1 to 5 years prior, 1,000's nCi	0.032	0.079	124,260	0	1.857

Summary statistics for the sample used in the empirical regressions are provided in Table 2.1. Six different specifications are reported in each table of the empirical section. Specifications 1 through 3 report the effect using the milk exposure variable and specifications 4 through 6 report the effect using the deposition variable.[14] For both the milk and deposition measures, specifications with only fixed effects, including time trends, and the full specification are reported.

[14]Using both variables together introduce substantial multicollinearity but results in positive and statistically significant effects for the milk measures and statistically insignificant effects for deposition measures.

Table 2.2: Short run mortality effects, crude death rate, 1940-1988

	(1)	(2)	(3)	(1)	(2)	(3)
	Milk Exposure, 1,000's nCi			Deposition Exposure, 1,000's nCi		
Exp, t	-0.113	0.997**	2.469**	0.181	-0.352	0.635
	(0.551)	(0.505)	(0.981)	(0.333)	(0.296)	(0.457)
Exp, t-1	1.475***	2.115***	4.286***	1.029***	0.415	0.949*
	(0.524)	(0.461)	(0.764)	(0.297)	(0.275)	(0.566)
Exp, t-2	2.006***	2.509***	4.379***	1.238***	0.689***	0.879**
	(0.570)	(0.493)	(0.937)	(0.277)	(0.246)	(0.406)
Exp, t-3	1.554***	1.378***	2.287***	0.884***	0.320	0.556
	(0.514)	(0.461)	(0.852)	(0.282)	(0.279)	(0.462)
Exp, t-4	2.866***	2.664***	2.708***	1.370***	0.806***	0.531
	(0.539)	(0.497)	(0.833)	(0.321)	(0.283)	(0.366)
Year FE	Yes	Yes	Yes	Yes	Yes	Yes
County FE	Yes	Yes	Yes	Yes	Yes	Yes
State Time Trends	No	Yes	No	No	Yes	No
State Year FE	No	No	Yes	No	No	Yes
N	124,260	124,260	124,260	124,260	124,260	124,260

* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$
All Standard Errors are Clustered by County. Exp denotes the yearly cumulative I-131 measures at the county level.

The discussion for the results refer to the specification with the most controls, which are specifications 3 and 6 in the tables. The results regarding short term mortality effects of radiation exposure appear in Table 2.2. Both milk exposure and deposition exposure measures are associated with increases in crude death rates over several years of lags. All of the milk exposure coefficients are statistically significant at the 5 percent level, but only the deposition coefficients for the first and second lags are statistically significant at the 10 percent level. Comparisons across specifications show that the inclusion of state-by-year fixed effects increases the magnitude of the estimated coefficients. The results suggest that 1,000 nCi of I-131 in the local milk supply leads to an additional 2.47 additional deaths per 10,000 residents in a given year, 2.89 deaths the subsequent year, 4.38 deaths two years later, 2.87 deaths three years later, and 2.71 four years later. The deposition estimates suggest that 1,000 nCi of deposition per m^2 increases the mortality rate by an additional 0.95 deaths per 10,000 two years following deposition and 0.88 deaths per 10,000 three years following deposition.

Table 2.3: Long run mortality effects, crude death rate, 1940-1988

	(1)	(2)	(3)	(4)	(5)	(6)
	Milk Exposure, 1,000's nCi			Deposition Exposure, 1,000's nCi		
Exp, t-1 to t-5	13.59***	11.29***	12.93***	7.734***	3.881***	1.878
	(1.684)	(1.584)	(2.774)	(1.264)	(1.204)	(2.083)
Exp, t-6 to t-10	13.11***	8.676***	7.041**	6.797***	3.501***	-0.362
	(1.599)	(1.565)	(2.962)	(1.263)	(1.181)	(1.794)
Exp, t-11 to t-15	10.39***	4.854***	0.143	5.314***	2.346**	-1.507
	(1.662)	(1.588)	(2.888)	(1.167)	(1.018)	(1.425)
Exp, t-16 to t-20	7.239***	1.411	-7.894**	2.667**	0.0859	-5.502***
	(1.786)	(1.680)	(3.520)	(1.140)	(0.979)	(1.353)
Exp, t-21 to t-25	7.834***	-2.317	-5.779**	2.513***	0.0434	-2.909***
	(1.915)	(1.414)	(2.801)	(0.847)	(0.587)	(1.110)
Year FE	Yes	Yes	Yes	Yes	Yes	Yes
County FE	Yes	Yes	Yes	Yes	Yes	Yes
State Time Trends	No	Yes	No	No	Yes	No
State Year FE	No	No	Yes	No	No	Yes
N	124,260	124,260	124,260	124,260	124,260	124,260

* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$
All Standard Errors are Clustered by County. Exp denotes the pooled five year averages of cumulative I-131 measures at the county level.

The long run mortality effects for both I-131 deposition and milk exposure channels appear in Table 2.3. Across most specifications there are positive and statistically significant increases in mortality attributable to NTS activities up to 25 years following the last atmospheric nuclear denotation at the NTS. Specifications including state-by-year fixed effects have negative coefficients on average exposure measures sixteen to twenty and twenty-one to twenty-five years following deposition. These results might arise from a harvesting effect if exposure to NTS fallout led to more people dying younger.

In specification 3, an average of 1,000 nCi in I-131 in milk one to five years prior contributes to an additional 12.93 deaths per 10,000 residents. An average of 1,000 a Ci in I-131 in milk six to ten years prior causes 7.04 additional deaths per 10,000. For average milk exposure eleven to fifteen years prior, and the coefficient reduces to 0.14 deaths per 10,000. The negative coefficients that appear after the inclusion of state-by-year fixed effects suggest that an average of 1,000 nCi in I-131 in milk sixteen to twenty and twenty-one to twenty-five years prior led to 7.89 and 5.78 fewer deaths per 10,000 individuals. Specification 6 finds no statistically significant and positive relationship between fallout deposition and mortality. The same coefficients for the exposure lags sixteen to twenty-five years following deposition suggest that 1,000 nCi of deposition led to 5.50 and 2.91 fewer deaths per 10,000. These coefficients are statistically significant at the 1 percent level.

2.4.2 Quantifying the Magnitude of the Effects and the Policy Implications of the Partial Nuclear Test Ban Treaty

The effects upon crude mortality are large relative to estimates by Simon and Bouville (2015) and comparable (or even larger) to the number of deaths attributable the atomic bombings of Hiroshima and Nagasaki. I perform a series of back-of-the envelope calculations to quantify the total mortality effect of NTS atomic testing. I use the long run coefficients of average exposure one to five, six to ten, and eleven to fifteen years prior to calculate this increase and then multiple them by the national crude death rate for the given year to estimate the total increase in the crude death rate per 10,000 individuals. I add together the three coefficients of interest to measure the total

Figure 2.3: Average Increase in Crude Deaths Per 10,000 attributable to I-131 in Milk, 1951 to 1973.
Source: Author's calculations

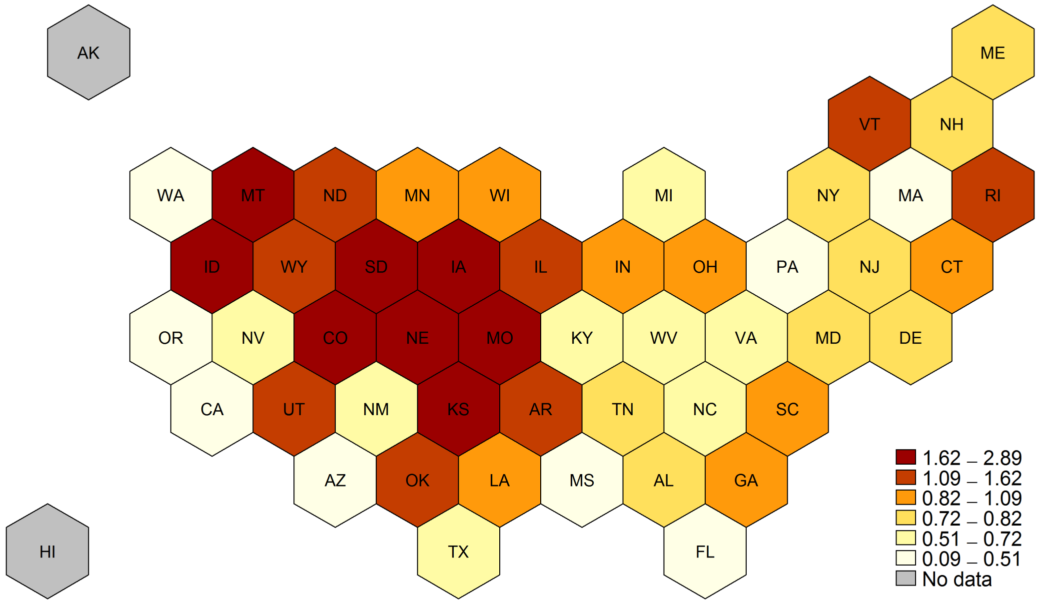
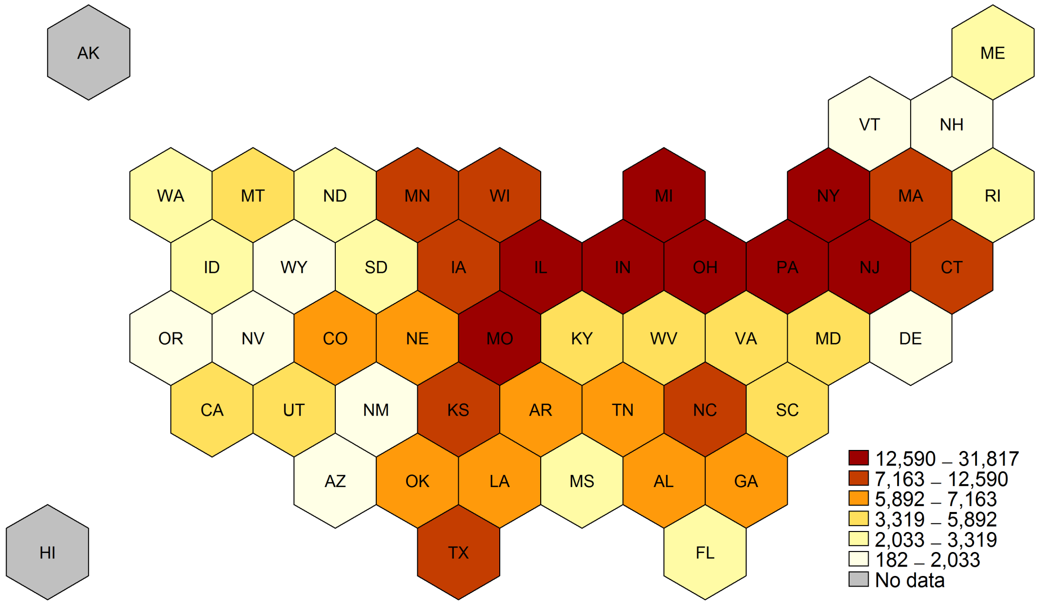


Figure 2.4: Total Increase in Crude Deaths to I-131 in Milk, 1951 to 1973.
Source: Author's calculations



increase in the crude death rate for each specific county year observation between 1951 and 1973.[15] I multiply the estimated mortality effect by annual county populations and sum the totals across counties across years to estimate the total number of deaths attributable to atmospheric testing.[16]

[15]The final atmospheric test in my data was in 1958.
[16]Specification 6 is excluded from these calculations because it reports a null effect upon mortality.

Table 2.4: Changes in county mortality patterns attributable to NTS fallout, 1951 to 1973

I-131 In Local Milk

	Mean	SD	Max	Total Deaths
Spec. 1	1.21	1.90	26.26	695,436
Spec. 2	0.81	1.32	20.98	458,506
Spec. 3	0.65	1.28	24.01	359,360

I-131 Ground Deposition

	Mean	SD	Max	Total Deaths
Spec. 4	1.06	1.78	51.10	692,407
Spec. 5	0.52	0.88	25.64	338,472
Spec. 6	-	-	-	-

Source: Author's calculations

Table 2.4 presents these calculated cumulative mortality effects. Depending on the regression specified, I-131 in milk contributed between 395,000 and 695,000 excess deaths from 1951 to 1973. The average increase in mortality across counties is between 0.65 and 1.21 additional deaths per 10,000 people for this same period. The estimates from deposition suggest that fallout contributed between 338,000 and 692,000 excess deaths over the same period. These effects are approximately 7 to 14 times larger than estimates provided by the NCI. When these effects are mapped out many of these estimated deaths occurred in regions far from the NTS. Figure 2.3 reports the average annual effects of radiation exposure through milk on mortality for years 1951 to 1973. Figure 2.4 reports the total increase in state deaths for the same period. The model suggests much of the death effect appears in the Midwest and Eastern U.S. where larger populations would have been exposed. The per capita mortality effects tend to be greatest out west in the Plains and in states north and east of the NTS.[17]

[17] Running the regressions and including the excluded counties surround the NTS does not substantially change the patterns described in these maps.

Table 2.5: Placebo test: Log crude death rate, 1937-1950

	(1)	(2)	(3)	(4)	(5)	(6)
	Milk Placebo , 1,000's nCi			Deposition Placebo, 1,000's nCi		
Exp, t	-1.215*	-0.476	-1.563	-0.339	-0.461	-0.232
	(0.688)	(0.707)	(1.751)	(0.269)	(0.281)	(0.369)
Exp, t-1	-0.511	-1.216**	-3.388	-0.297	-0.480	-0.460
	(0.589)	(0.594)	(2.425)	(0.298)	(0.312)	(0.647)
Exp, t-2	0.548	-1.219**	0.189	-0.114	-0.333	-0.0243
	(0.570)	(0.584)	(0.903)	(0.246)	(0.266)	(0.307)
Exp, t-3	2.999***	0.651	0.603	0.525**	0.258	-0.111
	(0.624)	(0.621)	(0.970)	(0.234)	(0.230)	(0.351)
Exp, t-4	2.824***	-0.589	1.055	0.464*	0.0748	0.0660
	(0.589)	(0.600)	(0.867)	(0.255)	(0.247)	(0.334)
Year FE	Yes	Yes	Yes	Yes	Yes	Yes
County FE	Yes	Yes	Yes	Yes	Yes	Yes
State Time Trends	No	Yes	No	No	Yes	No
State Year FE	No	No	Yes	No	No	Yes
N	42,096	42,096	42,096	42,096	42,096	42,096
Adj r^2	0.607	0.615	0.618	0.606	0.615	0.618

All Standard Errors are Clustered by County. Placebo Exp denotes the yearly cumulative I-131 measures at the county level. These placebo measures consist of I-131 measures being shifted forward thirteen years. i.e. Exposure in 1951 recoded as 1938, 1952 as 1939, 1953 as 1940, etc. Three tests for 1945 were conducted in New Mexico but their yields were relatively small. The corresponding Hardtack tests of 1958 were also small in scale and most radiation release remained near the Nevada test site in 1958.

2.4.3 Robustness Checks

I perform a falsification test to test whether unobserved underlying factors were driving the crude death results. I select a sample of counties from 1937 to 1950 and reassign the radiation exposure measures to the years of 1938, 1939, 1940, 1942, 1944, and 1945. The results are available in Table 2.5. I find no evidence that either the fallout deposition or fallout in milk measures had a systemic relationship with the log crude death rate between 1911 and 1950.[18]

2.5 Policy Implications of 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 $8.93 Trillion in 2016$ (Schwartz, 2011). These monetary costs, however, do not fully capture the full social cost of America's nuclear weapons program. Since the 1990's the Federal Government has paid some compensation to victims of America's domestic nuclear weapons program. This compensation has focused on workers involved in the nuclear weapons program and those who lived downwind of the NTS during the 1950's. The U.S. Department of Justice pays out compensation to domestic victims of the nuclear weapons program through the Radiation Exposure Compensation Act. As of 2015 the U.S. Department of Justice has paid out over $2 billion in compensation to victims (US Department of Justice, 2016).

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 $1.4 million and $8.8 million in 2016$. These values and my estimates from the preferred specification place the value of lost life between $473 billion and $6,116 billion in 2016$. Costa and Kahn (2004) use a hedonic wage regressions on industrial sector mortality risks to back out plausible market values for human life for each decade from 1940 to 1980. Using their values, I estimate the value of lost life from ground deposition between $1.24 and $2.56 trillion in 2016$. The estimates from milk exposure places the value of lost life between $1.17 and $2.63 trillion. The social cost of excess deaths attributable to atmospheric testing at the NTS

[18] Additional robustness checks included taking the log of the exposure variable, adjusting the number of lags, including the excluded counties, and interacting the structural parameters used in calculating the milk measures with deposition. The mortality effect remains robust to specification choice. The inclusion of the excluded counties does not change the mortality effect for the dairy measures but introduces additional imprecision with the deposition estimates. This imprecision is resolved either through interacting the exposure variable with and indicator variable for these counties or by logging the treatment variable.

ranges from approximately 5.3 percent to 68.4 percent of the total cost of America's nuclear weapons program. These values, however likely understate the magnitude of the social costs of this polluting and environmentally destructive activities. Exposure to radioactive fallout likely made millions of people less healthy, negatively affected human capital, and increased the cost of providing health services to these populations. These costs are not fully captured by measuring the effect of nuclear testing upon mortality rates.

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 (US Department of Energy, 2000).[19]

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 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 212,000 and 435,000 lives. Employing the same back of the envelope calculation, the Partial Nuclear Test Ban Treaty might have saved between 11.7 and 24.0 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

[19]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.

testing above ground. Second, even without the moratorium and treaty, there was mounting scientific and medical evidence that NTS activity were harmful to public health. 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 more pronounced. 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.

Table 2.6: AP2 ranking of 3,100 alternative nuclear test site locations

Location	Pollution Intensity	Rank
Locations Under Consideration by Policy Makers		
Nevada Test Site (Nye County), NV	1	39
White Sands (Dana Ana County), NM	3.327	953
Cape Hatteras (Dare County), NC	2.167	495
Top Five Least Polluting Counties		
Modoc County, CA	0.251	1
Lake County, OR	0.303	2
Monroe County FL	0.342	3
Klamath County, OR	0.394	4
Del Norte County, CA	0.394	5
Top Five Most Polluting Counties		
Nassau County, NY	186.829	3,096
Essex County, NJ	196.218	3,097
Hudson County, NJ	262.022	3,098
Bergen County, NJ	362.736	3,099
Queens County, NY	440.651	3,100

Parameters for AP2 provided by Nicholas Muller. 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 NTS. Emission location is excluded from the calculation.

The location of the NTS in Nye County, Nevada might have contributed towards the level of human exposure to radioactive pollution. In 1950, military and political leaders narrowed down the list of potential atomic bombing ranges to a few locations (Schwartz, 2011). Other locations given serious consideration included the Trinity Test Site located in White Sands, New Mexico and Cape Hatteras, North Carolina. I the use AP2 model from Muller et al. (2011) to construct a counter-factual scenario of potential pollution exposure from these alternative nuclear testing ranges. Nicholas Muller provided me a county to county matrix which measures the effect of pollution emissions from one source county on PM2.5 concentrations in all other counties. If radioactive dust created by atmospheric atomic tests follows similar dispersal patterns as other pollutants, then AP2 can provide a counter-factual scenario and rank counties by how polluting they could have been.

For all counties other than the source county, I weight the PM2.5 coefficients by county population in 1950. I then sum the cumulative effect of a single unit of emissions for each of the 3,100 source counties. This procedure allows me to rank the relative downwind effect of locating the NTS in an alternative county. Counties are ranked from least polluting to most polluting, and Table 2.6 presents the most and least polluting counties.[20] 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 White Sands and Cape Hatteras locations rank as the 953th and 495th least potentially polluting locations. Relatively speaking, White Sands would have been 3.45 times more polluting than the NTS and Cape Hatteras would have been 2.25 times more polluting.[21] These results show that atmospheric testing in the continental U.S. could have plausibly been much worse for American populations and public health if policy makers had chosen an alternative location.

[20] I rank the relative dirtiness of the three mentioned locations and the top and bottom five alternative locations provided by the model in the Appendix.

[21] Intuitively the most polluting locations in the model would be the region surrounding New York City. These predictions are confirmed by the AP2 model. Interestingly, the Pacific Northwest, the Florida Keys, and Upstate Maine are locations that AP2 suggests would have been cleaner locations for testing than Nye, County.

2.6 Conclusion

This paper explores the temporal and geographic extent of the harm caused by atmospheric nuclear tests conducted in Nevada between 1951 and 1958. Using a new national dataset of radiation deposition and quantities of I-131 in the dairy supply, this paper finds that radiation exposure increased crude deaths in areas hundreds to thousands of miles from the test site. The geographic scope of the mortality consequences of NTS activities is broader than what previous research has shown. The largest health effects appear in areas far beyond the scope of previous scientific and medical studies. The scientific and medical literature has studied the effects of atmospheric testing on populations residing in Downwind counties in Arizona, Nevada, and Utah. Counter-intuitively, the areas where fallout had the largest impact on the crude death rate was not in the region surrounding the test site, but rather in areas with moderate levels of radioactive fallout deposition in the interior of the country. Due to pasturing practices, large quantities of fallout wound up in local dairy supplies in these regions but not in the Downwind region. It is quite plausible that extrapolating out the health effects from small samples of persons who lived around the NTS substantially underestimates the health costs associated with atmospheric testing.

The empirical results of this paper suggest that nuclear testing contributed to hundreds of thousands of premature deaths in the United States between 1951 and 1972. The social costs of these deaths range between $473 billion to over $6.1 trillion dollars in 2016$. These losses dwarf the $2 billion in payments the Federal Government has made to domestic victims of nuclear testing through the Radiation Exposure Compensation Act and are substantial relative to the financial cost of the United States' nuclear weapons program. It is likely that the values of both the testing moratorium enacted in 1958 and the Partial Nuclear Test Ban Treaty are understated. These political compromises likely saved hundreds of thousands of additional lives at a minimum.

The evidence presented in this paper reveals that the health cost of domestic nuclear testing is both larger and more expansive than previously thought. The mortality estimates may understate the magnitude of the true number of deaths attributable to nuclear testing and the magnitude of the health costs of this polluting defense policy. It is plausible that these estimates are lower bounds of the true health effects. Migration and measurement error in treatment introduces attenuation bias, and the health effects of radiation exposure may only appear later in life for many individuals. Millions of people who grew up during the testing period are now retiring from the labor force and are drawing upon Medicare and other government provided services. Nuclear testing may have made an entire generation of people less healthy and thus increased the cost of providing health care well into the present. This paper reveals that there are more casualties of the Cold War than previously thought, but the extent to which society still bears the costs of the Cold War remains an open question.

Chapter 3

In the Shadow of the Mushroom Cloud: Nuclear Testing, Radioactive Fallout and Damage to U.S. Agriculture

In the 1950s the United States conducted scores of nuclear tests at the Nevada Test Site (NTS). Each test created tremendous quantities of harmful radioactive material and much of this material deposited across the country with precipitation. This paper is one of the first in the economics literature to measure some of the external costs of NTS activities. I find that fallout from nuclear tests adversely affected U.S. agriculture for large areas of the country. These empirical results show that nuclear testing had much broader economic and environmental impact than previously thought.

3.1 Introduction

The Cold War saw the rapid development and deployment of nuclear weapons. To expedite its nuclear weapons program, the United States started to conduct atmospheric nuclear tests at the Nevada Test Site (NTS) in 1951. This deliberate policy decision created immense quantities of radioactive debris and much of this material rained down across the U.S.. One estimate places the total atmospheric release of radioactive material from the NTS from 1951 to 1963 at 12 billion Curies. In comparison, the partial nuclear meltdown at Chernobyl released approximately 81 million Curies of radioactive material (LeBaron, 1998). Knowledge regarding the impact of this pollution is limited to scientific and health studies conducted in the regions surrounding the NTS. Nuclear testing had large pollution externalities associated with it, but the magnitude and extent of the nationwide harm caused by NTS activities have yet to be measured. This paper quantifies one dimension of the external costs of these activities by studying the adverse effects of radioactive fallout on U.S. agriculture.

The medical and scientific research studying the unintended effects of NTS activities and their social costs has focused primarily upon persons living in the region surround the test site in Nevada, Arizona, and Utah. This region is generally termed Downwind in the historical and popular literature. Researchers studying populations living in these areas have linked increases in thyroid cancer and leukemia to NTS activities (Gilbert et al., 2010; Kerber et al., 1993; Stevens et al., 1990). Furthermore, the experimental literature suggests that fallout from nuclear testing would have adversely affected agriculture (Bustad et al., 1957; Sparrow et al., 1971; Garner, 1963). To date no research has attempted to measure the actual effect radioactive fallout may have had upon U.S. agriculture hundreds to thousands of miles from the NTS.

To test if NTS fallout adversely affected U.S. agriculture and measure the geographic scale of the effects, I develop a new annual county-level panel of data measuring fallout exposure from records obtained from the National Cancer Institute (1997) through a Freedom of Information Act request. Combining this data with records on agricultural production, I exploit within county level variation in radioactive fallout deposition across years to measure the effect of nuclear testing upon U.S. agriculture between 1951 and 1970. This methodology allows me to measure to what extent NTS activities affected domestic agricultural production. This paper adds to a small but growing economics literature using variation in radioactive pollution as a source of exogenous variation. Almond et al. (2009) and Black et al. (2013) use low doses of ionizing radiation to test the fetal origins hypothesis in Scandinavian populations. Lehmann and Wadsworth (2011) and Danzer and Danzer (2016) research measure the effects of the Chernobyl disaster in Ukraine on self-reported measures of wellbeing. More recent studies have explored how perceptions of the Fukashima nuclear disaster have been internalized in land values (Kawaguchi and Yukutake, 2017) and consumer behavior (Ito and Kuriyama, 2017). I contribute to this literature by being the first in the economics literature to study the direct effects of radioactive pollution upon agricultural production. Apart from a concurrent paper measuring the effect of NTS fallout on U.S. mortality patterns, *redacted*, this is the first paper in the economics literature to study the effects of nuclear testing on the American economy.[1]

[1]Domestic atmospheric nuclear testing in the 1950's led to a unique intersection between government policy, pollution, and disaster. Past economic studies have used natural disasters, pests, and

3.2 Historical and Scientific Background

History of Nuclear Testing

In 1949 the Soviet Union defied expectations and detonated its first atomic bomb. This event caused the U.S. to accelerate its own nuclear weapons program. Most American nuclear tests occurred in the Pacific Ocean before 1951. These tests were logistically complicated, costly, and were implemented slowly. Policy makers wanted to start testing immediately and settled on establishing the Nevada Test Site (NTS) on public land just northwest of Las Vegas. The location of the base was chosen because of its relatively secluded location, access to public land, and proximity to government laboratories (National Cancer Institute, 1997).

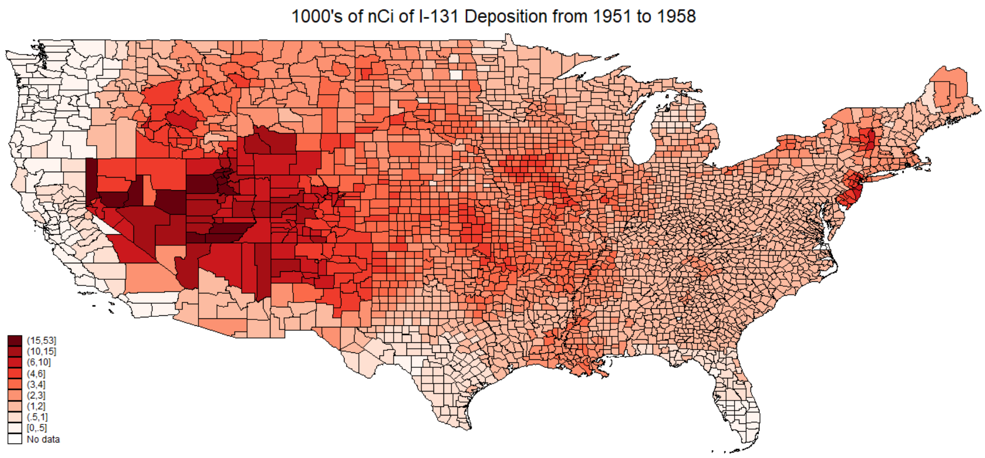


Figure 3.1: Total I-131 Fallout Deposition by County, 1951-1958.
Source: Created from National Cancer Institute (1997)

The period of domestic nuclear testing lasted from 1945 until 1992, as the United States conducted 1,054 tests in total. A total of 828 underground blasts and 100 above-ground detonations occurred at the NTS (US Department of Energy, 2000).[2] Above ground nuclear testing started at the site in 1951 and ended with the signing of the Partial Nuclear Test Ban Treaty in 1963. Figures 3.1 provides a county specific radiation deposition map created from the data used in this paper. This map reports

variation in weather to study the social costs of these rare events. See Lange et al. (2009), Boustan et al. (2012), and Hornbeck (2012) for studies regarding the effects of natural disaster on agriculture. For examples of how policy decisions made decades ago can have long run consequences see Troesken (2008) and Clay et al. (2014).

[2]The U.S. conducted 24 tests on behalf of the U.K. at the NTS and these are included in the total. 106 tests occurred in the Pacific and 20 more at various other locations.

cumulative deposition of I-131 per meter squared from 1951 to 1958 for the continental United States. The map highlights the variation in exposure to radiation attributable to these tests. The West Coast is upwind of the NTS and is relatively unexposed; regions surrounding the NTS would only experience dry precipitate from the tests as experimenters accounted for meteorological conditions within a few hundred km of the test sites when picking the test dates. The overwhelming majority of the fallout landed in the eastern United States as wet precipitate, far away from the NTS (National Cancer Institute, 1997).

The Science of Radiation Exposure

During the period of atmospheric testing and the decades following, the public generally did not know the extent to which the public was exposed to radioactive material generated from NTS tests. Even scientists were debating whether low doses of radioactive fallout were harmful and how much was entering the food supply. During the period of testing, academic researchers and persons in the medical field noticed that radioactive Iodine-131 started to appear in animal and human thyroids and connected these results with the timing and incidence of domestic atomic tests (Comar et al., 1957; Van Middlesworth, 1956; Beierwaltes et al., 1960). Other researchers found long lived isotopes of Strontium-90 absorbed by wheat hundreds to thousands of miles from the test site (Kulp et al., 1958,?; Rivera, 1961; Olson, 1962). The Public Health Service (PHS) and Atomic Energy Commission (AEC) at the time corroborated these findings but expressed doubt regarding the risks posed by these levels of radiation (Flemming, 1959, 1960; Wolff, 1957, 1959). Comprehensive studies measuring the extent to which American populations were exposed to NTS fallout began in the 1980's when Congress mandated that the Department of Health and Human Services study the issue (National Cancer Institute, 1997; Center for Disease Control, 2006).

America's nuclear weapons program was and continues to be surrounded by secrecy. During the testing period most research into the biological effects of radiation was funded through the AEC and internal reports suggesting that atmospheric testing posed a public health hazard were suppressed. In the region surrounding the NTS, the PHS and AEC actively spread disinformation regarding the dangers of radioactive pollution resulting from atomic tests. The suppression of medical information and these disinformation campaigns were only brought to public attention through Freedom of Information Act requests in 1978 (Ball, 1986; LeBaron, 1998; Fradkin, 2004).[3]

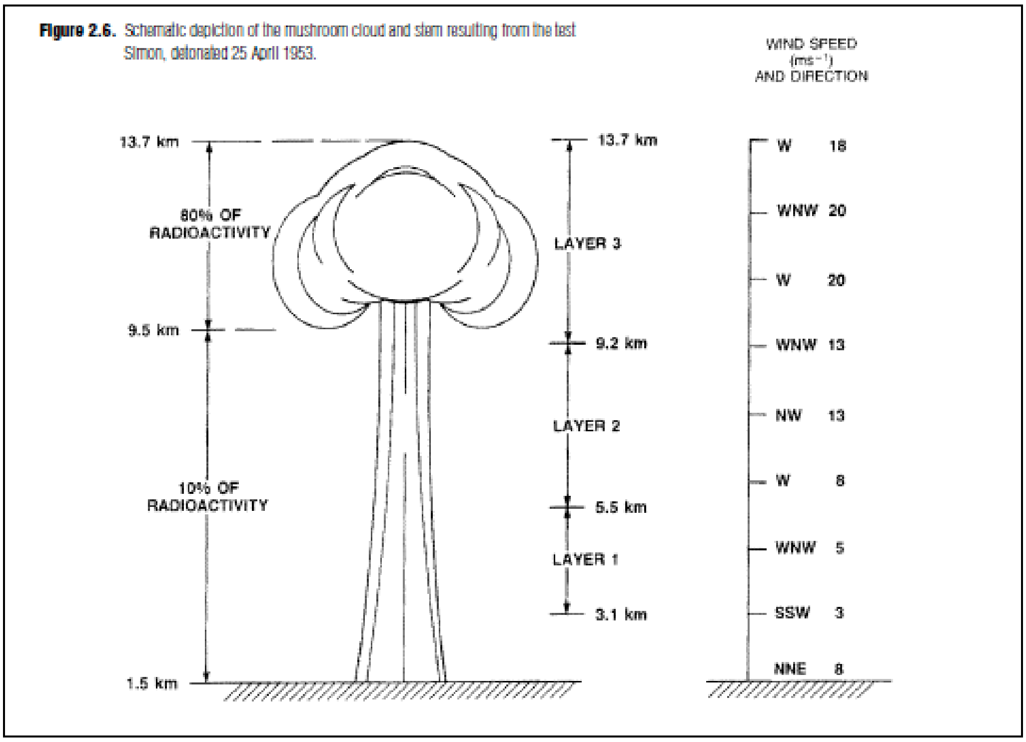


Figure 3.2: Mushroom Cloud and Wind Patterns.
Source: National Cancer Institute (1997)

When atomic bombs were detonated, a tremendous amount of energy was released and caused splitting of the atoms in surrounding material. Atmospheric denotations conducted near the surface of the earth irradiated thousands of tons of material. This material was then drawn up into a mushroom cloud many kilometers up into the atmosphere. Figure 3.2 provides a diagram describing the 1953 Simon test shot. This figure describes how winds intercepted radioactive material. A portion of the radioactive material was intercepted by low altitude winds and deposited in the surrounding area as dry precipitate. In the downwind region, this radiation was carried as radioactive dust blows. Most of the material, however, was carried higher up and intercepted by high altitude winds. This radioactive material traveled vast distances and was deposited hundreds to thousands of miles from the test site as wet precipitate. In the

[3]The Freedom of Information Act was first enacted in 1966. Obtaining internal government records from the PHS, DOD, and AEC prior to this legislation would have been very difficult if not practically impossible.

days following the test, areas outside of the Downwind region experienced radioactive fallout only if it happened to be raining while the radiation cloud was over head. Rain scavenged radioactive dust from the cloud and delivered it to the ground. The agricultural regions studied in this paper would only experience fallout exposure through wet precipitate. As such, radioactive deposition from atomic testing can be treated as any exogenous event that would be uncorrelated with unmeasured aspects of farm production.

After radiation was dispersed across agricultural fields, plants absorbed radioactive material and animals consumed contaminated grass. This radiation then might have caused sickness in animals and have been secreted in animal milk. Anecdotal and legal evidence suggests that nuclear test fallout harmed ranchers and farm animals living in the vicinity of the NTS. Note that this region is closer to the test site than the areas examined in this paper and the exposure mechanism differed because radioactive material was deposited through radioactive dust blows and not scavenged through precipitation. In 1954, ranchers in Iron County, UT sued the U.S. Federal Government asserting that their animals had died because of radioactive fallout from 1953 tests at the Nevada Test Site (NTS). These animals fell ill after consuming irradiated pasture in northern Nevada. In 1979 the U.S. Interstate and Commerce Committee opened an investigation into reported incidents of animal deaths from radiation poisoning because of the 1953 Upshot Knothole test series. The report discussed the fact that thousands of sheep and lambs belonging to the Iron County farmers died during the spring and summer of 1953. Around 12.1% of lambing ewes and 25.4% of new lambs died or were stillborn. The report also details independent veterinary assessments identifying radiation poisoning and birth defects in the animals and the subsequent government cover-up conducted by both the Atomic Energy Commission and Public Health Service (US Government Printing Office, 1980).

Further corroborating the story of the Utah ranchers, General Electric scientists Bustad et al. (1957) ran experiments on the biological and health effects of radioactive I-131 in sheep. Starting in 1950, they fed groups of sheep varying daily doses of I-131 from .005 nCi to 1800 nCi and followed the effects across years and generations. Starting at 15 nCi animals showed growth retardation and deformities, thyroid damage, reduced fertility, trouble nursing, motor difficulty, patchy skin, and balding. At higher doses researchers found that ewes that were impregnated failed to give birth to viable offspring. A comprehensive survey of the literature on the toxicity of radioactive isotopes by Garner (1963) suggests that radioactive toxicity is greater in sheep than cattle and that relatively low amounts of exposure reduced offspring viability, increased difficulty nursing, and stunted growth.

Scientific research also finds that ionizing radiation can adversely affect crops and that winter wheat is particularly vulnerable to damage. Radiation can hamper seedling development, weaken resilience, and cause plant sterility. Studies into how gamma and beta radiation exposure alter plant growth suggest that ionizing radiation hampers seed germination, growth, and reproduction (De Micco et al., 2011). Sparrow et al. (1971) summarize the effects of different levels of radiation for crop survival in experiments to explore the effects of a nuclear war upon agriculture. They found that large radiation doses can lead to diminished yields depending on the time crops are exposed. In this paper I test whether realized exposure to radioactive pollution resembles these experimental findings while also measuring the broader geographic extent of the damages from radiation releases from NTS tests.

According to Sparrow et al. (1971), winter wheat is particularly susceptible to harm. Irradiated winter wheat in field trials failed to survive winter hibernation. This evidence suggests that radioactive exposure to radioactive material reduces wheat's cold tolerance. Furthermore, winter wheat is planted in the fall and is harvested in the subsequent late summer or fall. This long growing period means that the crop would have had prolonged exposure to ionizing radiation. Most of the nuclear tests examined in this paper were conducted in March and April and thus radiation landed on fields when winter wheat was most vulnerable. This radiation may have stunted plants and led to crop failure.

3.3 Empirical Methodology and Data

Annual County Panel Regression Model

In order to test whether or not atmospheric nuclear testing at the NTS had adverse effects on U.S. agriculture, I perform a series of panel regressions with multiple lags of fallout deposition. These econometric models identify the effect of radioactive fallout had on agricultural production. Equation 3.3.1 represents the full specification of the regressions employed in measuring how fallout from nuclear tests altered agricultural productivity. This model allows me to test if fallout from nuclear tests affected crop production and livestock.

$$ln(Y_{it}) = \beta_0 * E_{it} + \beta_1 * E_{it-1} + \beta_2 * \overline{E_{it-2,t-5}} + \beta_3 * \overline{E_{it-6,t-10}} + \boldsymbol{X_i} * \boldsymbol{\gamma_t} + \boldsymbol{\lambda_{it}} * \phi + \boldsymbol{\alpha_i} + \epsilon_{it} \tag{3.3.1}$$

Y_{it} denotes the outcome of interest such as the bushels produced per acre planted in county i at time t, acres harvested, and livestock numbers. I use yield per acre planted because farmers may have opted to only harvest productive acreage in the event of sporadic crop damage. The use of yield per acre harvested, would understate the true magnitude of a negative productivity shock because it would not capture the losses associated with the acreage that was planted but abandoned and not harvested. This would lead to greater amounts of abandoned acreage and would be reflected in yield per acre planted.

The main variable of interest is E_{it}. This variable measures the total I-131 deposition in County i in Year t, as thousands of nCi per square meter. It is a proxy for total radioactive fallout deposition resulting from each nuclear test series. To determine potential longer ranged effects, I include a lag of E_{it} and average depositions for testing in prior year. I pool average deposition two to five years prior and six to ten years prior. Pooling these lags reduces a profusion of coefficients.[4]

[4] In the regressions measuring the effects of fallout on animal populations all specifications omit E_{it} as the animal data are enumerated on Jan 1 of the given year.

$\boldsymbol{\lambda it}$ denotes a vector of crop specific monthly precipitation levels and monthly temperature averages for county i in years t. Year fixed effects and county fixed effects are represented by $\boldsymbol{\gamma_t}$ and $\boldsymbol{\alpha_i}$ respectively. These fixed effects control for annual shocks that are common across counties and time invariant county-specific characteristics. I interact time fixed effects with a series of control variables, $\boldsymbol{X_i}$, that account for county characteristics in 1945. These controls include the share of farmland as pastured cropland, share of farmland as pasture, log number of farms, log agricultural land value per acre, log average farm size, percent of the labor force employed in agriculture, and population density per square mile.[5] ϵ_{it} denotes the heteroskedastic error term which is not observed by the researcher. Errors are clustered at the county level.[6]

Data and Identification Strategy

The data employed in the empirical analysis come from multiple sources. Annual agricultural data are provided through the National Agricultural Service's Quick Stats program (National Agricultural Statistics Service, 2015). Additional control county level variables come from Haines (2010) and Haines et al. (2015). Monthly temperature average and precipitation measures are provided by the Lawrimore et al. (2011). Radioactive fallout deposition measures are derived from records provided by the National Cancer Institute (1997).

[5] I opted to interact these pre-period characteristics rather than include them as time varying controls since fallout exposure may affect the control variables.

[6] In the appendix I incorporate spatially correlated errors using a modified version of code provided by Hsiang (2010) and which was edited by Thiemo Fetzer. Spatially correlated standard errors are provided with a cut off of 100km from the county 1950 centroids from the Minnesota Population Center (2016). These standard errors correct for temporal and geographic correlation of standard errors as discussed in Conley (1999).

Table 3.1: Summary statistics for each regression crop samples

Winter wheat: CA, CO, ID, KS, MT, OK, OR, SD, and WY

	mean	sd	min	max
Yield per acre planted	20.3	10.3	0.16	86
Acres harvested, W.Wheat	49,707.7	70,137.7	10	586,000
Acres planted, W.Wheat	57,500.5	79,606.6	10	615,000
Exposure, t	0.12	0.40	0	6.58
Avg exp, t-2/t-5	0.12	0.23	0	2.94
Avg exp, t-6/t-10	0.082	0.15	0	1.68
Observations	11,547			

Corn: IA, MT, ND, NE, SD, and WI

	mean	sd	min	max
Yield per acre planted	35.7	24.8	0.013	120.3
Acres harvested, Corn	56,585.7	50,882.1	10	282,460
Acres planted, Corn	63,681.2	51,263.1	30	285,800
Exposure, t	0.11	0.31	0	3.09
Avg exp, t-2/t-5	0.10	0.16	0	0.99
Avg exp, t-6/t-10	0.072	0.11	0	0.57
Observations	9,928			

The samples include years from 1945 to 1970. All counties included in the sample were observed in the period before the testing and during the testing. I make this restriction because the primary goal of this paper is to measure the direct effects of fallout on production. Balancing the panel from 1945 to 1970 removes Wisconsin from the corn production sample and Wyoming from the Wheat producing sample. This is because WI stopped reporting acres planted for corn in 1968 and Wyoming did not report wheat production data for 1963.[7] The variables examined and the samples used

[7]County border changes are accounted for by merging counties with changes together into temporally consistent units. Balancing the panel from 1945 to 1970 does not alter the estimates substantially

Table 3.2: Summary statistics for each regression animal sample

Sheep inventory: NE and SD

	mean	sd	min	max
# Sheep inventory, Jan 1	13,487.5	26,885.1	20	322,820
Exposure, t-1	0.11	0.31	0	3.09
Avg exp, t-2/t-5	0.11	0.17	0	0.99
Avg exp, t-6/t-10	0.076	0.11	0	0.57
Observations	4,056			

Sheep held for breeding: IL, MN, MT, and ND

	mean	sd	min	max
# Sheep held for breeding, Jan 1	10,925.8	17,143.3	100	195,400
Exposure, t-1	0.088	0.27	0	3.14
Avg exp, t-2/t-5	0.088	0.14	0	0.81
Avg exp, t-6/t-10	0.063	0.094	0	0.54
Observations	7,655			

Dairy cows: CO, IL, MN, MO, MT, ND, NE, and SD

	mean	sd	min	max
# Dairy cows	8,290.2	10,010.6	60	79,600
Gallons of milk per cow, MN SD	6,315.7	1,663.8	1,333.3	13,835.6
Exposure, t-1	0.044	0.22	0	2.26
Avg exp, t-2/t-5	0.12	0.16	0	0.99
Avg exp, t-6/t-10	0.11	0.11	0	0.57
Observations	16,403	(3,599 for Milk)		

are summarized in Tables 3.1 and 3.2 for each respective regression sample.

The main treatment variables of interest are annual and lagged county level fallout deposition measures from the National Cancer Institute (1997). These measures are reported as thousands of nCi of I-131 deposited per m^2 in a given year. The U.S. Congress in 1983 authorized the Secretary of Health and Human Services to investigate and measure thyroid doses from I-131 resulting from above ground nuclear tests to American citizens. The National Cancer Institute (NCI) undertook the task of gathering radiation data from historical records and estimating exposure from tests conducted at the NTS. In 1997, NCI released a report titled the "Estimated Exposures and Thyroid Doses Received by the American People from Iodine-131 in Fallout Following Nevada Atmospheric Nuclear Bomb Tests." The data employed here come from the I-131 deposition measures contained in the report.

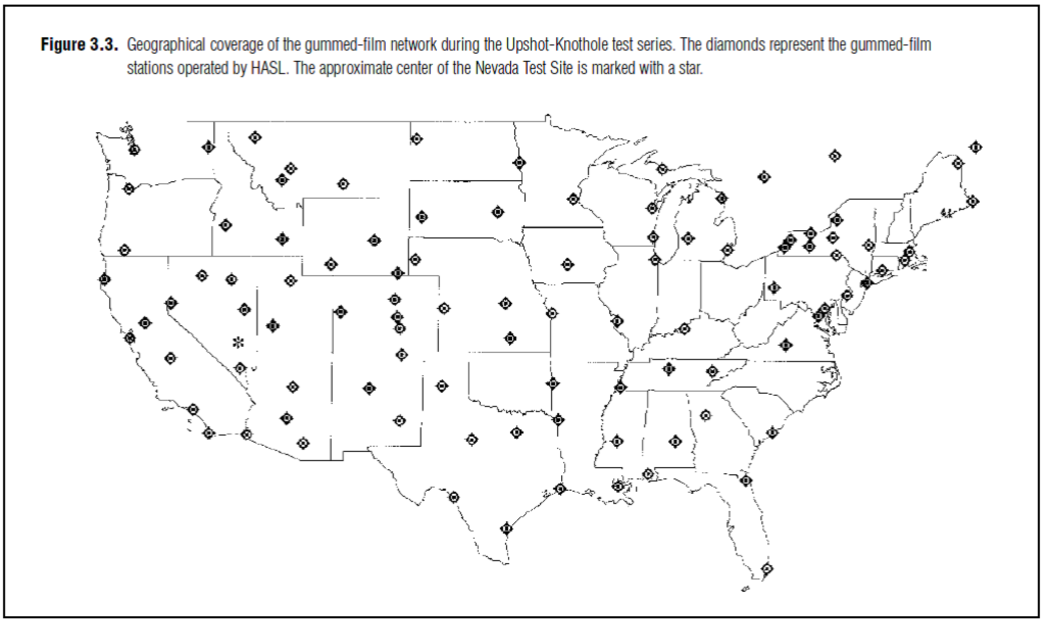


Figure 3.3: Map of National Radiation Monitoring Stations 1953. Source: National Cancer Institute (1997)

but excludes many counties who changed agricultural reporting in the years after atmospheric testing. Furthermore, while data is available for Delaware and Maryland, both states were excluded from the sample due to their geographic distance from all the other sample states. These states likely have different underlying production characteristics from other sample states and therefore excluded. Their exclusion does not alter the empirical results. Geographic information regarding county centroids comes from Minnesota Population Center (2016).

Deposition estimates exist for all tests from 1951 to 1970 with the exceptions of 3 tests in the Ranger series in 1951 and 6 tests from 1962 to 1970. I use measures from 1951 to 1958 as these are the only tests which resulted in detectable depositions in my sample.[8] These county level estimates are reported in terms of nano Curies per square meter (nCi). Much of the raw data came from national monitoring stations. The number of stations varies across time but never exceeded 100 stations.[9] Figure 3.3 provides a map of national monitoring stations for 1953. The military also engaged in air monitoring and used city-county stations around the NTS to track the radiation cloud (National Cancer Institute, 1997). This raw data allowed researchers to track the position of the radiation cloud over time and understand how much radiation precipitated down under differing meteorological conditions. The NCI applied Kriging techniques to interpolate county level depositions for each test.

The identification strategy of this paper uses within county variation in fallout patterns across time. In the most restrictive model specification, I use changes in fallout exposure across time within counties while controlling for national trends in agricultural productivity and county specific changes in weather conditions. There are a few potential challenges to this identification strategy. There is the possibility that the radiation measures were correlated with local weather patterns. Most of the fallout deposition resulting from the tests came down as wet precipitate. This means that radiation would have come down in a region if it was both raining and the radiation cloud was overhead. To control for any potential correlations with weather patterns I included monthly temperature averages and monthly precipitation totals specific to each crop's growing season window. For corn this is April to September. For winter wheat, this is the previous September until the subsequent August. Another challenge could be measurement error in the deposition measure. My fallout treatment variable is only positive during test years, but global fallout from nuclear testing in the USSR and Pacific could have led to more fallout deposition in the U.S.. This global fallout was much smaller in magnitude and more diffuse relative to the NTS fallout. If global fallout were an issue it would introduce attenuation bias and bias the treatment effect of the exposure variable towards zero.

[8]There was a testing moratorium from 1959 to 1961 and four low yield tactical nuclear tests at the NTS in 1962. The cumulative yield of these tests was less than two kilotons.

[9]The locations of the stations were not provided to me by the NCI.

The location of the site was not random, because it was chosen for its remote location and proximity to government labs, the tests themselves are exogenous events from the perspective of farmers. The precipitation of fallout across much of the United States can be treated as a quasi-exogenous shock because the United States government, Atomic Energy Commission and U.S. military provided little public information regarding the tests. Persons living far away from the site did not know where a fallout cloud traveled or the exact dates of nuclear tests. While test planners avoided meteorological conditions that could result in fallout in the immediate area around the base, they were unable to adjust test schedules for weather conditions far outside the region (National Cancer Institute, 1997).

Public knowledge of the dangers associated with nuclear testing were fairly underdeveloped early in the testing period at NTS. Persons living in the few counties downwind of the test site might have suspected the tests caused illness and were harmful to the environment, as they could visibly link tests with radioactive dust blows. These counties are excluded from my data sample because they are neither corn nor wheat producing areas. Furthermore, the livestock data also come from outside this local area. The public at large became aware of how dangerous atmospheric tests at the NTS were in the late 1970's after a series of Congressional inquiries and Freedom of Information Act requests revealed that the AEC and PHS mislead the public about radiation risks (Ball, 1986; LeBaron, 1998; Fradkin, 2004).

It is unlikely that farmers living hundreds of miles from the test site anticipated the dangers of fallout from tests, the position of fallout clouds, or possessed knowledge of how fallout precipitates down under various meteorological conditions. Farmers and ranchers whose animals resided in fields also were unaware of these risks to their animals. Radiation threats cannot be seen, smelled, or tasted. To engage in avoidance behaviors, farmers would have needed an understanding of fallout dispersal, but that knowledge was only being developed by researchers roughly at the same time or later. Furthermore, most of this research was classified until 1978. Even if the exposure variable is correlated with rainfall, monthly precipitation and temperature controls should control for this correlative effect. Simple correlations suggest that cumulative yearly rainfall is relatively uncorrelated with cumulative fallout deposition. As such, fallout dispersal should be unanticipated from the producer's perspective and uncorrelated with other factors affecting farm decisions. Therefore, fallout deposition should be orthogonal to the unobserved error term.

Table 3.3: Log winter wheat yield per acre planted: 1945-1970

	(1)	(2)	(3)	(4)
	Log yield per acre planted			
Exposure, t	-0.131***	-0.098***	-0.103***	-0.126***
	(0.021)	(0.020)	(0.019)	(0.016)
Exposure, t -1	-0.016	-0.033**	-0.038***	-0.030**
	(0.014)	(0.014)	(0.013)	(0.014)
Average Exposure 2-5 yrs ago	0.040	0.018	0.038	0.015
	(0.030)	(0.027)	(0.029)	(0.028)
Average Exposure 6-10 yrs ago	-0.267***	-0.219***	-0.101**	-0.198***
	(0.048)	(0.047)	(0.046)	(0.048)
Year FE	Yes	Yes	Yes	Yes
County FE	Yes	Yes	Yes	Yes
Weather Controls	No	Yes	Yes	Yes
State Time Trends	No	No	Yes	No
Robust Controls	No	No	No	Yes
N	11,547	11,547	11,547	11,339
$adj.r^2$	0.266	0.344	0.360	0.367

Standard Errors in parentheses are clustered by County. States in sample include CA, CO, ID, KS, MT, OK, OR, SD, and WY.. Samples restricted to counties observed continuously from 1945 to 1958. Exposure is measured as thousand of nCi of I-131 depositing per square meter in a given year. Weather Controls consist of month temperature averages and precipitation totals for the months January to August in the current year and months September to December of the previous year.
* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Table 3.4: Log corn yield per acre planted: 1945-1970

	(1)	(2)	(3)	(4)
	Log yield per acre planted			
Exposure, t	-0.272***	-0.247***	-0.123***	-0.135***
	(0.045)	(0.044)	(0.032)	(0.036)
Exposure, t-1	-0.417***	-0.357***	-0.196***	-0.167***
	(0.062)	(0.059)	(0.043)	(0.052)
Average Exposure 2-5 yrs ago	-1.665***	-1.035***	-0.635***	-0.858***
	(0.246)	(0.194)	(0.145)	(0.196)
Average Exposure 6-10 yrs ago	-0.428	-0.669*	0.307	0.068
	(0.400)	(0.351)	(0.239)	(0.325)
Year FE	Yes	Yes	Yes	Yes
County FE	Yes	Yes	Yes	Yes
Weather Controls	No	Yes	Yes	Yes
State Time Trends	No	No	Yes	No
Robust Controls	No	No	No	Yes
N	9,928	9,928	9,928	9,903
$adj.r^2$	0.075	0.198	0.511	0.352

Standard Errors in parentheses are clustered by County. States in sample include IA, MT, ND, NE, SD and WI. Samples restricted to counties observed continuously from 1945 to 1958. Exposure is measured as thousand of nCi of I-131 depositing per square meter in a given year. Weather Controls consist of month temperature averages and precipitation totals for the months January to September in the current year.
* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Table 3.5: Log winter wheat yield per acre harvested: 1945-1970

	(1)	(2)	(3)	(4)
	Log yield per acre harvested			
Exposure, t	-0.071***	-0.051***	-0.054***	-0.076***
	(0.011)	(0.010)	(0.010)	(0.009)
Exposure, t-1	-0.007	-0.019**	-0.021**	-0.018*
	(0.010)	(0.010)	(0.009)	(0.009)
Average Exposure 2-5 yrs ago	0.046**	0.030	0.040*	0.025
	(0.022)	(0.020)	(0.021)	(0.021)
Average Exposure 6-10 yrs ago	-0.246***	-0.196***	-0.117***	-0.199***
	(0.038)	(0.038)	(0.036)	(0.037)
Year FE	Yes	Yes	Yes	Yes
County FE	Yes	Yes	Yes	Yes
Weather Controls	No	Yes	Yes	Yes
State Time Trends	No	No	Yes	No
Robust Controls	No	No	No	Yes
N	11,547	11,547	11,547	11,339
$adj.r^2$	0.390	0.465	0.486	0.497

Standard Errors in parentheses are clustered by County. States in sample include CA, CO, ID, KS, MT, OK, OR, SD, and WY.. Samples restricted to counties observed continuously from 1945 to 1958. Exposure is measured as thousand of nCi of I-131 depositing per square meter in a given year. Weather Controls consist of month temperature averages and precipitation totals for the months January to August in the current year and months September to December of the previous year.
* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Table 3.6: Log corn yield per acre harvested: 1945-1970

	(1)	(2)	(3)	(4)
	Log yield per acre harvested			
Exposure, t	0.017	0.000	0.008	-0.008
	(0.014)	(0.013)	(0.013)	(0.012)
Exposure, t-1	-0.060***	-0.041***	-0.028**	-0.013
	(0.015)	(0.013)	(0.013)	(0.016)
Average Exposure 2-5 yrs ago	-0.337***	-0.182***	-0.151***	-0.318***
	(0.054)	(0.048)	(0.043)	(0.054)
Average Exposure 6-10 yrs ago	0.213**	0.020	0.102	-0.131
	(0.085)	(0.083)	(0.070)	(0.083)
Year FE	Yes	Yes	Yes	Yes
County FE	Yes	Yes	Yes	Yes
Weather Controls	No	Yes	Yes	Yes
State Time Trends	No	No	Yes	No
Robust Controls	No	No	No	Yes
N	9,928	9,928	9,928	9,903
$adj.r^2$	0.579	0.634	0.683	0.677

Standard Errors in parentheses are clustered by County. States in sample include IA, MT, ND, NE, SD and WI. Samples restricted to counties observed continuously from 1945 to 1958. Exposure is measured as thousand of nCi of I-131 depositing per square meter in a given year. Weather Controls consist of month temperature averages and precipitation totals for the months January to September in the current year.
* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

3.4 Empirical Model Results

The goal is to test whether more irradiated counties experienced decreases in crop yields, harvested acreage, and animal populations. Controlled scientific experimental evidence predicts that exposure to radioactive material can harm the development of commercial crops and that animals ingesting the material become less healthy. I report four different regression specifications in the corresponding tables. Specification (1) includes only county and year fixed effects. Specification (2) reports the regression results after adding monthly weather controls. Reporting these two specifications helps establish the consistency of the empirical results and establishes that the effects of radioactive fallout are distinct from those of weather. Specification (3) includes state specific time trends to control for possible underlying state specific trends that might be spuriously correlated with the treatment variable of interest. Specification (4) represents the regression specification discussed in the model section and includes the full set of 1945 county characteristics interacted with time indicator variables. These interactions flexibly control for the potentially confounding economic and demographic trends. All coefficient results discussed in this section refer to specification (4) and are statistically significant at the 5% level and below unless otherwise noted. All standard deviation measures refer to sample exposure values from Tables 3.1 and 3.2.

The results suggest that fallout from NTS activities caused reductions in crop yields per acre planted for both wheat and corn. Tables 3.3 and 3.4 report the effects of fallout upon wheat and corn yield respectively. Corn appears more sensitive to radioactive pollution with the magnitude of the reductions increasing over many years. Wheat experiences lagged effects six to ten years following deposition. A one standard deviation increase in I-131 deposition (400 nCi) reduced winter wheat yields by approximately 5% (coefficient of -0.126). A one standard deviation increase in I-131 deposition (310 nCi) caused corn yields to drop by 4.1% (coefficient of -0.135) in the year of deposition. In the year following the exposure event, a one standard deviation increase in exposure caused wheat yields to decrease another 1.2% (coefficient of -0.03) and corn yields to drop another 5% (coefficient of -0.167). A one standard deviation increase in average fallout exposure two to five years prior (230 nCi) reduced corn yields by another 12.8% (coefficient of -.0858). A one standard deviation increase in exposure six to ten years prior (150 nCI) for wheat caused yields to drop by another 2.9% (coefficient of -0.198).

Yields per acre harvested also declined in response to fallout deposition. Tables 3.5 and 3.6 report the effects of fallout on harvested yields. Since farmers could have selectively harvested the best acreage and abandoned failing acreage, the effect of fallout on yield per acre harvested would be expected to be smaller in magnitude than yields per acre planted. In fact they were. A one standard deviation increase in I-131 deposition in the current year reduced wheat yields by approximately 3% (coefficient of -0.076) while corn yields were unaffected. In the subsequent year a one standard deviation increase in exposure reduced wheat yields by approximately 0.7% (coefficient of -0.018). The effect for corn is statistically significant for all specifications except (4), but the negative coefficient suggests that a one standard deviation increase in exposure the previous year reduced corn yields per acre harvested by approximately 0.4%. An increase in average exposure two to five years prior decreased corn yields by approximately 5% (coefficient of -0.318) and an increase in average exposure six to ten years prior reduced wheat yields by 3% (coefficient of -0.199). These decreases in yield per acre harvested show that fallout deposition broadly affected crop yields and that the reductions in yield were not driven solely by farmers leaving cultivated acreage unharvested.

Table 3.7: Log winter wheat harvested conditioned on acres planted: 1945-1970

	(1)	(2)	(3)	(4)
	Log acres harvested			
Exposure, t	-0.060***	-0.047***	-0.048***	-0.050***
	(0.012)	(0.012)	(0.012)	(0.010)
Exposure, t-1	-0.008	-0.013**	-0.016**	-0.012
	(0.007)	(0.007)	(0.007)	(0.007)
Average Exposure 2-5 yrs ago	-0.005	-0.011	-0.001	-0.010
	(0.014)	(0.014)	(0.015)	(0.014)
Average Exposure 6-10 yrs ago	-0.019	-0.022	0.017	0
	(0.020)	(0.019)	(0.019)	(0.022)
Log Acres Planted	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes
County FE	Yes	Yes	Yes	Yes
Weather Controls	No	Yes	Yes	Yes
State Time Trends	No	No	Yes	No
Robust Controls	No	No	No	Yes
N	11,547	11,547	11,547	11,339
$adj.r^2$	0.857	0.863	0.865	0.868

Standard Errors in parentheses are clustered by County. States in sample include CA, CO, ID, KS, MT, OK, OR, SD, and WY.. Samples restricted to counties observed continuously from 1945 to 1958. Exposure is measured as thousand of nCi of I-131 depositing per square meter in a given year. Weather Controls consist of month temperature averages and precipitation totals for the months January to August in the current year and months September to December of the previous year.
* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Table 3.8: Log corn acres harvested conditioned on acres planted: 1945-1970

	(1)	(2)	(3)	(4)
		Log acres harvested		
Exposure, t	-0.295***	-0.252***	-0.131***	-0.121***
	(0.042)	(0.040)	(0.027)	(0.032)
Exposure, t-1	-0.354***	-0.315***	-0.168***	-0.154***
	(0.057)	(0.055)	(0.039)	(0.045)
Average Exposure 2-5 yrs ago	-1.276***	-0.829***	-0.484***	-0.533***
	(0.222)	(0.182)	(0.136)	(0.177)
Average Exposure 6-10 yrs ago	-0.568	-0.641*	0.204	0.243
	(0.368)	(0.328)	(0.227)	(0.301)
Log Acres Planted	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes
County FE	Yes	Yes	Yes	Yes
Weather Controls	No	Yes	Yes	Yes
State Time Trends	No	No	Yes	No
Robust Controls	No	No	No	Yes
N	9,928	9,928	9,928	9,903
$adj.r^2$	0.447	0.499	0.708	0.622

Standard Errors in parentheses are clustered by County. States in sample include IA, MT, ND, NE, SD and WI. Samples restricted to counties observed continuously from 1945 to 1958. Exposure is measured as thousand of nCi of I-131 depositing per square meter in a given year. Weather Controls consist of month temperature averages and precipitation totals for the months January to September in the current year.
* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

These drops in yield per acre planted also came in part from farmers not harvesting planted acreage. Tables 3.7 and 3.8 present results that reveal that damage to crops caused by radioactive fallout led farmers to abandon cultivated acreage. These reductions in acres harvested in part explain the reduction in yield per acre planted observed. A one standard deviation increase in fallout exposure caused wheat farmers to abandon 5% (coefficient of -0.05) more acreage and corn farmers to abandon 3.7% more acreage (coefficient of -0.121). The increase in abandoned acreage increases in the subsequent year to 4.7% (coefficient of -0.154). A one standard deviation increase in exposure two to five years prior causes corn farmers to abandon 8.2% (coefficient of -0.533) more acres than in the absence of NTS atomic testing.

Table 3.9: Log number of sheep in inventory in NE and SD: 1945-1970

	(1)	(2)	(3)	(4)
	Log number			
Exposure, t-1	-0.075**	-0.056	-0.056	-0.091**
	(0.036)	(0.037)	(0.037)	(0.042)
Average Exposure 2-5 yrs ago	-0.367***	-0.256*	-0.259*	-0.371**
	(0.139)	(0.150)	(0.151)	(0.169)
Average Exposure 6-10 yrs ago	-0.499*	-0.332	-0.335	-0.508
	(0.258)	(0.284)	(0.286)	(0.328)
Year FE	Yes	Yes	Yes	Yes
County FE	Yes	Yes	Yes	Yes
Weather Controls	No	Yes	Yes	Yes
State Time Trends	No	No	Yes	No
Robust Controls	No	No	No	Yes
N	4,056	4,056	4,056	4,030
$adj.r^2$	0.335	0.341	0.341	0.380

Standard Errors in parentheses are clustered by County. States in sample include NE and SD. Samples restricted to counties observed continuously from 1945 to 1958. Exposure is measured as thousand of nCi of I-131 depositing per square meter in a given year. Weather Controls consist of month temperature averages and precipitation totals for months of the previous year.
* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Table 3.10: Log number of sheep held for breeding in IL, MN, MT, and ND: 1945-1970

	(1)	(2)	(3)	(4)
	Log number			
Exposure, t-1	0.071***	0.078***	0.067***	0.081***
	(0.018)	(0.018)	(0.017)	(0.019)
Average Exposure 2-5 yrs ago	0.099	0.057	0.002	0.178**
	(0.078)	(0.078)	(0.076)	(0.086)
Average Exposure 6-10 yrs ago	0.138	0.102	0.038	0.209
	(0.121)	(0.120)	(0.115)	(0.143)
Year FE	Yes	Yes	Yes	Yes
County FE	Yes	Yes	Yes	Yes
Weather Controls	No	Yes	Yes	Yes
State Time Trends	No	No	Yes	No
Robust Controls	No	No	No	Yes
N	7,655	7,655	7,655	7,655
$adj.r^2$	0.441	0.453	0.472	0.543

Standard Errors in parentheses are clustered by County. States in sample include IL, MN, MT, and ND. Samples restricted to counties observed continuously from 1945 to 1958. Exposure is measured as thousand of nCi of I-131 depositing per square meter in a given year. Weather Controls consist of month temperature averages and precipitation totals for the months of the previous year.
* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

The effects of fallout upon grazing livestock were also large in magnitude. Ingestion of irradiated pasture likely decreased animal fertility and possibly killed some animals. Tables 3.9 and 3.10 report the effects of fallout on sheep inventories and numbers of sheep withheld for breeding purposes. Nebraska and South Dakota reported annual county level inventories of sheep and a one standard deviation increase in fallout during the previous year (310 nCi) caused a 2.8% (coefficient of -0.091) reduction in the number of sheep reported in inventory. A one standard deviation increase in exposure two to five years prior (170 nCi) led to a 6.1% (coefficient of -0.371) decrease in the number of sheep observed. Another set of states, Illinois, Minnesota, Montana, and North Dakota reported the number of sheep farmers withheld from sale for breeding purposes. If the ingestion of irradiated pasture made livestock less healthy and stunted animal growth, then farmers may have opted to hold on to animals until they increased in weight or had sufficient offspring to recover from the fallout induced damage. A one standard deviation increase in fallout during the previous year (270) caused farmers to hold on to 2.4% (coefficient of 0.081) more sheep. A one standard deviation increase exposure two to five years prior (140 nCi) led farmers to hold onto 2.5% (0.178) sheep for breeding.

Table 3.11: Log number of dairy cows in inventory: 1945-1970

	(1)	(2)	(3)	(4)
		Log number		
Exposure, t-1	0.002	0.005	-0.002	-0.012*
	(0.006)	(0.006)	(0.005)	(0.006)
Average Exposure 2-5 yrs ago	-0.029	-0.028	0.005	-0.055**
	(0.020)	(0.020)	(0.022)	(0.022)
Average Exposure 6-10 yrs ago	-0.202***	-0.246***	0.033	-0.145***
	(0.050)	(0.052)	(0.041)	(0.051)
Year FE	Yes	Yes	Yes	Yes
County FE	Yes	Yes	Yes	Yes
Weather Controls	No	Yes	Yes	Yes
State Time Trends	No	No	Yes	No
Robust Controls	No	No	No	Yes
N	16,403	16,403	16,403	16,221
$adj.r^2$	0.704	0.712	0.767	0.752

Standard Errors in parentheses are clustered by County. States in sample include CO, IL, MN, MO, MT, ND, NE, and SD. Samples restricted to counties observed continuously from 1945 to 1958. Exposure is measured as thousand of nCi of I-131 depositing per square meter in a given year. Weather Controls consist of month temperature averages and precipitation totals for the months of the previous year.
* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Table 3.12: Log lbs milk per head of cow: 1954-1970

	(1)	(2)	(3)	(4)
	Log lbs milk per cow			
Exposure, t-1	-0.074***	-0.059***	-0.052**	-0.035
	(0.022)	(0.022)	(0.022)	(0.023)
Average Exposure 2-5 yrs ago	-0.243***	-0.123	-0.112	-0.070
	(0.083)	(0.078)	(0.076)	(0.082)
Average Exposure 6-10 yrs ago	-0.081	0.005	-0.011	0.129
	(0.112)	(0.128)	(0.131)	(0.147)
Year FE	Yes	Yes	Yes	Yes
County FE	Yes	Yes	Yes	Yes
Weather Controls	No	Yes	Yes	Yes
State Time Trends	No	No	Yes	No
Robust Controls	No	No	No	Yes
N	2,483	2,483	2,483	2,466
$adj.r^2$	0.659	0.678	0.678	0.733

Standard Errors in parentheses are clustered by County. States in sample include SD starting in 1954 and MN starting in 1955. Exposure is measured as thousand of nCi of I-131 depositing per square meter in a given year. Weather Controls consist of month temperature averages and precipitation totals for the months of the previous year.
* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Cattle are larger than sheep and are more resilient to damage from ingesting irradiated pasture. Nevertheless, cows that consumed irradiated pasture might have experienced decreased lactation, reductions in fertility and offspring viability, and become unhealthier. To test whether dairy cows were adversely affected by fallout I examine dairy cow inventories and average annual milk production per cow. Tables 3.11 and 3.12 report the effects of fallout on dairy cow inventories and milk production. The impact of exposure on the number of dairy cows in a county six to ten years following deposition is consistently negative and statistically significant. A one standard deviation in exposure six to ten years prior decreased dairy cow populations by approximately 1.6%. Specification (4) suggests that cow populations decreased in the year following deposition and the magnitude of this negative effect increased over time. The marginal effect of a standard deviation increase in exposure however is small and less than 1%. Milk per head of cow are available from 1954 onwards for South Dakota and 1955 onwards for Minnesota. These regressions suggest that the ingestion of irradiated pasture decreased lactation in cows but the magnitude and statistical significance of the negative coefficients attenuates with the inclusion of more controls.

Table 3.13: Cumulative effects of fallout upon agricultural production

Average production values from 1945-1950 for relevant samples

	Quantity	Acres Harvested	Acres Planted	
Winter wheat	425 M bushels	26 M acres	28.8 M acres	-
Corn	917 M bushels	24.4 M acres	26.7 M acres	-
Sheep inventories	2.1 M	-	-	-
Sheep held for breeding	3.7 M	-	-	-
Dairy cow inventories	5.6 M	-	-	-

Implied cumulative effects of fallout exposure by lag

Exposure Event Timing	t	t-1	t-2/t-5	t-6/t-10
Winter wheat output, bu	-141 M bushels	-36.1 M bushels	-	-195 M bushels
Corn output, bu	-313 M bushels	-380 M bushels	-1.82 B bushels	-
Wheat Acres Harvested	-3.9 M acres	-	-	-
Corn Acres Harvested	-7.9 M acres	-9.9 M acres	-33.5 M acres	-
Sheep inventories	-	-526,000	-2.1 M	-
Sheep held for breeding	-	784,000	1.7 M	-
Dairy cow inventories	-	-169,000	-770,000	-1.4 M

All calculations are based on regression coefficients from specification (4) and their relevant tables. Each county had its effect calculated from the coefficient and deposition measures. These effects were then multiplied against the 1945/1950 average values (and acres planted for crop output) to estimate the cumulative effect. Acres harvested total was based on actual acres planted. Totals were summed up for each respective regression sample.

3.5 Quantifying the Magnitude of the Effects

In order to estimate the magnitude of these production effects I developed a series of back-of-the-envelope estimates. These estimates are reported in Table 3.13 along with averages of annual totals for the years 1945 to 1950 for each regression sample. To calculate the total effects, I first take coefficients from specification (4) and calculate the effect of fallout exposure for each county year. This gives the county specific percent change in output attributable to fallout for each year. To measure the effect on wheat and corn yields, I multiply these fallout effects by planted acreage and the average county specific yield from 1945 to 1950. I use these average yields as a counterfactual yield baseline in the absence of NTS nuclear testing. I then add up the effects across county years from 1950 to 1970. I repeat the same procedure when calculating animal populations. When estimating how much planted acreage was abandoned, I just multiplied the estimated fallout effect by how much corn or wheat acreage was planted that year.

Between 1951 and 1970 atmospheric testing at the NTS decreased winter wheat output by a total of 331.1 million bushels. This was roughly three fourths of the 1945/1950 average annual production for the region. The value of this loss using nominal prices from 1951 to 1970 is $610.5 million ($5.18 billion in 2016$). The CPI adjusted values are provided provided in parentheses.[10] The total drop in output for corn was greater. The cumulative loss in output was approximately 2.5 billion bushels, which is more than two and a half years of 1945/1950 average production. The nominal value of this loss was $13.1 billion dollars ($26.5 billion). Over 3.9 million acres of planted wheat and 51.3 million acres of planted corn went unharvested due to NTS nuclear tests. Inventories for animals also changed as a result of fallout exposure. Total inventories of sheep dropped by as much as 2.6 million head and dairy cow populations decreased by as much as 2.3 million head. The values of these losses are approximately $41.8 million ($358.1 million) for sheep and $463.9 million ($3.8 billion) for cows.

[10]The nominal value of the loss uses annual crop prices from (Carter et al., 2006) and real prices are adjusted by annual CPI measures from the Bureau of Labor Statistics. The present discounted value (PVD) of total wheat losses using a 3% real interest rate was $1.06 billion in 2016$. For corn the PDV was $5.2 billion. The PDV of the sheep and cattle losses were $72 million and $835 million respectively.

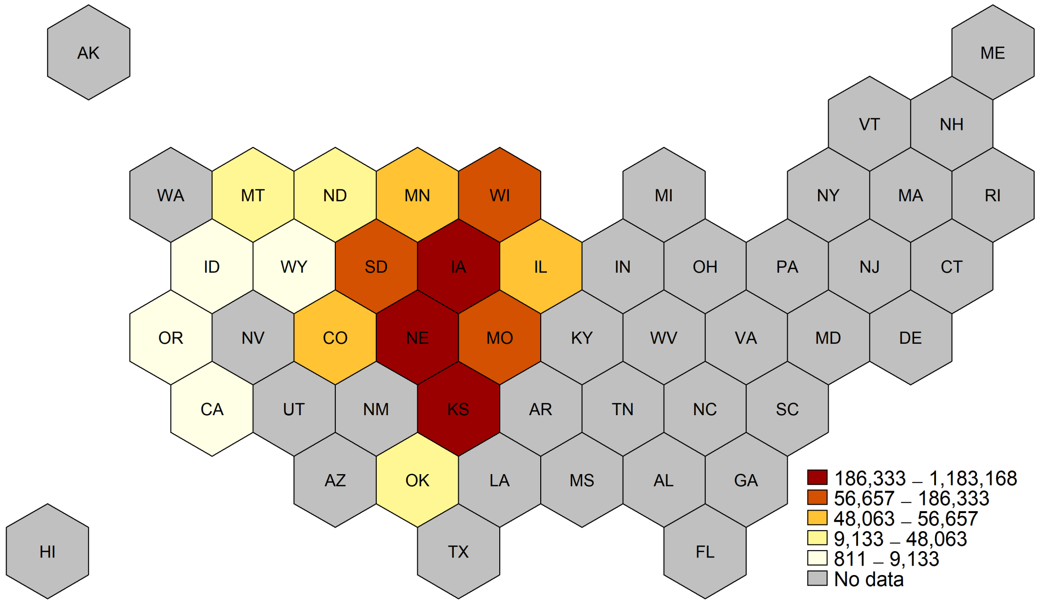


Figure 3.4: Cumulative Agricultural Losses, 2016 $. Source: Author's calculations

According to the empirical estimates Iowa, Kansas, and Nebraska experienced the greatest amount of harm from NTS atmospheric testing. Figure 3.4 plots out these cumulative losses by state.[11] This map shows that areas with large amounts of corn and wheat cultivation experienced the greatest amount of harm. These areas are far from the NTS and show that the externalities associated with NTS activities had a broader geographic extent than what was previously known.

The U.S. Justice Department has paid out approximately $2 billion in compensation to victims of domestic nuclear testing since 1990 (US Department of Justice, 2016). This program compensates persons who lived in a number of Downwind counties in Nevada, Arizona, and Utah during the period of testing and their decedents. The program also compensates persons who were involved with the U.S. nuclear weapons program. I find that radioactive pollution depositing far beyond the compensation region had substantial effects on total agricultural output over a twenty year period and the value of these losses dwarf the amount of compensation the U.S. government has provided victims of nuclear testing.[12]

[11]Maps of crop and animal specific losses are in the appendix.

[12]One irony is that U.S. agricultural policy sought to curb over production of agricultural commodities during the same period. The adverse effects of radioactive fallout upon agriculture may have inadvertently aided in achieving this policy objective.

3.6 Conclusion

The social costs of atmospheric nuclear weapons tests are not yet fully understood and contemporary research is only beginning to grapple with the scale and scope of these costs. The scientific and medical research studying the effects on nuclear testing in Nevada has focused almost exclusively on regions surrounding the NTS. These studies, however, have not measured the external costs of these polluting activities nor the geographic extent of the harm. To study externalities associated with nuclear testing, I construct a new dataset of county level fallout deposition for each year from 1951 to 1958. With this new dataset I can use within county changes in fallout exposure across time while controlling for national shocks, local weather effects, and underlying trends in agricultural productivity.

The results show that fallout from nuclear testing had direct adverse effects on the U.S. economy and these effects were felt in many Plains and Midwestern states. My research is the first to connect reductions in agricultural output to radioactive fallout originating from atmospheric nuclear tests conducted at the Nevada Test Site. This paper shows that the greatest amount of economic harm occurred in areas not studied in the previous literature. Much of the agricultural damage occurred hundreds to thousands of miles from the NTS and damage from fallout contamination persisted for many years following the deposition of radioactive materials.

These results establish that the harm caused by the U.S.'s domestic nuclear weapons program was much larger and more extensive than what was previously known. Recent literature suggests that radioactive pollution resulting from nuclear testing and nuclear power accidents have profound long run effects on human capital and wellbeing. This paper reveals that similar radioactive pollutants had adverse first order effects for agriculture during the period of testing for large areas of the United States. Much of this radioactive material entered the food supply and was subsequently consumed by millions of people. These facts raise important questions regarding the long-term costs of NTS activities on public health and wellbeing. It is quite likely that the full magnitude of the social costs are larger than any previous estimates.

Chapter 4

Measuring Policy's Role in Mediating Responses to Agricultural Productivity Shocks

As the effects of climate change become more pronounced, policy's role in shaping producer responses to adverse shocks becomes more relevant. Contemporary agricultural policies such as crop insurance are often tied to farmers' production histories. Using changes in agricultural productivity caused by radioactive fallout from nuclear testing between 1951 to 1958, I find such "use-it or lose-it" policies can encourage producers to divert resources toward rather than away from adversely affected crops. Treating policy as a fixed factor may obscure the role policies play in shaping producer behavior and can lead to misestimation of the social costs associated with disruptive events. Government policies that regulated production based on producer history encouraged farmers to "double down" on adversely affected crops, and led producers to plant an additional 2.6 million acres of wheat in the years following fallout exposure.
JEL N42, N52, Q18, Q53, Q58; Keywords: Nuclear testing, radioactive fallout, agricultural policy, producer behavior

4.1 Introduction

Disruptive events such as natural disasters, disease outbreaks, and extreme temperatures often alter the production environment. A growing body of research focuses on extreme temperature events to draw insight about the social costs of climate change. Weather conditions are often observable and shocks can be serially correlated over time. People might take actions in anticipation of future shocks and these actions may reduce the measured effect of the productivity shock. This complication potentially obscures the role government policy plays in shaping responses to changes in productivity. To draw insight about how policy and productivity interact, I study how farmers adjusted their planting decisions in response to unanticipated agricultural productivity shocks caused by radioactive fallout from nuclear testing between 1951 and 1958. The unique characteristics of radioactive fallout provide an attractive context in which to study how policy affects producers' responses to changes in productivity.

Nuclear testing occurred in an environment where U.S. agricultural policy heavily regulated agricultural production. During the 1950s, the USDA regulated the amount of cropland farmers could harvest. In my analysis, I focus specifically on two regulated crops, corn and winter wheat, which both had wide geographic distribution in production and differences in regulations. Farm level regulations on corn acreage were not tied to a farmer's past production history. Conversely, farm level regulations on wheat acreage were specifically tied to a farmer's past production history and agricultural productivity. This created a "use-it or lose-it" scenario for wheat farmers where adverse productivity shocks from fallout could have negatively affected their wheat acreage and thus income in future years.

Typically, if an agricultural producer experiences an adverse productivity shock specific to one crop, they will reduce planting of that crop in the next year if they treat shocks as serially correlated across time. I find that U.S. agricultural policy for wheat promoted the opposite response to a productivity shock. The policies that alloted wheat acreage to farmers were based on multi-year average of past acres harvested. Thus, when disasters cut acres harvested, wheat producers had an incentive to increase their planting to ensure that their average did not fall below their allotment. In this case, allotment policies caused wheat farmers to "double-down" on the adversely affected crop and divert land from other uses towards wheat production. Corn producers, who were not subject to such policies, treated fallout-induced productivity shocks as transitory and did not alter their planting decisions. The results of this paper reveal that policy can interact with productivity in perverse ways that alter the effects of a productivity shock. Overlooking the role policy plays in shaping producer behavior may misattribute the effects of policy to a disruptive event and inaccurately measure the social costs of these events.

Contemporary crop insurance programs in the United States include similar "use-it or lose-it" provisions akin to those in the 1950s. Federal crop insurance payments are a function of a farm's past crop specific production history.[1] These policies distort farmers' incentives, and researchers find the crop insurance program encourages the cultivation of marginal land, reductions in crop rotation, continuous corn planting, and causes soil erosion (Goodwin and Smith, 2013; Glauber, 2013; Miao et al., 2016; Claassen et al., 2017).[2] These policies likely also encourage maladaptation. Government policy can incentivize agricultural producers to invest and specialize in crops and production methods that will increase their exposure to climate change. Evidence from Annan and Schlenker (2015) suggests that temperature affects corn and soy yields with greater intensity in counties with greater crop insurance coverage. Understanding how policy affects producers' responses to productivity shocks is of increasing importance as the effects of climate change intensify, but the research studying policy's role in shaping adaptive responses is relatively sparse.

Radiation from nuclear testing provides a particularly effective way of identifying productivity shocks and measuring how policy affects producer behaviors. Nuclear testing at the Nevada Test Site (NTS) from 1951 to 1963 generated enormous quantities of radioactive matter. Much of this invisible pollution deposited on agricultural fields hundreds to thousands of miles from the original test site and negatively affected

[1] The 2014 Farm Bill determines insurance payments on up to ten years of farm production information and requires minimum of four years of crop specific production information. Years of low production traditionally reduces payments, though now farmers can exclude low performing years due to a 2014 policy change under certain conditions. If a farmer has few years of data, then their insurance coverage faces greater exposure risk to adverse years. For additional information see `https://www.rma.usda.gov/news/currentissues/aphye/`

[2] Continuous corn denotes cultivation of corn year after year.

agricultural productivity. NTS fallout reduced corn output by more than 2.5 billion bushels and winter wheat output by over 300 million bushels from 1951 to 1967 (Meyers, 2017b). The same regions produced on average 900 million bushels of corn and 400 million bushels of wheat per year between 1945 and 1950. The value of this lost product exceeds over $30 billion in 2016$.

If agents anticipate productivity shocks they might make adjustments that partially mitigate the observed effect of the shock. Serial correlation in weather across time may induce people to make investments that are correlated with future weather. For example, the purchase of a combine harvester could have increased yields through more efficient harvesting and enabled the farmer to harvest (and thus plant) more arable land. A farmer might have made such an investment if they anticipated favorable growing conditions in the future. If shocks are anticipated, then the investments that are often unobservable to the econometrician can bias the estimated welfare impact of future shocks. One method to avoid such mitigating actions is to use variation from unexpected events (Moretti and Neidell, 2011). To circumvent the challenges posed by unobserved adaptive actions, I use unanticipated radioactive fallout dispersal patterns generated by atmospheric nuclear testing at the NTS.

During the period of testing, information regarding nuclear testing and contamination caused by radioactive fallout was classified information.[3] The full geographic extent of radioactive contamination from NTS testing became known many decades after atmospheric testing had ended (National Cancer Institute, 1997; Center for Disease Control, 2006). Farmers living hundreds to thousands of miles from the NTS would have neither anticipated productivity shocks caused by radioactive fallout nor would they have been able to observe the cause of the decreased productivity. Given the nature of fallout deposition, this pollutant is plausibly uncorrelated with farmers' underlying production decisions that affect both productivity in one year and planting the next.

[3] A Freedom of Information Act request in 1978 revealed to the public that the Atomic Energy Commission (AEC), Public Health Service (PHS), Department of Defense (DOD), and federal government hid both the dangers of nuclear testing from the public and the scope of the radioactive contamination. See US Government Printing Office (1980); Ball (1986); LeBaron (1998) and Fradkin (2004) for additional information.

Increases in global temperatures caused by climate change have the potential to drastically alter agricultural production in the coming decades. A growing body of research measuring the social costs of climate change studies how the agricultural sector responds to short run variation in temperatures (Deschênes and Greenstone, 2007, 2012; Schlenker and Roberts, 2009; Burke and Emerick, 2016). These studies indirectly measure adaptation by studying the effects of extreme temperatures on agricultural land values and crop yields. Apart from Annan and Schlenker (2015), these studies generally abstract away from the role government policy plays in shaping responses to extreme temperatures. As extreme temperatures become more frequent, policies that encourage producers to specialize in crops vulnerable to climate change may magnify the cost of adaptation. Failing to account for the role policy plays in shaping producer behavior may misstate the direct costs of climate change.

4.2 Background and Related Literature

Economists interested in measuring the potential disruptive costs of climate change have long studied agriculture. The agricultural sector is directly affected by climatic conditions and likely would be the economic sector most vulnerable to climate change. Mendelsohn et al. (1994) introduce Ricardian analysis and measure the effect of climatic variables upon agricultural land values using a cross sectional approach. Schlenker et al. (2005) reveal that irrigation plays a key role in climatic sensitivity, and Schlenker et al. (2006) introduce agronomic measures of growing degree days as cumulative measures of agricultural temperature exposure. Deschênes and Greenstone (2007) pioneer the use of panel data methods and short run variation in weather to measure the effects of temperature on agricultural productivity and land values. Schlenker and Roberts (2009) find that corn and soybean yields are becoming more sensitive to increasing temperatures over time. Burke and Emerick (2016) corroborate this finding using long-differences between two cross sections of data. They find that yield sensitivities to extreme heat are not decreasing over time and suggest that the agricultural sector has not adapted to increasing temperatures.

As the climate and agriculture literature has moved towards using short run weather variation, it becomes increasing plausible that farmers are making adaptive investments that are correlated with the weather treatment variables of interest. I add to this research by using radioactive fallout to address this issue of unobserved adaptive investments made in anticipation of productivity shocks. Using radioactive fallout to instrument for productivity allows me to explore how farmers adjust their planting decisions in response to adverse productivity shocks. Finally, government policy is an aspect often treated as fixed in the climate change and agricultural literature. The unique variation in agricultural productivity fallout provides and agricultural policy environment during the period of atmospheric nuclear testing allow me to analyze how policy can interact with productivity shocks.

Economists also study historical episodes where large events affected productivity and the adjustments agents made in response to these shocks. Lange et al. (2009) analyze how cotton farmers responded to the anticipated arrival of the Boll Weevil and find that cotton farmers tried to squeeze out one last large harvest before the arrival of the pest. They also find that following the pest's arrival, farmers moved away from cotton production. Hornbeck (2012) measures the long run adaptation made by farmers following Dust Bowl erosion. He finds long run out migration and shifts away from wheat production in more eroded counties. Boustan et al. (2012) study migratory responses to tornadoes and floods. Their results show that government expenditures on flood control following disasters induced in-migration. Hornbeck and Naidu (2014) measure agricultural and migratory responses to the 1927 Mississippi flood. Out migration in more flooded areas caused agricultural production to become more capital intensive. This paper adds to this historical literature by measuring the short run adaptive responses agricultural producers made in response to damage from nuclear testing.

This paper belongs to a set of concurrent research papers studying the consequences and adverse effects of domestic nuclear testing conducted at the Nevada Test Site (NTS) in Nye County, Nevada. Meyers (2017b) finds that fallout depositing across much of the Great Plains and Midwest adversely affected agricultural output. Radioactive pollution from NTS tests resulted in farmers leaving millions of planted acres of cropland unharvested and decreased agricultural output by billions of dollars. Over 331 million fewer bushels of wheat and 2.5 billion bushels of corn were produced as a result of NTS testing. The total cost of this damage exceeded $30 billion (2016$). Meyers (2017a) studies the health effects of this radioactive pollution using annual vital statistics records and finds that nuclear testing contributed to hundreds of thousands of deaths in the twenty-year period following testing. The areas most affected by the pollution were in the Midwest and Great Plains and far beyond the regions studied in the medical literature. These results suggest that in addition to affecting agriculture, NTS nuclear tests likely affected public health and worker productivity. Prenatal exposure to radioactive pollution is associated with decreases in human capital. Almond et al. (2009) and Black et al. (2013) show that fetal exposure to low doses of ionizing radiation negatively affects educational attainment and income of exposed cohorts in Scandinavia.

Atmospheric nuclear testing was a deliberate and destructive policy conducted for the purpose of national defense. From 1945 to 1993 the U.S government detonated 1,030 nuclear weapons (US Department of Energy, 2000). Of these tests, 100 atmospheric tests occurred at the NTS during the 1951-1963 time period. Atmospheric nuclear testing by the U.S. effectively ended in 1963 with the signing of the Partial Nuclear Test Ban Treaty, though from 1958 to 1961 there was a testing moratorium between the U.S. and USSR that led to a secession of atmospheric testing. Over 12 billion curies of radioactive material was released into the environment by these atmospheric tests in the U.S.. In comparison, the worst nuclear disaster in human history, the partial meltdown at Chernobyl, released approximately 80 million Curies of radioactive material into the environment (LeBaron, 1998).[4] The public at large did not know about the harm caused by nuclear testing until 1978. This knowledge environment changed when a Freedom of Information Act request revealed the environmental and public health dangers NTS activities had for populations living near the test site (Ball, 1986; LeBaron, 1998; Fradkin, 2004). This revelation prompted Congressional investigations (US Government Printing Office, 1980) and a government inquiry into

[4]These measures relate to the amount of radioactive debris created and not radioactive gases such as tritium that were released by these events. Such radioactive gases would not deposit on the surface of the earth. Fukashima released less radioactive material than Chernobyl due to differences in reactor design.

the public health risks posed by nuclear testing (National Cancer Institute, 1997; Center for Disease Control, 2006). As such, it is unlikely that farmers residing in areas hundreds to thousand of miles from the NTS would have known that their crops were being exposed to fallout from nuclear tests in Nevada.

Table 4.1: Model predictions on 2SLS effects

Mechanism	Effect of fallout induced productivity shock on planting	
	Wheat	Corn
Transitory Shock	(0)	(0)
Resource Constraint	(-)	(-)
Beliefs in Persistent Shock	(-)	(-)
Policy Constraint	(+)	(0)

4.3 Model and U.S. Agricultural Policy

To illustrate the effects of farm policy and how it interacts with fallout-induced productivity shocks, I expand upon a model developed by Hornbeck (2012). Hornbeck's model describes how farmers responded to permanent soil degradation resulting from Dust Bowl erosion. I adapt this model to study how farmers adjust their short-run planting decisions in the year following an adverse productivity shock. This paper's model describes the mechanisms through which an agricultural productivity shock can affect a farmer's planting decision in the subsequent year. There are several potential mechanisms to examine. The baseline scenario involves a farmer who is an unconstrained maximizer and faces productivity shocks are treated as completely transitory. Under this scenario, a productivity shock in the past would not affect acreage planted.

The next three cases describe mechanisms through which a transitory shock may have persistent effects on planting decisions. The beliefs scenario describes a case where the agent farmer is an unconstrained maximizer and believes the fallout shock will be persistent across years. The resource constraint scenario involves an adverse productivity shock in the previous year that causes a resource constraint to bind. In both the second and third cases, productivity shocks and acreage are positively related. The policy scenario involves a wheat specific policy constraint that restricts the amount of acreage a farmer can harvest in the future based on his or her past production history. This policy creates an acreage target for farmers. Since fallout caused farmers to abandon cultivated acreage in the previous year, this could cause the regulators to restrict the amount of land farmers could harvest in future years. Producers could potentially partially offset this regulation and insure themselves against another year of reduced harvest by increasing the amount of land they planted as wheat in the year following the shock. This policy makes it possible for productivity shocks and cultivated acreage to be negatively related. Table 4.1 describes the empirical predictions of the model.

4.3.1 Baseline Model

In this model there are two different production technologies and a single unit of land that can be divided between them. Both technologies have concave and twice differentiable profit functions denoted by $f(\cdot)$ and $g(\cdot)$. In the context of agriculture, let $f(\cdot)$ denote the profit the farmer receives from alternative land uses and $g(\cdot)$ denote the profit the farmer receives from producing wheat. In each year the farmer must decide how to divide his or her unit of land between the two technologies. Let θ_t denote the division of this single unit of land between $f(\cdot)$ and $g(\cdot)$.

Equation (4.3.1) describes the unconstrained maximization problem of the farmer. If the farmer is an unconstrained maximizer, then by the concavity of the profit function she allocates land such that at θ_t the marginal profit of land for the two technologies are equal. The first order conditions for equation (4.3.1) appear in equation (4.3.2) and describe the optimal allocation decision.

$$\max_{\theta_t \ \epsilon[0,1]} g(\theta_t) + f(1 - \theta_t) \tag{4.3.1}$$

$$g'(\theta_t) - f'(1 - \theta_t) = 0 \tag{4.3.2}$$

This static one-period model also describes the optimal land division when productivity shocks are transitory. A transitory shock will affect realized profits in one year, but will not affect the farmers' optimal planting decision in subsequent year. That is the optimal θ_t equals the optimal θ_{t-1}. For productivity shocks to show persistence in this model they need to either affect agents' beliefs, agents' available resources, or interact with policy.

4.3.2 Beliefs in persistent damages

Productivity shocks in the previous year might affect farmers' beliefs about growing conditions in the next year and these beliefs might make them adjust their planting decisions in subsequent years. For example, suppose weather shocks are serially correlated across multiple years. Then if a given year has little rainfall, the agent farmer might believe the subsequent year will be drier than average and thus allocate less land toward water intensive crops. Suppose there is an anticipated damage function denoted by $\delta(\cdot)$ that is between zero and one. This damage variable is an increasing function of fallout-induced damage in the previous year, η_{t-1}. Assume the agent believes this damage function affects only the productivity of technology g. If the productivity shock is treated as persistent, then the farmer's profit maximization problem becomes:

$$\max_{\theta_t \ \epsilon[0,1]} \delta(\eta_{t-1})g(\theta_t) + f(1-\theta_t) \tag{4.3.3}$$

The value $\delta(\cdot)$ decreases the perceived profitability of wheat relative to alternative land uses. The non-wheat productivity is unaffected by fallout shocks, while wheat crop productivity is affected. In the empirical analysis, such a belief mechanism would imply a positive relationship between prior productivity and the share of current acreage planted in wheat. The first order condition in (4.3.4) shows the effect of beliefs in persistent damages on the optimal land allocation. The optimal allocation when there is no productivity shock is $\theta_t = \theta_{t-1}$, but this value no longer equates the two marginal profits.

$$\delta(\eta_{t-1})g'(\theta_t) - f'(1-\theta_t) = 0 \tag{4.3.4}$$

If $\delta(\eta_{t-1})g'(\theta_t) < f'(1-\theta_t)$ when $\theta_t = \theta_{t-1}$, then by the concavity of $f(\cdot)$ and $g(\cdot)$ the optimal θ_t must decrease. As with Hornbeck (2012), this scenario leads the farmer to reallocate land away from crop production towards alternative uses. This mechanism reveals that farmers will reallocate resources from wheat towards alternative uses as the effect of the productivity shock is treated as persistent. This result means that farmers would reduce the amount of wheat cultivated in the subsequent year if they believe adverse productivity shocks to be persistent. Thus θ_t is smaller relative to the previously optimal allocation of θ_{t-1}.

4.3.3 Resource constraint mechanism

If the adverse productivity shock from fallout in the previous year is large enough, then the negative income shock may reduce the feasible amount of land the farmer can dedicate towards wheat production in the subsequent year. Fallout from nuclear testing caused substantial yield reductions and losses in agricultural output. If farmers faced imperfect capital markets, then they might not be able to afford to plant as much wheat as they were planning to following a fallout shock. Let $Y(\eta_{t-1})$ denote the amount of income the farmer received in the year fallout deposited across his fields. Y is decreasing in fallout damage from the previous year, Let the cost, C, of planting wheat be an increasing function of θ_t. If the negative productivity shock is large enough, then the amount of resources the farmer has to plant this year at $\theta_t = \theta_{t-1}$ is less than the cost (i.e.: $Y(\eta_{t-1}) < C(\theta_{t-1})$). Therefore, the unconstrained maximization problem becomes a constrained problem as in equation (4.3.5).

$$\max_{\theta_t \ \epsilon[0,1]} g(\theta_t) + f(1-\theta_t) \ s.t. \ 0 \leq C(\theta_t) \leq Y(\eta_{t-1}) \tag{4.3.5}$$

When the maximization problem is unconstrained, the cost of production C must be less than or equal to Y. If the damage is great enough in the previous year such that the constraint binds, then the previously optimal allocation, θ_{t-1}, is no longer feasible.

$$g'(\theta_t) - f'(1-\theta_t) - \lambda C'(\theta_t) \leq 0 \tag{4.3.6}$$

If the budget constraint binds, then $\lambda C'(\theta_t) > 0$ and ensures the inequality (4.3.6) holds when θ_t is less that θ_{t-1}. Therefore, decreasing the amount of land allocated towards wheat at time t satisfies the resource constraint. In the econometric analysis, I test whether farmers are liquidity constrained by comparing OLS and two-stage least squares estimates. The liquidity constraint mechanism suggests a positive relationship between agricultural productivity and acreage.

4.3.4 Agricultural Policy Mechanism

The federal government has intervened in the agricultural sector since 1933 and it played an active role in regulating agricultural production during the period of atmospheric nuclear testing. The U.S. Department of Agriculture supported prices of major commodities through price support loans and regulated production through restrictions on cultivate acreage and quotas on marketed commodities. Both corn and wheat were subject to acreage restrictions in the 1950s, but the structure of the restrictions differed at the farm level for the two crops.

When the USDA subsidized crop prices using price support programs, these programs distorted incentives and increased agricultural production. This would in turn place additional downward pressures on the prices of agricultural commodities. The government regulated the amount of acreage farmers could harvest to prevent such production responses. Farmers were given a base acreage which then adjusted acreage allotments annually according to a government multiplier (Cochrane and Ryan, 1976; Burt and Worthington, 1988). When the government held large excess supplies of crops or when it expected production to be greater than the government's production target, this multiplier would determine the acreage allotment and regulated the number of planted acres a farmer could harvest.

For corn producers, these base acreage values were a function of a farm's fixed characteristics such as a farm's tillable acreage, crop rotation practices, soil quality, and topography (U.S. Department of Agriculture, 1950; U.S. Congress, 1954; Bailey et al., 2016; U.S. Department of Agriculture, 1956; Cochrane and Ryan, 1976). Corn producers' base acreage for corn was not a function of their production histories. As such corn producers' base acreage would be fixed.

In contrast, wheat producers' base acreage adjusted in response to farmers' harvesting decisions and wheat production histories. A farm's wheat base was generally a function of the farm's past harvested acreage from between two and five years prior (U.S. Department of Agriculture, 1950; U.S. Congress, 1954; Bailey et al., 2016; U.S. Department of Agriculture, 1956; Cochrane and Ryan, 1976). This regulation gave county agricultural boards the authority to reallocate base acreage from farmers who did not use their allotments and other wheat producers. This policy also provided wheat producers a harvested acreage target. While exceptions for drought to other weather-related damage were made at the state and national level, if a farmer failed to harvest their acreage allotment, regulators could then reduce his base acreage. Such an event could adversely affect a farmers' future income.[5]

The enforcement mechanisms of the regulations also differed between wheat and corn. Regulators made price support for both wheat and corn conditional on farmers meeting their allotment restrictions. Corn producers would receive a lower price subsidy if they exceeded their allocation. Wheat producers who exceeded their allotments not only lost eligibility for price supports but also faced additional punishments such as fines and reductions in acreage allotments (Cochrane and Ryan, 1976; Burt and Worthington, 1988). An additional policy of marketing quotas tied wheat producers' incomes to their base acreage and regulated how many bushels of wheat farmers could markets based off their acreage allotment.

The incentive structure created by wheat regulations formed a "use it or lose it" scenario for wheat producers, while such a policy was not present for corn producers (U.S. Congress, 1938, 1948, 1949; Cochrane and Ryan, 1976). Wheat farmers could petition for allotment increases but these allotment requests in total could not exceed 3% of the county's cumulative allotment restriction. Some accommodations were

[5] For example, in June 1950 the USDA notified farmers that their 1951 allotments would be a function of acreage seeded for harvest for the years 1946 to 1949 for the western U.S. and 1947 to 1949 for the eastern U.S. (USDA, 1950B) These restrictions were lifted after farmers seeded winter wheat acreage in the fall of 1950 due to Korean War demands.

made in response to known adverse weather events such as drought or flooding, but these exceptions were probably not made in response to an unexplained productivity shock from radiation. The regulatory incentive structure made reducing cultivated wheat acreage in response to unknown adverse productivity shocks less attractive to farmers. This policy would punish farmers more if crop failure caused by radioactive fallout forced them to abandon cultivated acreage. In cases where cultivated land went unharvested due to failure, farmers faced reductions in the future acreage they could plant.[6]

Winter wheat producers planted in the fall and would receive notification regarding acreage restrictions for the subsequent season in late spring or early summer of the current growing season (USDA, 1950B; and USDA, 1956). Let the fallout shock be denoted by η_{t-1}. Suppose this fallout event caused farmers to abandon acreage in year $t-1$, then this decrease in harvested acreage would affect their wheat acreage allotment at year $t+1$ as the acreage allotments for the subsequent year were determined prior to the realized damage. This timing potentially provides wheat farmers a one year window to respond to the productivity shock before the policy might affect their planting. If farmers planted more acreage in the following year, then they have the option to harvest more acreage and offset the allotment constraint (regulations allowed farmers to place excess output in storage for sale at a later date.)

I incorporate this allotment constraint into a two-period model where the farmer responds to a fallout-induced productivity shock, η_{t-1}, that will cause the allotment constraint to bind in subsequent years. For simplicity, assume that harvested acreage equals planted acreage, that the farmer has one year where they can freely respond to the productivity shock, and that in every year following this one year adjustment period the allotment constraint restricts the farmer's planting decision. Let $A(\cdot)$ denote the allotment function that restricts wheat acreage in all subsequent years, i.e.: $\theta_{t+1} = A(\cdot)$. Let the allotment function be a function of η_{t-1}, the fallout event, and harvested

[6] In 1955, farm regulators switched from using acreage planted for the intent of harvest to using only harvested acreage in their allotment calculations (Cochrane and Ryan, 1976). Policy makers believed using acreage "planted for harvest" discouraged hedging by wheat farmers. By switching to acreage harvested, regulators would not punish farmers who increased planted acreage to hedge against crop failure.

acreage in year t.[7] Increases in fallout exposure caused farmers to harvest fewer acres of planted wheat acreage and this action will reduce the value of the average acreage in the farmer's future allotment unless he increases the average in year t. Equation (4.3.7) describes the two-period model. The discounted stream of future profits is denoted by the concave function $V(\theta_{t+1})$ and is discounted by $\beta \,\epsilon\, [0,1]$.[8]

$$\max_{\theta_t \;\epsilon [0,1]} g(\theta_t) + f(1-\theta_t) + \beta V(A(\eta_{t-1}, \theta_t)) \tag{4.3.7}$$

Taking the derivative with respect to θ_t and rearranging the values results in expression (4.3.8).

$$\beta \frac{\delta A}{\delta \theta_t} V'(A(\eta_{t-1}, \theta_t)) \leq f'(1-\theta_t) - g'(\theta_t) \tag{4.3.8}$$

The first order conditions show that the marginal discounted value of future profits must equal net marginal profit in the current year. At $\theta_t = \theta_{t-1}$ the left-hand side of the expression is larger than the right-hand side (by concavity of $V(\cdot)$ and because of η_{t-1}). When the fallout shock occurs, the farmer will increase the amount of land allocated towards wheat in year t to an amount greater than θ_{t-1}. By the concavity of f, g, and V, this will decrease the left-hand side of the inequality and increase the value of the right-hand side of the inequality until both terms are equated.

4.4 Empirical Strategy and 2SLS Model

To isolate how farmers respond to exogenous variation in productivity, I perform Two-Stage Least Squares (2SLS) regressions and instrument for crop yields using radiation deposition. Both weather conditions and radioactive fallout affect crop productivity. Variation in productivity due to weather affects farm income and plausibly provides the farmer information about future growing conditions. Furthermore, farm policy considered weather conditions when determining acreage allotments (Cochrane and Ryan, 1976). Fallout induced changes in productivity, by contrast, only affected

[7] I assume that the policy binds for all subsequent years to simplify the model.

[8] I collapse the second period profit function into a single function to simplify notation. $V(\cdot)$ denotes the value of a discounted an infinite geometric sum, $\Sigma_{k=1}^{\infty} \beta^k (g(A(\eta, h(\theta_t)) + f(1 - A(\eta_{t-1}, h(\theta_t))))$.

income as farmers would have little information regarding the cause of the productivity shock.[9]

$$ln(Acres_{it}) = \delta ln(YPA_{it-1}) + \boldsymbol{\lambda_{it-1}}\beta + \boldsymbol{\alpha_i} + \boldsymbol{\gamma_t} + \tau_{st} + \mu_{it} \qquad (4.4.1)$$

The second stage regression denoted by equation (4.4.1) reports the effect of a crop yield shock in the previous year upon acres planted of that crop in the next year. The empirical model includes a set of fixed effects to control for time invariant county specific factors and common annual shocks that affected farmers' planting behavior. County and year fixed effects are denoted by $\boldsymbol{\alpha_i}$ and $\boldsymbol{\gamma_t}$. A vector of crop specific monthly precipitation and temperature controls for the previous growing season are denoted by $\boldsymbol{\lambda_{it-1}}$. τ_{st} denotes state specific time trends that control for common state specific trends in crop acreage. The heteroskedastic standard errors ϵ_{it-1} and μ_{it} are clustered at the county level.

YPA_{it-1} denotes yield per acre planted in the past year and is a measure of agricultural productivity. It is plausible that this variable is correlated with unobserved factors that affect both productivity in the previous year and a farmers' planting decisions in the next year. Instrumenting for productivity using weather variation would require weather to only affect farmers' planting decisions through its effects on productivity in the previous year. It is plausible that observable shocks such as weather influence farmers' decisions by changing their expectations about future weather conditions in addition to weather's effect on productivity in the prior year. As such, weather variation would not make a good candidate to instrument for productivity, because it would directly affect planting decisions in year t. Therefore, I use plausibly exogenous variation in radioactive fallout to instrument for agricultural productivity.

$$ln(YPA_{it-1}) = \theta Z_{it-1} + \boldsymbol{\lambda_{it-1}}\phi + \boldsymbol{\alpha_i} + \boldsymbol{\gamma_t} + \tau_{st} + \epsilon_{it-1} \qquad (4.4.2)$$

I instrument for agricultural productivity using radioactive fallout from nuclear testing. Equation (4.4.2) denotes the first stage regression where the exogenous instrument Z_{it-1} represents radiation deposition. Z_{it-1} reports the average amount of fallout de-

[9]Radioactive fallout is relatively uncorrelated with cumulative precipitation during the growing season.

positing on a square meter of land in a given county and year. This measure is reported in thousands of nanoCuries of iodine-131 and is indicative of cumulative fallout deposition. Radioactive fallout would have been uncorrelated with farmer's investment decisions that would both affect the productivity and planting relationship, because the farmer did not know of his fallout exposure.

The only way fallout can affect a farmer's planting decision is through its effects on productivity. Fallout provides an unanticipated productivity shock and this quality makes it an ideal instrument for crop productivity. A positive δ would imply that productivity in one year is positively related to planting in the subsequent year. A positive coefficient would be consistent with the model's predictions suggesting that fallout-induced productivity shocks either limited farmers' resources or that farmers' believed damage caused by unobserved fallout would continue into the next year. A negative δ would imply that a negative productivity shock in the previous year caused farmers to increase planting in the subsequent year. This result would be consistent with the model associated with a "use-it or lose-it" wheat policy. Such a response would be driven by farmers trying to offset the drop in average output that would have reduced the farmer's future allotment. If damage from fallout caused farmers to abandon planted acreage, then it is plausible that government regulations on land allocation became tighter in response to these abandonment decisions.

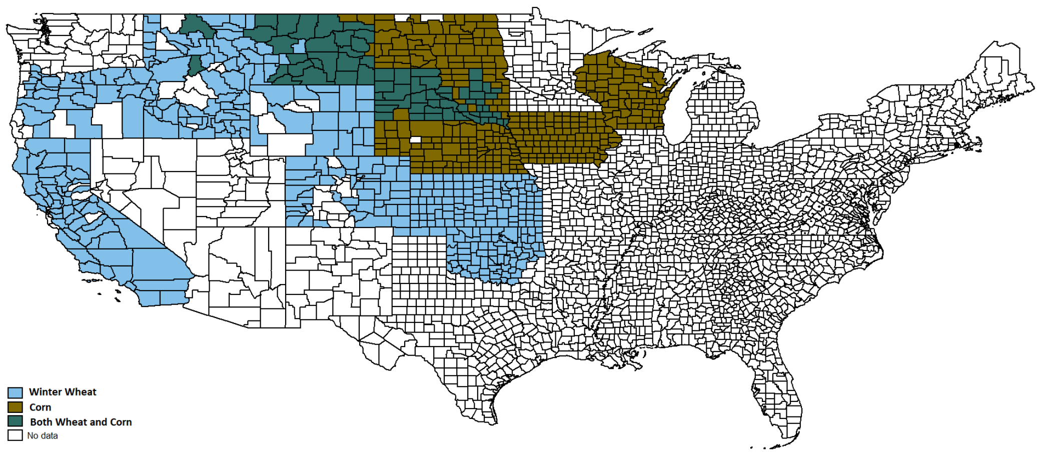


Figure 4.1: Empirical Sample of Corn and Wheat Producing Counties.

Table 4.2: Summary statistics for corn and wheat samples

Summary statistics winter wheat, CA CO ID KS MT OK OR SD WY				
	mean	sd	min	max
Yield Per Acre Planted	19.0	9.89	0.16	86
Acres planted, W.Wheat	57,456.5	79,535.6	10	615,000
Exposure, t	0.10	0.37	0	6.58
Observations	13,400			

Summary statistics corn, IA MT ND NE SD WI				
	mean	sd	min	max
Yield Per Acre Planted	33.6	23.3	0.013	120.3
Acres planted, Corn	63,757.1	50,709.4	30	292,660
Exposure, t	0.090	0.29	0	3.09
Observations	11,852			

4.5 Data

This paper combines annual county level agricultural production measures with historic weather records and a new dataset measuring radioactive fallout dispersal at the county level. The sample is an unbalanced panel from 1939 to 1970. This range of data includes years before atmospheric nuclear testing and years after the cession of nuclear testing in 1963 (NTS atmospheric testing concluded in 1958 apart from a few small tactical tests in 1962.) States in the winter wheat sample include CA, CO, ID, KS, MT, OK, OR, SD, and WY. States in the corn sample include IA, MT, ND, NE, SD and WI. Summary statistics for each sample are reported in Table 4.2.

National Agricultural Statistics Service (2015) provides annual county level information on winter wheat and corn output, yields, harvesting, and planting. Since the counties that report crop production information might change over time, I restrict the sample to counties where acres planted are observed continuously from 1945 to 1958. This restriction ensures that counties that were exposed to radioactive fallout are observed before, during, and after atmospheric testing. Several states started reporting information on wheat and corn in the mid-1940s and many more states started reporting crop production information at later dates.[10] Figure 4.1 reports counties that are include in the winter wheat and corn samples.

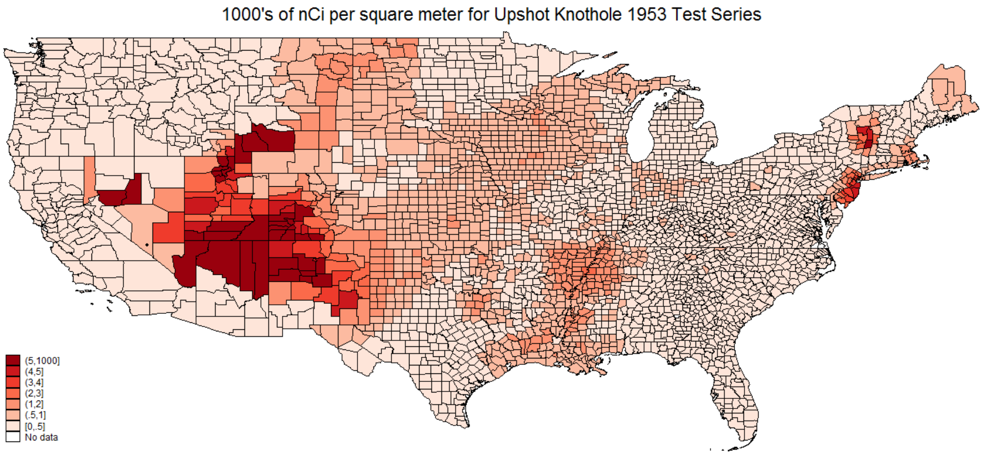


Figure 4.2: Cumulative I-131 Deposition in 1953. Source: Created from National Cancer Institute (1997)

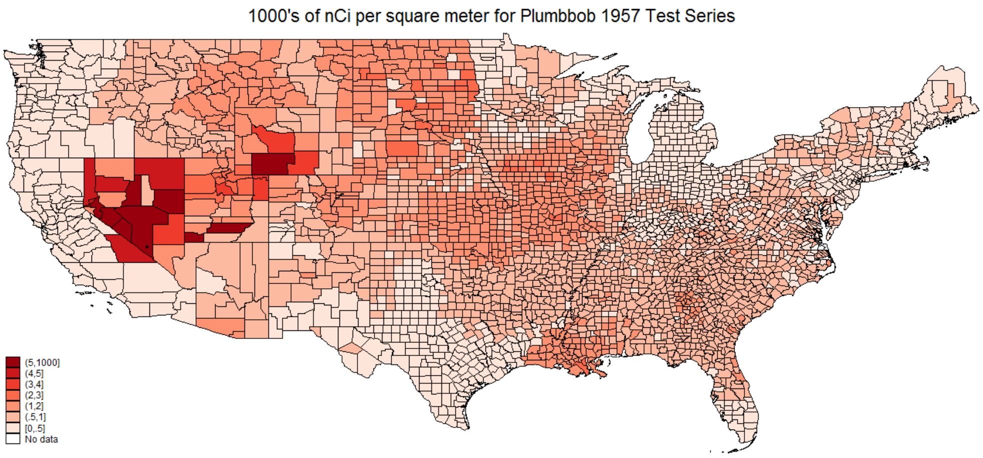


Figure 4.3: Cumulative I-131 Deposition in 1957. Source: Created from National Cancer Institute (1997)

County level fallout deposition records for each atmospheric nuclear test conducted at the Nevada Test Site are provided by the National Cancer Institute (1997). These variables cover each test conducted from 1951 to 1958.[11] The NTS is located just northwest of Las Vegas in Nye County, Nevada. There were major test series in 1951,

[10]CA reports winter wheat starting in 1945. WY is missing wheat data for 1963. MT starts reporting corn planting in 1944. WI stops reporting corn planting in 1967.

[11]Note, deposition measures for the first three tests conducted in 1951 are not available as the radiation monitoring station network was not yet set up.

1952, 1953, 1955, and 1957. A series of small atmospheric tests occurred in 1958 right before the U.S. entered a testing moratorium in 1958. In 1961 the moratorium broke down and a set of small atmospheric tests with a cumulative yield less than two kilotons occurred in 1962 before the enactment of the Partial Nuclear Test Ban Treaty in 1963 (US Department of Energy, 2000). The treaty ended all atmospheric nuclear tests by the U.S. and USSR after 1963. Most tests occurred between the months of March and July. Fallout dispersal maps for the 1953 Upshot Knothole and 1957 Plumbbob test series are presented in Figures 4.2 and 4.3. These measures report cumulative iodine-131 dispersal per meter squared. This measure is highly correlated with cumulative fallout deposition since the deposition is occurring in the days following each test and therefor it makes an appropriate proxy for cumulative radiation exposure (National Cancer Institute, 1997). I aggregate each of these measures up to the year level. County level data on monthly temperature averages and monthly precipitation totals come from the Global Historical Climatology Network version 3 and were created by Lawrimore et al. (2011). These records control for the effects of weather on agricultural productivity and potential information provided to farmers about future weather conditions.

Table 4.3: OLS effects of yield shock on acres planted next year, 1939-1970

	(1)	(2)	(3)	(4)	(5)	(6)
	ln wheat acres			ln corn acres		
ln Yield, t	0.127***	0.135***	0.126***	0.035***	0.027**	0.027**
	(0.019)	(0.021)	(0.018)	(0.012)	(0.012)	(0.014)
Year FE	Yes	Yes	Yes	Yes	Yes	Yes
County FE	Yes	Yes	Yes	Yes	Yes	Yes
Weather Cont.	No	Yes	Yes	No	Yes	Yes
State TT	No	No	Yes	No	No	Yes
N	13,400	13,400	13,400	11,852	11,852	11,852
$Adj.r^2$	0.932	0.933	0.940	0.950	0.952	0.958

All yields are yield per acre planted for their respective crop. Standard Errors in parentheses are clustered by County. States in the winter wheat sample include CA, CO, ID, KS, MT, OK, OR, SD, and WY. States in the corn sample include IA, MT, ND, NE, SD and WI. Samples restricted to counties observed continuously from 1945 to 1958. Exposure is measured as thousand of nCi of I-131 depositing per square meter in a given year. Weather controls for wheat consist of month temperature averages and precipitation totals for the months January to August in the current year and months September to December of the previous year. Weather controls for corn consist of month temperature averages and precipitation totals for the months January to September in the current year.
* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Table 4.4: 2SLS effects of wheat yield shock on wheat acres planted next year, “Use-it or lose-it policy constraint" 1939-1970

	Log acres planted, t+1		
Log yield, t	-0.437***	-0.520**	-0.729***
	(0.156)	(0.238)	(0.252)
	First Stage		
Exposure, t	-0.124***	-0.091***	-0.093***
	(0.019)	(0.020)	(0.019)
Year FE	Yes	Yes	Yes
County FE	Yes	Yes	Yes
Weather Controls	No	Yes	Yes
State Time Trends	No	No	Yes
K-P Wald rk F-stat	40.60	21.60	23.11
N	13,400	13,400	13,400

All Standard Errors are Clustered by County.

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

All yields are yield per acre planted for their respective crop. Standard Errors in parentheses are clustered by County. States in the winter wheat sample include CA, CO, ID, KS, MT, OK, OR, SD, and WY. Samples restricted to counties observed continuously from 1945 to 1958. Exposure is measured as thousand of nCi of I-131 depositing per square meter in a given year. Weather controls for wheat consist of month temperature averages and precipitation totals for the months January to August in the current year and months September to December of the previous year.
* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Table 4.5: 2SLS effects of corn yield shock on corn acres planted next year, No policy constraint 1939-1970

	Log acres planted, t+1		
Log yield, t	-0.054	0.013	-0.045
	(0.109)	(0.104)	(0.158)
		First Stage	
Exposure, t	-0.156***	-0.167 ***	-0.108***
	(0.035)	(0.036)	(0.030)
Year FE	Yes	Yes	Yes
County FE	Yes	Yes	Yes
Weather Controls	No	Yes	Yes
State Time Trends	No	No	Yes
K-P Wald rk F-stat	19.47	19.47	21.04
N	11,852	11,852	11,852

All Standard Errors are Clustered by County.

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

All yields are yield per acre planted for their respective crop. Standard Errors in parentheses are clustered by County. States in the corn sample include IA, MT, ND, NE, SD and WI. Samples restricted to counties observed continuously from 1945 to 1958. Exposure is measured as thousand of nCi of I-131 depositing per square meter in a given year. Weather controls for corn consist of month temperature averages and precipitation totals for the months January to September in the current year.
* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

4.6 Empirical results

4.6.1 Main empirical results

The OLS relationship between the productivity proxy and next years planting is positive for both wheat and corn. Table 4.3 presents the OLS regression estimates of the relationship between agricultural yield in the previous year and acres planted. This relationship between productivity and planting in the subsequent year are subject to potential upward bias in the OLS models because of unobserved investments and potential belief effects. To address these endogeniety issues, I measure responses to fallout-induced productivity shocks. These results are captured in the 2SLS regressions in Tables 4.4 and 4.5. I run three different model specifications for each crop. Specifications (1) and (4) include only year and county fixed effects and provide a baseline for comparison to other specifications. In specifications (2) and (5), I add crop specific monthly temperature and precipitation controls. These specifications control for potential correlations between fallout deposition and weather conditions that affect agricultural productivity. Specifications (3) and (6) add state specific linear time trends to control for potential underlying trends that are shared across counties within the same state. All coefficients discussed in this section refer to the specifications (3) and (6) and are statistically significant at least at the 5% level unless otherwise noted. Finally, I present additional evidence to further establish the credibility of the estimates through a series of robustness checks.

The OLS regression results find a positive and statistically significant relationship between yield per acre planted in the previous year and acres planted in the subsequent year for both wheat and corn. A 1% decrease in yields in year t results in wheat farmers decreasing wheat acreage by approximately 0.13% and corn acreage by 0.03% in year $t+1$. Wheat farmers appear to respond more to yield shocks than corn planters. These OLS results are consistent with either farmers treating productivity shocks as serially correlated or a resource constraint scenario. The 2SLS results differ substantially from these OLS results for both wheat and corn.

For the 2SLS estimates, the first stage effects of fallout on yields are negative and statistically significant. The Kleibergen-Paap Wald rk F statistics suggest the instrument is sufficiently strong. A one standard deviation increase in fallout exposure caused winter wheat yields to drop approximately 3.4% and corn yields to drop approximately 3.1%. These reductions in yields and agricultural productivity resulted from farmers abandoning planted acreage. Fallout induced productivity shocks caused farmers to reduce acre harvested in the year of these shock, and this crop abandonment is what would decrease future wheat allotments to farmers. Decreases in harvested acreage by corn producers would not affect their future allotments. To show this, I regress harvested acreage on acres planted and on the fallout exposure variable.

Table 4.6: Log acres harvested conditioned on log acres planted: 1939-1970

	(1)	(2)	(3)	(4)	(5)	(6)
	ln wheat acres			ln corn acres		
exposure	-0.060***	-0.046***	-0.047***	-0.193***	-0.166***	-0.128***
	(0.012)	(0.012)	(0.012)	(0.032)	(0.032)	(0.026)
ln acres planted	0.989***	0.990***	0.985***	1.201***	1.142***	1.038***
	(0.006)	(0.006)	(0.006)	(0.064)	(0.056)	(0.040)
Year FE	Yes	Yes	Yes	Yes	Yes	Yes
County FE	Yes	Yes	Yes	Yes	Yes	Yes
Weather Cont.	No	Yes	Yes	No	Yes	Yes
State TT	No	No	Yes	No	No	Yes
N	13,871	13,871	13,871	12,224	12,224	12,224
$Adjr^2$	0.989	0.990	0.990	0.901	0.913	0.948

All yields are yield per acre planted for their respective crop. Standard Errors in parentheses are clustered by County. States in the winter wheat sample include CA, CO, ID, KS, MT, OK, OR, SD, and WY. States in the corn sample include IA, MT, ND, NE, SD and WI. Samples restricted to counties observed continuously from 1945 to 1958. Exposure is measured as thousand of nCi of I-131 depositing per square meter in a given year. Weather controls for wheat consist of month temperature averages and precipitation totals for the months January to August in the current year and months September to December of the previous year. Weather controls for corn consist of month temperature averages and precipitation totals for the months January to September in the current year.
* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Table 4.6 reports the effects of fallout deposition on how much planted acreage farmers harvested. This measure approximates the extent to which fallout caused crop abandonment. Farmers abandoned cultivated wheat and corn in response to fallout deposition. A one standard deviation increase in fallout exposure caused wheat farmers to abandon approximately 1.7% more planted acreage. Corn producers exhibited greater sensitivity to fallout exposure and a one standard deviation increase in fallout caused them to abandon approximately 3.7% more planted acreage. Fallout exposure reduced both wheat and corn productivity, but the harvesting actions of wheat producers in response to the shocks caused future allotments to decrease.

In the second stage of the 2SLS regression, I analyze how agricultural producers adjusted their planting behavior in response to unanticipated productivity shocks from fallout. Wheat producers increased the amount of wheat acreage they planted following a negative productivity shock. These responses to fallout-induced productivity shocks were shaped by government policy constraints that tied their productivity histories to their future streams of income. Fallout caused farmers to harvest fewer acres of planted wheat and this action could adversely affect their future wheat allotments and thus their future income. By planting more, farmers created the option to harvest more and offset the tightening policy constraint. A 1% fallout-induced decrease in winter wheat yield per acre planted in the previous year would have caused wheat producers to plant 0.73% additional acres the subsequent year.

In contrast corn producers, who were not subject to a regulatory constraint tied to agricultural production, did not adjust their planting in response to fallout-induced productivity shocks. The only information producers had regarding the fallout-induced productivity shock were the observable changes in productivity. Since radioactive fallout was invisible, they would have been unable to identify the specific cause of the diminished productivity.

Producers' responses to fallout-induced productivity shocks differed across both corn and wheat. Assuming the covariance between the corn and wheat models is zero, I find that producer responses to fallout-induced productivity shocks are different in a statistically significant way.[12] Between specifications (1) and (4), the difference is statistically significant at the 10% level. For specifications (2) and (5) and specifications (3) and (6) the difference is statistically significant at the 5% level.

Table 4.7: Placebo test, fallout exposure shifted forward 15 years : 1939-1950

	(1)	(2)	(3)	(4)	(5)	(6)
	ln acres planted		ln yield per acre planted		ln yield per acre harv.	
	Wheat	Corn	Wheat	Corn	Wheat	Corn
Placebo, t-1	0.021	0.012	-0.023	-0.039	-0.014	-0.021
	(0.022)	(0.011)	(0.028)	(0.032)	(0.019)	(0.028)
Year FE	Yes	Yes	Yes	Yes	Yes	Yes
County FE	Yes	Yes	Yes	Yes	Yes	Yes
Weather Cont.	No	No	No	No	No	No
State TT	No	No	No	No	No	No
N	4,939	4,615	4,942	4,615	4,942	4,615
$Adj.r^2$	0.953	0.978	0.470	0.770	0.549	0.757

Fallout deposition was reassigned to the same counties but 15 year before nuclear testing started at the NTS. Standard Errors in parentheses are clustered by County. States in wheat sample include CA, CO, ID, KS, MT, OK, OR, SD, and WY. States in corn sample include IA, MT, ND, NE, SD, and WI. Exposure is measured as thousand of nCi of I-131 depositing per square meter in a given year. Weather Controls for wheat consist of month temperature averages and precipitation totals for the months January to August in the current year and months September to December of the previous year. Weather Controls for corn consist of month temperature averages and precipitation totals for the months January to August in the current year.
* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

[12]Estimating the covariance between two different regression specifications usually employs Seemingly Unrelated Regressions and OLS. OLS estimates substituting fallout for yield per acre suggest the covariance factor for fallout between the two models is positive and thus assuming the covariance measure between the 2SLS models as zero likely understates statistical difference between the corn and wheat coefficients. 2SLS with different samples requires a custom three-stage-least-squares estimator to estimate the covariance matrix between the two regressions.

Table 4.8: Randomized placebo treatment, fallout for each test randomly reassigned to county within same test year: 1939-1970

	(1)	(2)	(3)	(4)	(5)	(6)
	ln acres planted		ln yield per acre planted		ln yield per acre harv.	
	Wheat	Corn	Wheat	Corn	Wheat	Corn
Placebo	0.022	-0.008	0.029	-0.019	0.018	0.003
	(0.019)	(0.007)	(0.019)	(0.021)	(0.011)	(0.010)
Year FE	Yes	Yes	Yes	Yes	Yes	Yes
County FE	Yes	Yes	Yes	Yes	Yes	Yes
Weather Cont.	No	No	No	No	No	No
State TT	No	No	No	No	No	No
N	12,933	11,418	13,400	11,852	13,400	11,852
$Adj.r^2$	0.932	0.952	0.490	0.586	0.582	0.780

Fallout deposition was randomly reassigned to counties within the sample within the same year of the test. Standard Errors in parentheses are clustered by County. States in wheat sample include CA, CO, ID, KS, MT, OK, OR, SD, and WY. States in corn sample include IA, MT, ND, NE, SD, and WI. Exposure is measured as thousand of nCi of I-131 depositing per square meter in a given year. Weather Controls for wheat consist of month temperature averages and precipitation totals for the months January to August in the current year and months September to December of the previous year. Weather Controls for corn consist of month temperature averages and precipitation totals for the months January to August in the current year.
* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

4.6.2 Placebo falsification tests

In order to test the robustness of the 2SLS estimates and the exogenous nature of the fallout instrument, I report two different falsification tests. Tables 4.7 and 4.8 report the results showing the validity of the fallout instrument. The first test reassigns fallout exposure to a period fifteen years earlier so that deposition is artificially assigned to the years between 1936 and 1943. This tests for underlying unobserved prior aspects of farmers that might be geographically correlated with fallout that might bias econometric estimates. The second test randomly reassigns fallout exposure within each year of occurrence, i.e. fallout exposure in 1951 is randomly shifted to another sample county in 1951. This reassignment tests for potential unobserved variables that are temporally correlated with the fallout variable. For both corn and wheat, I test for a potentially spurious relationship between fallout exposure and the variables of interest. These variables include log acres planted, log yield per acre planted, and log yield per acre harvested. Each regression only includes county and year fixed effects and the samples consists of counties included in the main analysis. In either placebo test, I find small statistically insignificant relationships between fallout exposure and the variables of interest. The results suggest that the instrument is uncorrelated with potentially unobserved factors that might affect farmers' planting and harvesting decisions.

4.7 Discussion

Radioactive fallout shocks interacted with U.S. agricultural policy and added to the damage directly caused by nuclear testing at the NTS. In the sample, the average amount of land in winter wheat production between 1945 and 1950 was 17.4 million acres. To understand the size of this policy induced distortion, I calculated the marginal effect of each year's fallout deposition on wheat yields in the first stage regressions, multiplied this effect by the coefficient for log yields from Table **??** specification (3), and multiplied this marginal effect by the average amount of land planted for wheat between 1945 and 1950. This "back-of-the-envelop" calculation suggest that on average fallout reduced winter wheat yields by 4.7% (with a 6.4% standard deviation) in the years of deposition. These fallout-induced productivity shocks caused winter wheat producers to plant an additional 2.6 million acres of winter wheat. The average sample county increased winter wheat acreage by approximately 960 acres (with a 3,160 acre standard deviation) in the years following these shocks.

One portion of the cost of this policy induced behavior was the increased seed cost for the additional acreage. U.S. Agricultural Statistics volumes report the per bushel prices for wheat, high quality wheat seeds, and average sowing rates per acre. From this information I estimate the additional seed cost for sowing this land was between $43.4 million and $63 million (2016$).[13] The total cost of this additional planting is likely many times greater than these estimates.

Corn producers were not subject to policy constraints that penalized them for abandoning acreage in response to fallout-induced crop damage. Their responses to these unanticipated productivity shocks were to treat it as a transitory event. These farmers did not adjust their planting behavior and this result suggests that producers' budget constraints did not alter their planting decisions. Wheat farmers engaged in costly actions in response to negative productivity shocks. Producers who were constrained by a tightened budget would not have been able to make such a response. These two results suggest that liquidity constraints are not the mechanism behind the OLS relationship between productivity and planting.

4.8 Conclusion

Policy incentives can fundamentally alter the responses producers make to productivity shocks. Government has the potential to magnify or mitigate the costs of adverse shocks. Many times it is empirically difficult to isolate the mechanisms that contribute to the overall measured effect of a shock. A confluence of factors can disguise the costs of policy mechanisms. I model these mechanisms using a framework Hornbeck (2012) developed and employ a unique source of variation to isolate the direct effect of a productivity shock to agriculture.

In the empirical analysis, I instrument for agricultural productivity using radioactive fallout from nuclear testing. Radioactive fallout differs fundamentally from typical

[13] I used nominal prices in January 1959 and the Bureau of Labor statistics CPI calculator to convert these values to January 2016$.

productivity shocks and OLS productivity shocks. Unlike weather, fallout provides an unanticipated productivity shock. Since weather conditions tend to be correlated over time, weather shocks can potentially provide information about future growing conditions and affect producer responses though channels other than productivity. Corn farmers treated fallout-induced productivity shocks as transitory and did not adjust their planting in response to these shocks. Wheat farmers' reactions to fallout were shaped by policy restrictions that tied future farm income to their harvesting history.

This paper reveals that government policy can interact with productivity shocks and shape responses to such shocks. From regulating pollution to subsidizing wages through the Earned Income Tax Credit to mandating health insurance coverage, governments intervene in many areas of economic life. The potential costs of these policies are likely obscured by other mechanisms in empirical analyses of disruptive events. As the effects of climate change become more pronounced, measuring the social costs associated with such temperature shifts becomes more relevant. One dimensions of these costs are the social costs attributable to government policy. Policies such as crop insurance and ethanol mandates push farmers towards practices that likely increase their exposure to climate change. Treating policy as a fixed factor can overlook its role in shaping adaptation and may misstate the estimated effects of climate change.

Chapter 5

Conclusion: Summarizing the Economic Consequences of Atmospheric Nuclear Testing

Through the threat of nuclear annihilation, the Cold War brought a period of sustained peace between world powers. This peace, however, had substantial environmental and social costs. Not only were resources diverted towards the development and production of nuclear weapons, but myopic decisions by leaders concerned with strategic dominance resulted in catastrophic quantities of harmful radioactive fallout. During the 1950s, the continental United States experienced the equivalent of multiple Chernobyl disasters. This pollution not only spread throughout the region surrounding the NTS, but also deposited in areas hundreds to thousands of miles from its point of origin.

In Chapter 2, "Some Unintended Fallout from Defense Policy: Measuring the Effect of Atmospheric Nuclear Testing on American Mortality Patterns," I study how nuclear testing at the NTS affected U.S. public health and the geographic and temporal extent of the harm. This chapter combines data from U.S. Vital Statistics with measures of radioactive iodine-131 exposure. I-131 is an isotope that entered the food supply and that was ingested in large quantities.

The effects of these tests were broadly felt and suggest that nuclear testing also adversely affected the health of millions of people. I find that fallout from nuclear testing led to persistent and substantial increases in overall mortality for large portions of the country. The largest mortality effects appear in areas of the Great Plains and Midwest, which are regions not studied in the medical and scientific literature. My estimates suggest that nuclear testing at the NTS contributed to approximately as many deaths as the bombings of Hiroshima and Nagasaki. Over a twenty year period, exposure to ionizing radiation from irradiated milk contributed to between 340,000 and 460,000 deaths.

Throughout the Great Plains and Midwest, radioactive fallout landed on crops and pasture. The ionizing radiation emitted from this matter led to reductions in crop yields and the number of grazing animals observed in county inventories. In the chapter titled, "In the Shadow of the Mushroom Cloud: Nuclear Testing, Radioactive Fallout and Damage to U.S. Agriculture," I measure the direct effects of radioactive fallout from Nevada Test Site activities on agricultural production in the Great Plains and Midwest. Farmers abandoned cultivated acreage following fallout deposition suggesting that fallout induced crop failure. The direct economic damage to U.S. agriculture exceeds 25 billion dollars (2016$). Wheat losses totaled to approximately 1/3 of the sample's 1945-50 average total yearly output. Corn losses totaled to approximately 2.5 times the sample's 1945-50 average total yearly output.

In Chapter 4 titled "Measuring Policy's Role in Mediating Responses to Agricultural Productivity Shocks," I use the unanticipated nature of radioactive fallout to study how farmers respond to productivity shocks. During the period of nuclear testing, the public was generally unaware that they were being exposed to radioactive material created hundreds to thousands of miles away. As such, radioactive fallout depositing on farmers' fields would have been uncorrelated with any adaptive actions or investments agricultural producers made. Using a two stage least squares framework, I measure how farmers adjust their planting decisions in response to adverse productivity shocks in the previous year.

USDA policy incentives magnified the costs of these fallout induced productivity shocks. I find that wheat specific "use-it or lose-it" government policies that regulated future production based on past production histories caused farmers to increase wheat cultivation in the years following fallout induced productivity shocks. This behavior was an attempt by farmers to offset the negative effects of a (potentially) tightening policy constraint. From 1952 to 1959, wheat producers planted 2.6 million additional acres of wheat (approximately 17 million acres of wheat were planted on average from 1945-50). Corn producers, who were not subject to a policy constraint, treated fallout induced productivity shocks as transitory.

Contemporary agricultural policies, such as crop insurance, implemented using information from producers' past production histories. The climate change and agricultural literature has been relatively agnostic regarding the role policy plays in shaping adaptive responses to temperature shocks. My results suggest that policy incentives can fundamentally shape producer responses to productivity shocks and this could alter the estimated social cost of disruptive events. Policy is not a fixed factor in relation to productivity shocks, and overlooking the role it plays in shaping producer responses to, for example, temperature fluctuations can misstate the social costs economists extrapolate regarding climate change.

Atmospheric nuclear testing has the hallmarks of a broadly felt environmental disaster and the United States is one of many governments that conducted atmospheric tests. These tests not only had broad negative effects for public health, but also directly affected the economy and industry of the nation. The social costs measured and detailed in this dissertation relate only to a small number of nuclear tests conducted by the United States, but many other nations engaged in similar activities during the Cold War. The French performed tests in the Algerian desert, the Chinese in Lop Nur, and the Soviets in Kazakhstan and the Arctic. Much of this material eventually precipitated in populated regions and likely had similar effects on mortality rates and agricultural productivity. It is plausible that society still bears the costs of the Cold War and the public health consequences of atmospheric nuclear testing are understated.

Appendix A: Chapter 2 Appendix

Table A1: Short run mortality effects, log crude death rate conditioned on log population, 1940-1988

	(1)	(2)	(3)	(1)	(2)	(3)
	Milk Exposure, 1,000's nCi			Deposition Exposure, 1,000's nCi		
Exp, t	0.0410***	0.0126**	0.0276***	0.00910***	-0.00638**	0.00393
	(0.00609)	(0.00499)	(0.00985)	(0.00340)	(0.00283)	(0.00447)
Exp, t-1	0.0521***	0.0190***	0.0391***	0.0147***	0.00178	0.00716
	(0.00546)	(0.00489)	(0.00793)	(0.00387)	(0.00255)	(0.00531)
Exp, t-2	0.0590***	0.0259***	0.0437***	0.0162***	0.00647**	0.00770*
	(0.00528)	(0.00446)	(0.00846)	(0.00359)	(0.00254)	(0.00407)
Exp, t-3	0.0416***	0.0133***	0.0230**	0.0128***	0.00270	0.00564
	(0.00550)	(0.00481)	(0.00930)	(0.00371)	(0.00272)	(0.00499)
Exp, t-4	0.0516***	0.0280***	0.0283***	0.0169***	0.00675**	0.00301
	(0.00534)	(0.00512)	(0.00836)	(0.00399)	(0.00293)	(0.00380)
Year FE	Yes	Yes	Yes	Yes	Yes	Yes
County FE	Yes	Yes	Yes	Yes	Yes	Yes
State TT	No	Yes	No	No	Yes	No
State Yr FE	No	No	Yes	No	No	Yes
N	124,260	124,260	124,260	124,260	124,260	124,260
Adj r^2	0.725	0.752	0.755	0.724	0.752	0.755

* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$
All Standard Errors are Clustered by County. Panel includes controls for log population. Exposure denotes the yearly cumulative I-131 measures at the county level.

Table A2: Short run mortality effects, log crude death rate, 1940-1988

	(1)	(2)	(3)	(1)	(2)	(3)
	Milk Exposure, 1,000's nCi			Deposition Exposure, 1,000's nCi		
Exp, t	0.00776	0.0143**	0.0284**	0.00396	-0.00653**	0.00626
	(0.00597)	(0.00555)	(0.0111)	(0.00385)	(0.00323)	(0.00517)
Exp, t-1	0.0216***	0.0236***	0.0441***	0.0127***	0.00283	0.00994*
	(0.00583)	(0.00515)	(0.00852)	(0.00339)	(0.00286)	(0.00598)
Exp, t-2	0.0293***	0.0302***	0.0510***	0.0159***	0.00771***	0.0107**
	(0.00584)	(0.00498)	(0.0103)	(0.00319)	(0.00268)	(0.00480)
Exp, t-3	0.0213***	0.0169***	0.0303***	0.0122***	0.00359	0.00792
	(0.00562)	(0.00501)	(0.00961)	(0.00343)	(0.00299)	(0.00559)
Exp, t-4	0.0341***	0.0298***	0.0339***	0.0162***	0.00771**	0.00519
	(0.00583)	(0.00536)	(0.00918)	(0.00365)	(0.00314)	(0.00437)
Year FE	Yes	Yes	Yes	Yes	Yes	Yes
County FE	Yes	Yes	Yes	Yes	Yes	Yes
State TT	No	Yes	No	No	Yes	No
State Yr FE	No	No	Yes	No	No	Yes
N	124,260	124,260	124,260	124,260	124,260	124,260
Adj r^2	0.661	0.699	0.705	0.661	0.698	0.705

* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$
All Standard Errors are Clustered by County. Panel excludes controls for log population. Exposure denotes the yearly cumulative I-131 measures at the county level.

Table A3: Long run mortality effects, log crude death rate conditioned on log population, 1940-1988

	(1)	(2)	(3)	(1)	(2)	(3)
	Milk Exposure, 1,000's nCi			Deposition Exposure, 1,000's nCi		
Exp, t-1 to t-5	0.244***	0.113***	0.120***	0.0940***	0.0388***	0.0245
	(0.0168)	(0.0138)	(0.0261)	(0.0179)	(0.0113)	(0.0203)
Exp, t-6 to t-10	0.147***	0.0783***	0.0477*	0.0760***	0.0385***	0.00872
	(0.0137)	(0.0127)	(0.0261)	(0.0146)	(0.0108)	(0.0169)
Exp, t-11 to t-15	0.0958***	0.0507***	-0.00304	0.0565***	0.0311***	0.0128
	(0.0139)	(0.0133)	(0.0261)	(0.0123)	(0.00962)	(0.0148)
Exp, t-16 to t-20	0.0324**	0.0155	-0.0813***	0.0258**	0.0128	-0.0265**
	(0.0146)	(0.0143)	(0.0301)	(0.0105)	(0.00951)	(0.0126)
Exp, t-21 to t-25	-0.0411***	-0.0113	-0.0674***	0.00583	0.00806	-0.0148
	(0.0148)	(0.0127)	(0.0242)	(0.00705)	(0.00614)	(0.0102)
Year FE	Yes	Yes	Yes	Yes	Yes	Yes
County FE	Yes	Yes	Yes	Yes	Yes	Yes
State TT	No	Yes	No	No	Yes	No
State Yr FE	No	No	Yes	No	No	Yes
N	124,260	124,260	124,260	124,260	124,260	124,260
Adj r^2	0.726	0.752	0.755	0.725	0.752	0.755

* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$
All Standard Errors are Clustered by County. Panel includes controls for log population. Exposure denotes the pooled five year averages of cumulative I-131 measures at the county level.

Table A4: Long run mortality effects, log crude death rate, 1940-1988

	(1)	(2)	(3)	(4)	(5)	(6)
	Milk Exposure, 1,000's nCi			Deposition Exposure, 1,000's nCi		
Exp, t-1 to t-5	0.159***	0.124***	0.158***	0.0972***	0.0453***	0.0304
	(0.0190)	(0.0171)	(0.0331)	(0.0165)	(0.0141)	(0.0253)
Exp, t-6 to t-10	0.130***	0.0832***	0.0906***	0.0820***	0.0424***	0.00560
	(0.0165)	(0.0161)	(0.0327)	(0.0152)	(0.0131)	(0.0199)
Exp, t-11 to t-15	0.0976***	0.0428***	0.0190	0.0669***	0.0342***	0.00256
	(0.0172)	(0.0165)	(0.0329)	(0.0144)	(0.0122)	(0.0186)
Exp, t-16 to t-20	0.0571***	0.00274	-0.0781**	0.0393***	0.0143	-0.0423***
	(0.0173)	(0.0166)	(0.0342)	(0.0139)	(0.0121)	(0.0156)
Exp, t-21 to t-25	0.0638***	-0.0244	-0.0656**	0.0229**	0.00429	-0.0300**
	(0.0197)	(0.0154)	(0.0312)	(0.0105)	(0.00760)	(0.0131)
Year FE	Yes	Yes	Yes	Yes	Yes	Yes
County FE	Yes	Yes	Yes	Yes	Yes	Yes
State TT	No	Yes	No	No	Yes	No
State Year FE	No	No	Yes	No	No	Yes
N	124,260	124,260	124,260	124,260	124,260	124,260
Adj r^2	0.662	0.699	0.705	0.663	0.699	0.705

* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$
All Standard Errors are Clustered by County. Panel excludes controls for log population. Exposure denotes the pooled five year averages of cumulative I-131 measures at the county level.

Table A5: Changes in county mortality patterns attributable to NTS fallout, 1951 to 1973

	I-131 Ground Deposition			
Table A3	Mean	SD	Max	Total Deaths
Specification 1	1.626	2.695	48.637	919,930.300
Specification 2	0.772	1.258	21.153	438,896.900
Specification 3	0.521	1.091	22.392	285,953.800

	I-131 Ground Deposition			
Table A3	Mean	SD	Max	Total Deaths
Specification 4	1.176	1.999	61.394	768,609.900
Specification 5	0.553	0.928	24.857	363,744.700
Specification 6	0.230	0.397	15.414	149,369.400

	I-131 in Local Milk			
Table A4	Mean	SD	Max	Total Deaths
Specification 1	1.265	2.009	30.404	724,033.300
Specification 2	0.797	1.337	23.163	450,844.700
Specification 3	0.865	1.603	30.219	482,489.200

	I-131 Ground Deposition			
Table A4	Mean	SD	Max	Total Deaths
Specification 4	1.283	2.158	63.592	840,690.700
Specification 5	0.623	1.046	28.852	409,208.300
Specification 6	0.191	0.425	19.209	119,680.600

Source: Author's calculations.

Appendix B: Chapter 3 Appendix

B1 Falsification Test

I conduct a set of placebo tests to test if fallout had an effect on agricultural production before the period of NTS testing. I shift fallout exposure 10 years forward and 15 years forward. Since fallout is correlated year to year during the testing period, I only analyze the effects of the placebos on output on data from 1931 to 1958. Each regression includes weather controls, year fixed effects, and county fixed effects. I run each regression specification with the first exposure term from the regression. For crops it is t-0 and animals it is t-1.

Table B1: Placebo crops, log outcomes: 1931-1950

	(1)	(2)	(3)	(4)	(5)	(6)
	Wheat Yield		Wheat	Corn Yield		Corn
	Planted	Harv	Acres Harv	Planted	Harv	Acres Harv
Placebo, t+10	-0.020	-0.008	-0.011	0.142***	0.109***	0.023**
	(0.0144)	(0.010)	(0.007)	(0.030)	(0.023)	(0.0105)
Placebo, t+15	-0.022	-0.020*	-0.003	-0.014	-0.032	-0.013
	(0.018)	(0.012)	(0.011)	(0.031)	(0.026)	(0.012)
Year FE	Yes	Yes	Yes	Yes	Yes	Yes
County FE	Yes	Yes	Yes	Yes	Yes	Yes
Weather Cont.	Yes	Yes	Yes	Yes	Yes	Yes
N	7,547	7,574	7,547	7,020	7756	7020
Adj r^2	0.521	0.598	0.977	0.777	0.790	0.980

All Standard Errors are Clustered by County.

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

Table B2: Placebo livestock, log outcomes: 1931-1950

	(1)	(2)	(3)
	Sheep inventory	Sheep held for breeding	Milk cows inventory
Placebo, t+11	-0.060	-0.010	-0.009*
	(0.050)	(0.019)	(0.005)
Placebo, t+16	0.045	0.062*	-0.001
	(0.043)	(0.034)	(0.007)
Year FE	Yes	Yes	Yes
County FE	Yes	Yes	Yes
Weather Controls	Yes	Yes	Yes
N	3,120	3,680	11,587
Adj r^2	0.885	0.970	0.982

All Standard Errors are Clustered by County.

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

B2 Spatially Correlated Standard Errors

I incorporate spatially correlated errors using a modified version of code provided by Hsiang (2010) and which was edited by Thiemo Fetzer. Spatially correlated standard errors are provided with a cut off of 100km from the county 1950 centroids from the Minnesota Population Center (2016). These standard errors correct for temporal and geographic correlation of standard errors as discussed in Conley (1999). I only report spatially correlated standard errors for a 100km cut off and for specifications (1), (2), and (3) from the main regressions. Interacted controls with time dummies complicates the calculation of the standard errors due to the proliferation of coefficients.

Table B3: Log winter wheat yield per acre: 1945-1970

	(1)	(2)	(3)	(4)	(5)	(6)
	Acres Planted			Acres Harvested		
Exposure						
t	-0.131***	-0.0984***	-0.103***	-0.0713***	-0.0510***	-0.0543***
	(0.0248)	(0.0241)	(0.0236)	(0.0124)	(0.0117)	(0.0113)
t-1	-0.0159	-0.0330*	-0.0377**	-0.00700	-0.0193	-0.0214*
	(0.0178)	(0.0174)	(0.0168)	(0.0130)	(0.0121)	(0.0118)
t-2/5	0.0395	0.0177	0.0379	0.0460**	0.0299	0.0402*
	(0.0343)	(0.0334)	(0.0334)	(0.0229)	(0.0213)	(0.0213)
t-6/10	-0.267***	-0.219***	-0.101**	-0.246***	-0.196***	-0.117***
	(0.0439)	(0.0425)	(0.0431)	(0.0330)	(0.0324)	(0.0321)
Year FE	Yes	Yes	Yes	Yes	Yes	Yes
County FE	Yes	Yes	Yes	Yes	Yes	Yes
Weather	No	Yes	Yes	No	Yes	Yes
State TT	No	No	Yes	No	No	Yes
N	11,547	11,547	11,547	11,547	11,547	11,547
Adj r^2	0.010	0.114	0.136	0.0102	0.132	0.166

100 km cut off. Conley SE in brackets.

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

Table B4: Log corn yield per acre: 1945-1970

	(1)	(2)	(3)	(4)	(5)	(6)
	Acres Planted			Acres Harvested		
Exposure						
t	-0.272***	-0.247***	-0.123***	0.0170	0.000469	0.00793
	(0.0565)	(0.0540)	(0.0428)	(0.0238)	(0.0200)	(0.0194)
t-1	-0.417***	-0.357***	-0.196***	-0.0603***	-0.0415**	-0.0279*
	(0.0691)	(0.0617)	(0.0501)	(0.0216)	(0.0172)	(0.0166)
t-2/5	-1.665***	-1.035***	-0.635***	-0.337***	-0.182***	-0.151***
	(0.165)	(0.142)	(0.118)	(0.0586)	(0.0516)	(0.0504)
t-6/10	-0.428	-0.669***	0.307	0.213**	0.0204	0.102
	(0.271)	(0.239)	(0.188)	(0.0859)	(0.0834)	(0.0788)
Year FE	Yes	Yes	Yes	Yes	Yes	Yes
County FE	Yes	Yes	Yes	Yes	Yes	Yes
Weather	No	Yes	Yes	No	Yes	Yes
State TT	No	No	Yes	No	No	Yes
N	9,928	9,928	9,928	9,928	9928	9,928
Adj r^2	0.032	0.161	0.488	0.0122	0.140	0.257

100 km cut off. Conley SE in brackets.

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

Table B5: Log winter wheat acres harvested conditioned on acres planted: 1945-1970

	(1)	(2)	(3)
ln acres planted	0.990***	0.994***	0.988***
	(0.00638)	(0.00619)	(0.00660)
Exposure, t	-0.0598***	-0.0471***	-0.0479***
	(0.0148)	(0.0149)	(0.0148)
Exposure, t-1	-0.00822	-0.0134*	-0.0156**
	(0.00790)	(0.00807)	(0.00795)
Avg. Exp. 2-5 yrs ago	-0.00496	-0.0112	-0.000623
	(0.0171)	(0.0181)	(0.0180)
Avg. Exp. 6-10 yrs ago	-0.0195	-0.0219	0.0168
	(0.0191)	(0.0190)	(0.0197)
Year FE	Yes	Yes	Yes
County FE	Yes	Yes	Yes
Weather Cont.	No	Yes	Yes
State TT	No	No	Yes
N	11,547	11,547	11,547
Adj r^2	0.850	0.856	0.859

100 km cut off. Conley SE in brackets.

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

Table B6: Log corn acres harvested conditioned on acres planted: 1945-1970

	(1)	(2)	(3)
ln acres planted	1.247***	1.182***	0.995***
	(0.0357)	(0.0342)	(0.0274)
Exposure,t	-0.295***	-0.252***	-0.131***
	(0.0504)	(0.0476)	(0.0364)
Exposure, t-1	-0.354***	-0.315***	-0.168***
	(0.0620)	(0.0580)	(0.0458)
Avg. Exp. 2-5 yrs ago	-1.276***	-0.829***	-0.484***
	(0.139)	(0.125)	(0.101)
Avg. Exp. 6-10 yrs ago	-0.568**	-0.641***	0.204
	(0.240)	(0.217)	(0.169)
Year FE	Yes	Yes	Yes
County FE	Yes	Yes	Yes
Weather Controls	No	Yes	Yes
State Time Trends	No	No	Yes
N	9,928	9,928	9,928
Adj r^2	0.277	0.346	0.619

100 km cut off. Conley SE in brackets.

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

Table B7: Log number of sheep in inventory

	(1)	(2)	(3)
Exposure, t-1	-0.075**	-0.056	-0.056
	(0.0377)	(0.0380)	(0.0378)
Average Exposure 2-5 yrs ago	-0.367***	-0.256***	-0.259***
	(0.0829)	(0.0842)	(0.0841)
Average Exposure 6-10 yrs ago	-0.499***	-0.332**	-0.335**
	(0.129)	(0.137)	(0.138)
Year FE	Yes	Yes	Yes
County FE	Yes	Yes	Yes
Weather Controls	No	Yes	Yes
State Time Trends	No	No	Yes
N	4,056	4,056	4,056
Adj r^2	0.00449	0.0133	0.0135

100 km cut off. Conley SE in brackets.

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

Table B8: Log number of sheep held for breeding

	(1)	(2)	(3)
Exposure,t-1	0.071***	0.078***	0.067***
	(0.0194)	(0.0211)	(0.0208)
Average Exposure 2-5 yrs ago	0.099**	0.057	0.002
	(0.0447)	(0.0474)	(0.0469)
Average Exposure 6-10 yrs ago	0.138*	0.102	0.038
	(0.0734)	(0.0768)	(0.0783)
Year FE	Yes	Yes	Yes
County FE	Yes	Yes	Yes
Weather Controls	No	Yes	Yes
State Time Trends	No	No	Yes
N	7,655	7,655	7,655
Adj r^2	0.00190	0.0227	0.0569

100 km cut off. Conley SE in brackets.

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

Table B9: Log number of dairy cows

	(1)	(2)	(3)
Exposure,t-1	0.002	0.005	-0.002
	(0.00802)	(0.00891)	(0.00728)
Average Exposure 2-5 yrs ago	-0.029	-0.028	0.005
	(0.0183)	(0.0191)	(0.0173)
Average Exposure 6-10 yrs ago	-0.202***	-0.246***	0.033
	(0.0364)	(0.0368)	(0.0338)
Year FE	Yes	Yes	Yes
County FE	Yes	Yes	Yes
Weather Controls	No	Yes	Yes
State Time Trends	No	No	Yes
N	16,403	16,403	16,403
Adj r^2	0.00286	0.0289	0.215

100 km cut off. Conley SE in brackets.

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

B3 Cumulative Losses by Agricultural Commodity

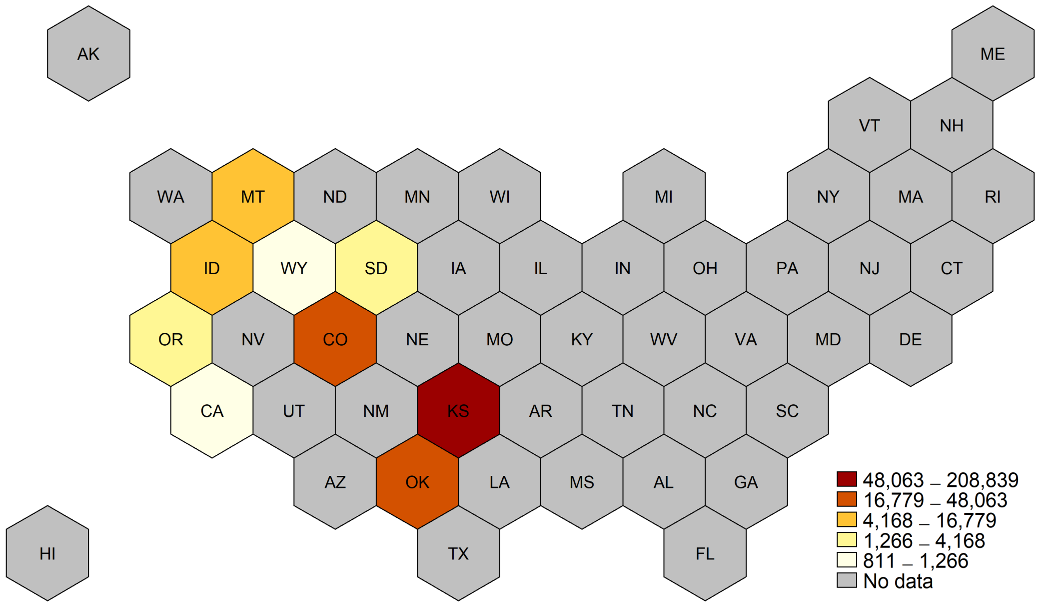


Figure B1: Cumulative Wheat Losses, 2016$. Source: Author's calculations

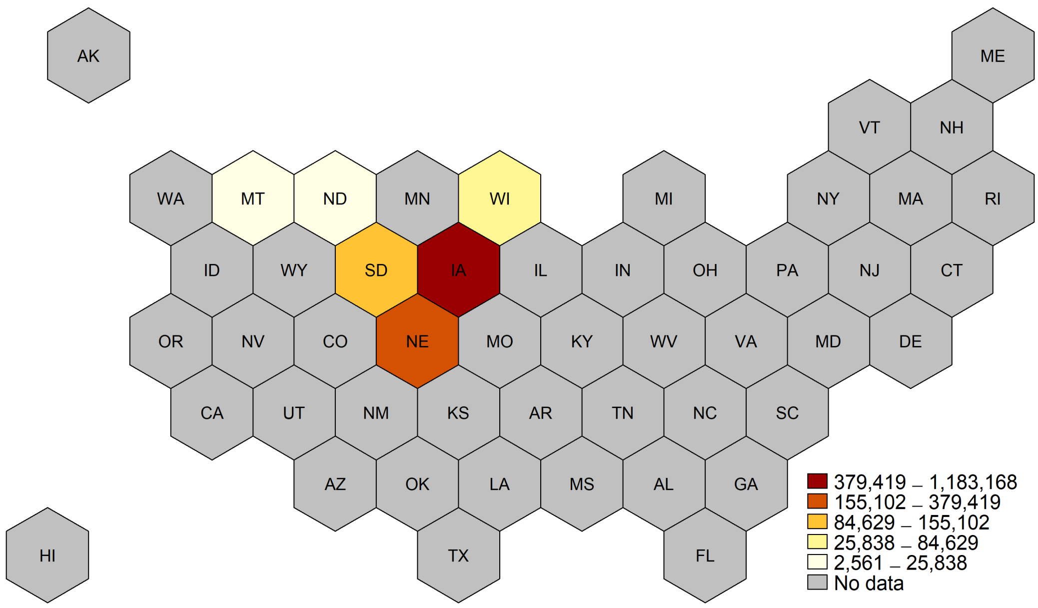


Figure B2: Cumulative Corn Losses, 2016$. Source: Author's calculations

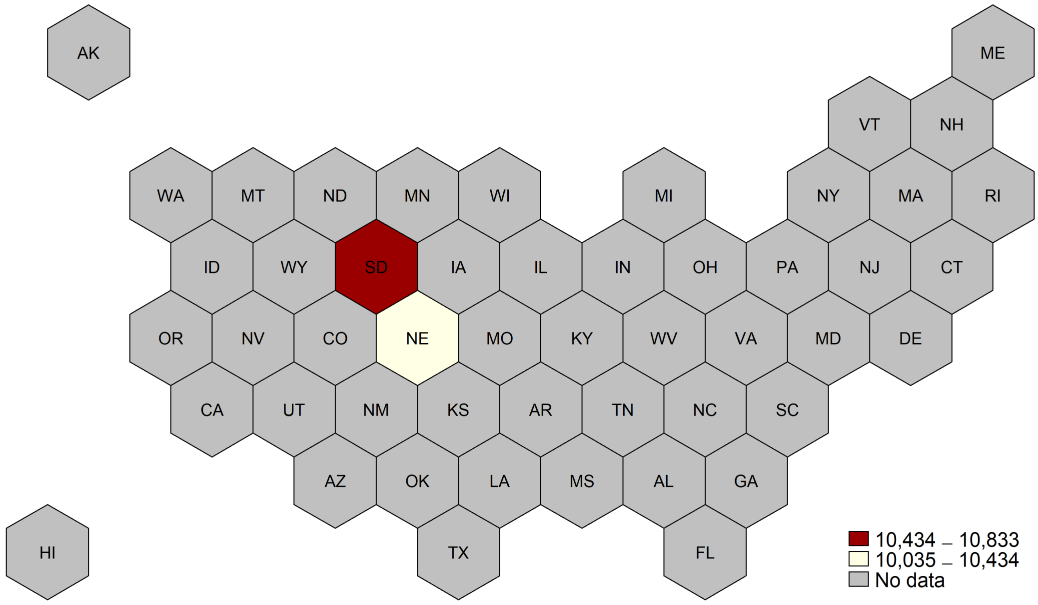


Figure B3: Cumulative Sheep Inventory Losses, 2016\$. Source: Author's calculations

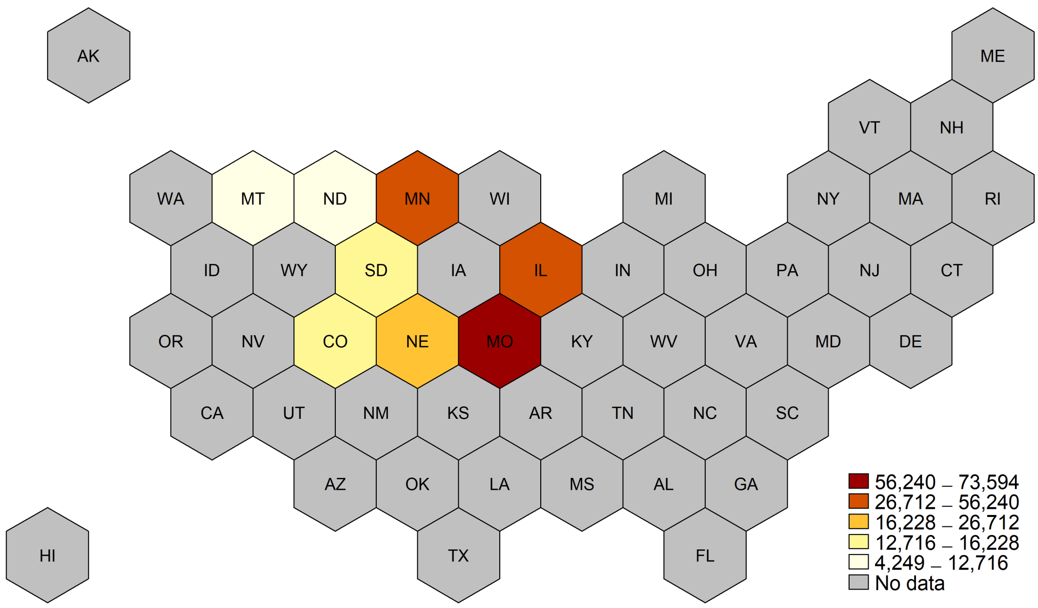


Figure B4: Cumulative Dairy Cow Inventory Losses, 2016\$. Source: Author's calculations

Appendix C: Chapter 4 Appendix

C1 Robustness Checks

Learning responses following fallout events

Farmers might observe fallout-induced productivity shocks and develop beliefs about future growing conditions. Bayesian learning suggests that fallout-induced productivity shocks would be more informative in areas where there is low variability in agricultural yields. The intuition behind this prediction is that agricultural producers would be better able to discern that something is damaging crops from underlying noise in production when variance in productivity is low. If underlying productivity is highly variable, then it becomes more difficult for producers to discern whether fallout-induced productivity shocks from random variation productivity.

Suppose that agricultural yields, denoted by Y_t are distributed normally with known variance σ and unknown mean μ_t, i.e. $Y_t \sim N(\mu_t, \sigma)$. The farmer has prior beliefs regarding the distribution of μ_t where $\mu_t \sim N(\mu_0, \tau)$. After experiencing a realized level of agricultural productivity the farmer adjusts her beliefs regarding future agricultural productivity for period $t+1$. This updated expectation is the weighted average of the observed Y_t and the prior beliefs the farmer holds. Equation (C1.1) describes how the farmer updates their value of μ_{t+1}.

$$\mu_{t+1} = \frac{\sigma^2 * \mu_0}{\sigma^2 + \tau^2} + \frac{\tau^2 * Y_t}{\sigma^2 + \tau^2} \tag{C1.1}$$

As underlying variance in crop productivity, σ, increases the farmer weights the released yields in year t, Y_t, less and weights the prior beliefs relatively more. I test this Bayesian prediction by interacting the fallout exposure variable with the inverse of county specific yield variances from 1939 to 1950 in an OLS regression. The inverse variance variable increases as variation in yields decreases. If farmers learn from fallout and adjust their behavior in response to fallout-induced shocks, then areas with lower variability should decrease acreage in response to fallout shocks.

Table C1 reports information regarding the inverse yield variance measures. The OLS results are reported in Table A4. I find that the fallout exposure variable interacted with inverse yields has a consistently negative coefficient for both wheat and corn. Only specifications (2) and (3) for wheat find statistically significant effects at the 5% and 10% levels respectively. A one standard deviation increase in the inverse variance measure offsets the increase in planted acreage by approximately 2.2%. These results suggest that farmers in areas with less variability in productivity were more likely to treat fallout-induced productivity shocks as persistent events and that this learning offsets the policy induced planting behavior estimated in the 2SLS analysis.

Table C1: Summary statistics of yield variance measures

Variable	Obs	Mean	Std. Dev.	Min	Max
Winter Wheat Sample					
Inverse Yield Variance	33,744	0.06	0.04	0.01	0.26
Interaction	33,744	0.00	0.02	0.00	0.81
Corn Sample					
Inverse Yield Variance	34,732	0.04	0.10	0.01	1.52
Interaction	34,732	0.00	0.01	0.00	0.82

The effect of a binding policy constraint

From 1939 to 1949, the government did not restrict the amount of acreage farmers could harvest but it did collect the information to determine farmers' base acreages. In 1950, the government enforced acreage allotments on both wheat and corn. These were lifted due to the Korean War between 1951 and 1953 and reinstated in 1954 (Cochrane and Ryan, 1976). I interact my fallout variable with an indicator variable for years after 1954 in an OLS framework to test whether farmers reacted differently to fallout

Table C2: OLS effects of fallout and underlying yield variability: 1939-1970

	(1)	(2)	(3)	(4)	(5)	(6)
	ln wheat acres			ln corn acres		
Exposure, t-1	0.064***	0.093***	0.086***	0.015	0.008	0.017
	(0.025)	(0.025)	(0.025)	(0.014)	(0.014)	(0.014)
Exposure, t-1 X	-0.258	-0.727**	-0.549*	-0.183	-0.233	-0.277
Inv. Yield Var.	(0.305)	(0.335)	(0.315)	(0.190)	(0.190)	(0.202)
Year FE	Yes	Yes	Yes	Yes	Yes	Yes
County FE	Yes	Yes	Yes	Yes	Yes	Yes
Weather Controls	No	Yes	Yes	No	Yes	Yes
State Time Trends	No	No	Yes	No	No	Yes
N	12,113	12,113	12,113	11,280	11,280	11,280
Adj r^2	0.927	0.929	0.933	0.947	0.948	0.956

Standard Errors in parentheses are clustered by County. Inverse yield variances for each . States in the winter wheat sample include CO, ID, KS, MT, OK, OR, SD, and WY. States in the corn sample include IA, ND, NE, SD and WI. Samples restricted to counties observed continuously from 1939 to 1958. Exposure is measured as thousand of nCi of I-131 depositing per square meter in a given year. Weather controls for wheat consist of month temperature averages and precipitation totals for the months January to August in the current year and months September to December of the previous year. Weather controls for corn consist of month temperature averages and precipitation totals for the months January to September in the current year.
* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

once the government started regulating farmers. It is plausible that farmers reacted more to government policy when the government was actively restricting allotments.

Since I do no have multiple instruments, I run the interaction directly in OLS with fallout replacing yield per acre planted. Table C3 reports farmers' responses once policy became binding. Corn producers whose productivity was not tied to acreage allotments did not adjust their planting in response to fallout shocks. The interaction term for wheat producers suggests that farmers started to increase cultivated acreage after the policy was binding.

Table C3: OLS effects of binding policy on harvested acreage: 1939-1970

	(1)	(2)	(3)	(4)	(5)	(6)
	Log wheat acres			Log corn acres		
Exposure, t	-0.001	-0.007	0.030	0.005	0.019	-0.019
	(0.023)	(0.024)	(0.024)	(0.032)	(0.037)	(0.035)
1[Year $\geq$ 1953]	0.132***	0.133***	0.093***	0.006	-0.033	0.036
X Exposure	(0.031)	(0.034)	(0.032)	(0.036)	(0.043)	(0.040)
Year FE	Yes	Yes	Yes	Yes	Yes	Yes
County FE	Yes	Yes	Yes	Yes	Yes	Yes
Weather Controls	No	Yes	Yes	No	Yes	Yes
State Time Trends	No	No	Yes	No	No	Yes
N	13,400	13,400	13,400	11,852	11,852	11,852
Adj r^2	0.931	0.933	0.939	0.950	0.951	0.957

Standard Errors in parentheses are clustered by county. States in the winter wheat sample include CO, ID, KS, MT, OK, OR, SD, and WY. States in the corn sample include IA, ND, NE, SD and WI. Samples restricted to counties observed continuously from 1939 to 1958. Exposure is measured as thousand of nCi of I-131 depositing per square meter in a given year. Weather controls for wheat consist of month temperature averages and precipitation totals for the months January to August in the current year and months September to December of the previous year. Weather controls for corn consist of month temperature averages and precipitation totals for the months January to September in the current year.
* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

C2 Measuring Response to Weather Shocks

Changes in planting in response to weather

Realized weather events likely affect farmers' planting decisions through weather's effects on agricultural productivity and through secondary belief channels. It is unlikely that farmers responses to weather events are wholly driven through weather's effects on productivity. Therefore, instrumenting for agricultural productivity using weather variables plausibly violates the exclusion restriction and the instrument is correlated with unobservable factors such as beliefs or adaptive investments. These unobserved factors would likely affect the estimated planting response farmers make towards productivity shocks in the previous year. Since a 2SLS analysis using weather shocks as an IV would likely violate the exclusion restriction, I use an OLS framework to measure weather's effects on corn and wheat yields. I then compare planting responses farmers make in the next year to these same weather measures. If farmers treat weather shocks as serially correlated across years, then a increases in temperatures associated with decreased crop productivity should decrease planting of that same crop next year and vice-versa. I pool temperature into three month average from January to December and aggregate precipitation to crop specific growing season totals to prevent a perfusion of coefficients. Temperature averages generally align with the growing season window used in the main analysis. [1] The results in Table C4 and for both corn and wheat. Increases in average temperatures that are associated with decreased corn or wheat yields result in farmers planting fewer acres of corn the next year. Warmer than average summers increase wheat yields and result in farmers planting more winter wheat for the subsequent growing year. A mild winter also increase planting but has no statistically significant effects on yields. These results suggest that agricultural producers responded to weather events in a manner consistent with a scenario where productivity shocks are serially correlated.

[1]The appendix reports correlations between these weather variables across years after the variables were demeaned of county and year fixed effects.

Table C4: OLS yield and planting responses to weather: 1939-1970

	(1)	(2)	(3)	(4)
	Corn		Wheat	
	ln yield, t-1	ln acres planted, t	ln yield, t-1	ln acres planted, t
Avg Temp				
Oct-Dec, t-2			0.006*	-0.004
			(0.003)	(0.004)
Jan-Mar, t-1			0.002	0.019***
			(0.002)	(0.002)
Apr-June, t-1	-0.023***	-0.011***	-0.042***	-0.013***
	(0.006)	(0.003)	(0.003)	(0.004)
July-Sept, t-1	-0.094***	-0.028***	0.020***	0.013***
	(0.007)	(0.004)	(0.003)	(0.004)
Precip.	0.107***	-0.029***	0.035***	0.004
	(0.007)	(0.004)	(0.002)	(0.003)
Precip. Sq.	-0.002***	0.001***	-0.001***	-0.000**
	(0.000)	(0.000)	(0.000)	(0.000)
Year FE	Yes	Yes	Yes	Yes
County FE	Yes	Yes	Yes	Yes
State TT	Yes	Yes	Yes	Yes
N	11,852	11,852	13,400	13,400
Adj r^2	0.772	0.957	0.533	0.939

Standard Errors in parentheses are clustered by county. States in the winter wheat sample include CO, ID, KS, MT, OK, OR, SD, and WY. States in the corn sample include IA, ND, NE, SD and WI. Samples restricted to counties observed continuously from 1939 to 1958. Exposure is measured as thousand of nCi of I-131 depositing per square meter in a given year. Weather controls for wheat consist of month temperature averages and precipitation totals for the months January to August in the current year and months September to December of the previous year. Weather controls for corn consist of month temperature averages and precipitation totals for the months January to September in the current year.
* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

C3 Data Appendix

Fallout Data Creation

Atmospheric nuclear denotations conducted near the surface of the earth irradiated thousands of tons of material. This material was then drawn up into a mushroom cloud many kilometers up into the atmosphere. Figure C1 provides a diagram describing the 1953 Simon test shot. This figure describes how winds intercepted radioactive material. A portion of the radioactive material was intercepted by low altitude winds and deposited in the surrounding areas as dry precipitate. In the downwind region, this radiation was carried as radioactive dust blows. Most of the material, however, was carried higher up and intercepted by high altitude winds. Figure C2 denotes where the resulting fallout debris clouds traveled in the days following the test. This radioactive material traveled vast distances and was deposited hundreds to thousands of miles from the test site as wet precipitate. In the days following the test, areas outside of the Downwind region experienced radioactive fallout only if it happened to be raining while the radiation cloud was over head. Rain scavenged radioactive dust from the cloud and delivered it to the ground. The agricultural regions studied in this paper would only experience fallout exposure through wet precipitate. As such, radioactive deposition from atomic testing can be treated as any exogenous event that would be uncorrelated with unmeasured aspects of farm production.

Deposition estimates exist for all tests from 1951 to 1970 with the exceptions of 3 tests in the Ranger series in 1951 and 6 tests from 1962 to 1970. I use measures from 1951 to 1958 as these are the only tests which resulted in detectable depositions in my sample.[2] These county level estimates are reported in terms of nano Curies per square meter (nCi). Much of the raw data came from national monitoring stations. The number of stations varies across time but never exceeded 100 stations.[3] Figure C3 provides a map of national monitoring stations for 1953. The military also engaged in air monitoring and used city-county stations around the NTS to track the radiation cloud (National Cancer Institute, 1997). This raw data allowed researchers

[2]There was a testing moratorium from 1959 to 1961 and four low yield tactical nuclear tests at the NTS in 1962. The cumulative yield of these tests was less than two kilotons.

[3]The locations of the stations were not provided to me by the NCI.

to track the position of the radiation cloud over time and understand how much radiation precipitated down under differing meteorological conditions. The NCI applied Kriging techniques to interpolate county level depositions for each test. Specific details regarding the techniques and calculations are available in National Cancer Institute (1997).

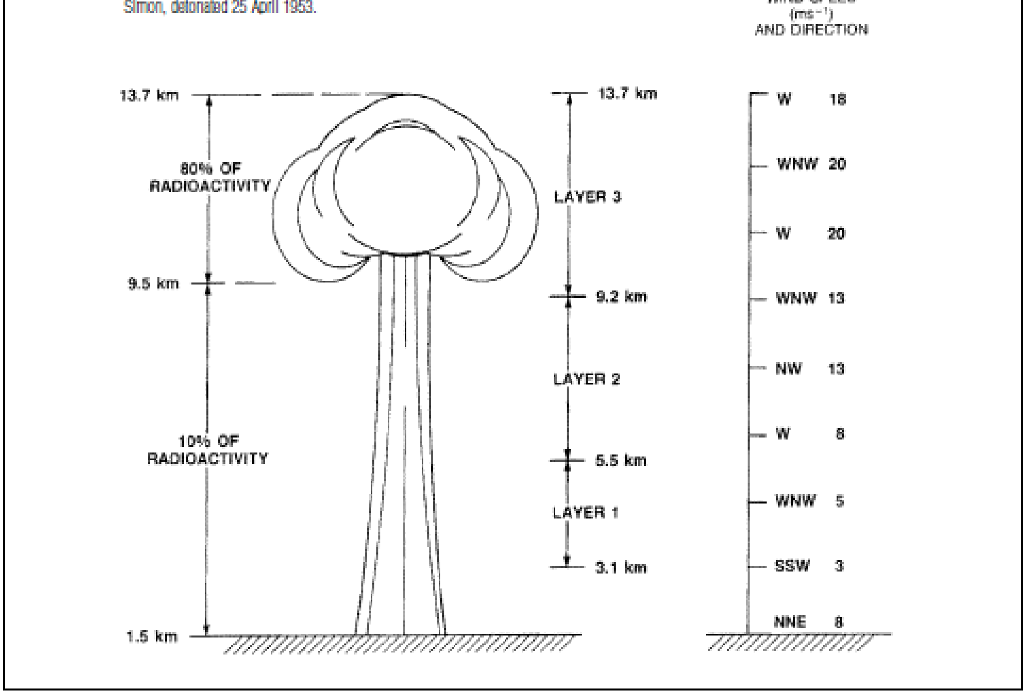


Figure 2.6. Schematic depiction of the mushroom cloud and stem resulting from the test Simon, detonated 25 April 1953.

Figure C1: Mushroom Cloud and Wind Patterns, 1953 Simon Shot. Source: National Cancer Institute (1997)

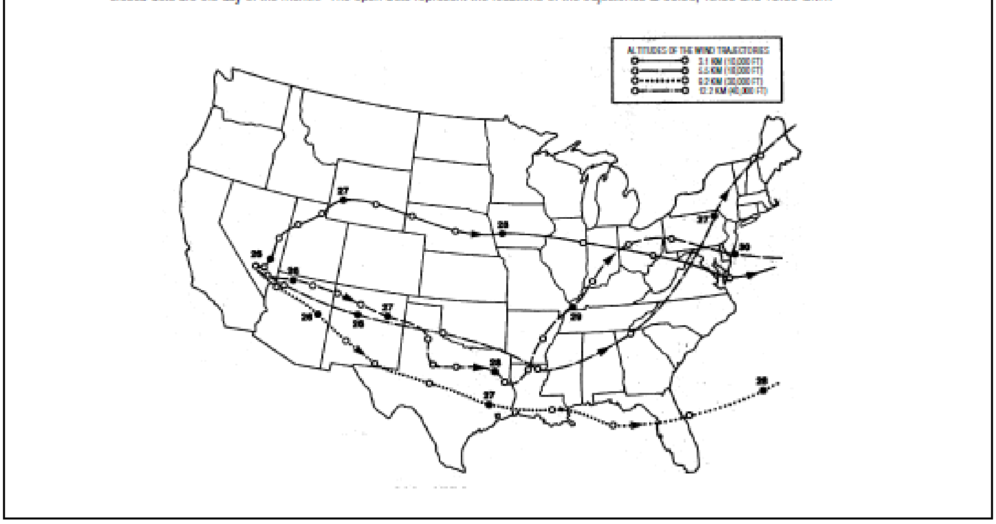


Figure 2.7. Paths of the trajectories followed by portions of the radioactive cloud at the altitudes of 3.1, 5.5, 9.2, and 12.2 km above mean sea level (MSL) resulting from the test Simon detonated 25 April 1953. The closed dots represent the locations of the trajectories at 00:00 GMT, while the numbers near the closed dots are the day of the month. The open dots represent the locations of the trajectories at 06:00, 12:00 and 18:00 GMT.

Figure C2: Trajectories of the 1953 Simon Shot's Radiation Clouds. Source: National Cancer Institute (1997)

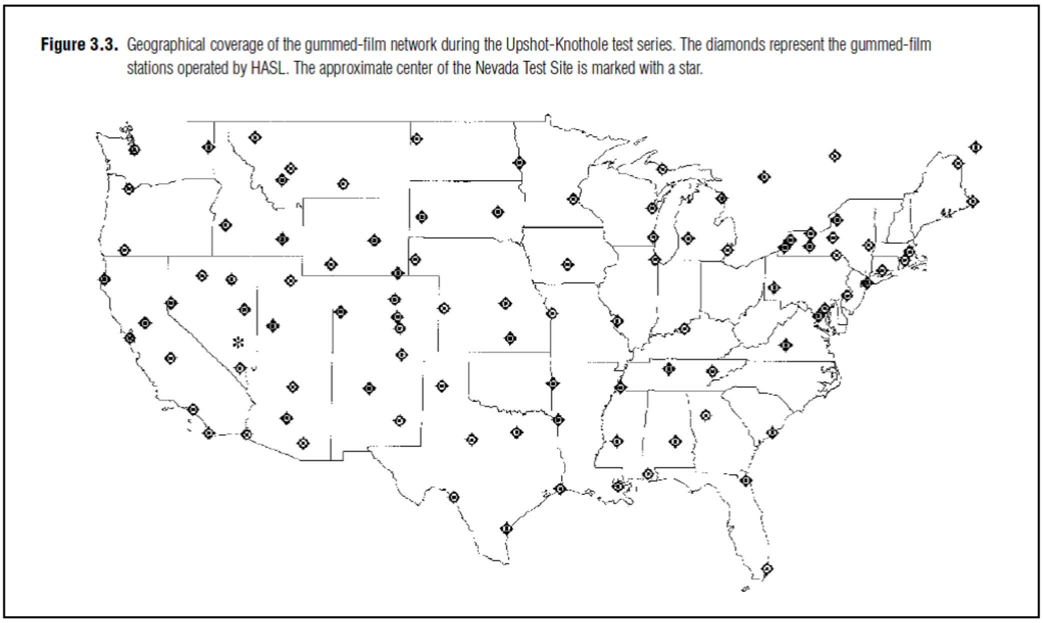


Figure C3: Map of National Radiation Monitoring Stations 1953. Source: National Cancer Institute (1997)

Table C5: Yearly correlation of I-131 fallout deposition

	t	t-1	t-2	t-3	t-4
t	1	-	-	-	-
t-1	0.0886	1	-	-	-
t-2	0.2009	0.0886	1	-	-
t-3	0.0311	0.2009	0.0886	1	-
t-4	0.1233	0.0311	0.2009	0.0886	1

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