In the Shadow of the Mushroom Cloud:

Nuclear Testing, Radioactive Fallout and Damage to U.S. Agriculture

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Abstract

In the 1950's the United States conducted scores of nuclear tests at the Nevada Test Site just northwest of Las Vegas. Each test was a controlled catastrophic event that created tremendous amounts of radioactive matter. Much of this radioactive pollution deposited across large portions of the country. This paper uses annual county level deposition of radioactive material as an exogenous shock to agricultural productivity and measures adjustments the agricultural sector made in response to damage caused by this radioactive pollution. This paper finds that radioactive fallout from atmospheric tests conducted in Nevada directly altered agricultural production. Fallout led to large reductions in wheat and corn yields. I show that farmers abandoned cultivated acreage in more irradiated counties and substantially adjusted their planting schedules following exposure to radioactive pollution.[1]

Pollution and disaster often alter trajectories of economic development. Economists have studied the implications of many shocks and even measured to what extent adaption mitigates these events. At times, government policy and actions act as the source of these shocks and distortions. With domestic atmospheric nuclear testing in the 1950's there is a unique intersection between government policy, pollution, and disaster. These tests generated tremendous quantities of harmful radioactive material. One estimate places the total

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atmospheric release of radioactive material from the Nevada Tests Site (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). The scientific and medical literature shows that fallout from these domestic tests harmed human and animal populations (Bustad et al., 1957; Garner, 1963; National Cancer Institute, 1997) and it is quite plausible that pollution created from nuclear testing had first order effects upon domestic agriculture.

Radioactive fallout from domestic nuclear testing in the 1950's deposited on agricultural lands hundreds and even thousands miles from the initial test site in Nevada. This radioactive pollution is imperceptible and invisible but nevertheless adversely affects biological systems. As such, radioactive fallout would adversely affect crop yields and agricultural productivity. Farmers who experienced damage from nuclear fallout would be unable to determine the proximate cause of this damage. Unlike easily observable weather events, radioactive pollution from nuclear testing would not provide a clear informative signal regarding future growing conditions. The analysis of this paper has two empirical aims. The first measures how NTS activities directly altered agricultural production in the United States. The second focus studies how farmers adjust their behavior in response to pure productivity shocks that do not convey informative signals about future growing conditions.

The unique historical circumstance of nuclear testing provides a rare opportunity to study how farmers react to unanticipated productivity shocks when the proximate cause of the shock is unobservable. To study how atmospheric nuclear testing affected agricultural production, I construct a new annual panel dataset of fallout deposition for U.S. counties from 1951 to 1958. Using this new dataset, I exploit annual county level variation in radioactive fallout deposition across years to measure the effect of nuclear testing upon U.S. agriculture. This methodology allows me to measure to what extent NTS activities affected domestic agriculture and measure how farmers responded to these productivity shocks. This paper adds to a small but growing economics literature using variation in radioactive pollution as a source of exogenous variation. This work uses low doses of ionizing radiation to test the fetal origins hypothesis in Scandinavian populations (Almond et al., 2009; Black et al., 2013), and measures the social costs of the Chernobyl disaster in Ukraine (Lehmann and Wadsworth, 2011; Danzer and Danzer, 2016). This paper is the first in the economics literature to study the direct effects of radioactive pollution upon agriculture. Apart from a concurrent paper measuring the effect of NTS fallout on U.S. mortality patterns Meyers (2017), this paper is the first paper in the economics literature to study the effects of nuclear testing on domestic populations.

Previous studies of have used natural disasters, pests, and variation in weather to study adjustments made by farmers in response to adverse shocks. Researchers often study disasters because these events provide exogenous variation in underlying economic conditions. By measuring how agents adjust and adapt to these adverse events, economists develop insight about how people might respond to adverse events in the future. Work by Boustan et al. (2012) studies the adaptive migratory responses to tornadoes and floods. Hornbeck (2012) highlights the short run and long run productivity responses to Dust Bowl soil erosion. Lange et al. (2009) use the Boll Weevil to study how farmers responded to anticipated disasters. Nuclear testing possesses the hallmarks of natural disaster. Each atomic test was a deliberate catastrophic event which launched thousands of tons of irradiated matter into the atmosphere.

Economists interested in the potential costs of climate change also study how agents respond to adverse weather shocks. Econometric analyses of the relationship between weather variables and outcomes of interest face some econometric hurdles. The main challenge is that researchers cannot vary the climate states within a region and a large portion of the research has focused on overcoming this limitation (Hsiang, 2016). Due to this limitation, economists have relied on weather variation to draw incite about the potential economic consequences of climate change. The use of weather variation in studies regarding agriculture and climate change have identified direct effects of weather on productivity, but this research has also yielded varying predictions regarding adaptation (Schlenker et al., 2006; Burke and Emerick, 2016; Deschênes and Greenstone, 2012). With respect to agriculture, weather variation plausibly provides a region-specific forecast regarding future growing conditions. It is likely that this often-unobserved forecast affects adaptive responses made by agents. I circumvent this omitted variable issue, by using exogenous nature of radioactive fallout patterns to instrument for crop productivity and measure the short run planting responses made by farmers to adverse productivity shock. This identification strategy allows me to isolate the effect of a pure productivity shock that is divorced from informative signals potentially provided by weather variation.

In my identification strategy, I use variation in U.S. agricultural policy across crops and across time to test whether farmers treat productivity shocks from radioactive fallout differently from situations where the source of the productivity shock is observable. I use the fact that the government regulated farm specific wheat acreage based on the farmers past three years of planting and harvesting decisions. Other crops such as corn were not regulated based on farmers' previous decisions. Much of the climate change and agricultural literature attempts to control for agricultural policy through time fixed effects and robust time trends. These controls might inadequately control for the role policy plays in shaping farmers' decisions, especially if agriculture policy constraints bind at the same level of variation as the treatment variable of interest. Annan and Schlenker (2015) show that increased crop insurance coverage at the county level makes farmers more sensitive to temperature shocks. My results suggest that responses to fallout induced productivity shocks differed fundamentally from typical productivity shocks. Specifically, I find that damage from radioactive pollution caused policy constraints to bind at the same level of variation as the treatment variable of interest. If agricultural productivity shocks are positively correlated across years, then acreage should weakly decrease in the year following poor yields. I find the opposite response. Counties increase the amount winter wheat acreage in cultivation in the year following radiation induced productivity shocks. This response suggests farmers might have sought to hedge against tightening land allocation constraints and possible crop failure in the future by increasing cultivation.

Finally, this paper provides insight regarding the unintended consequences of government policy by measuring agricultural impact of radiative pollution from domestic nuclear tests. Government policy can have profound and long lasting unintended consequences. Studies by Troesken (2008) and Clay et al. (2014) find that the adoption of lead water pipes had substantial public health costs. The expansion of coal heating and policies promoting electrification using coal power also had substantial social costs. Barreca et al. (2014) found declines in coal consumption in home heating led to declines in winter mortality. Clay et al. (2016) find that the expansion of coal generation stations had mixed effects on mortality and property values during the mid 20th century. In the appendix, I present preliminary results suggesting that exposure to radioactive pollution altered the long run development of many agricultural counties. In particular, I find that more irradiated counties moved away from crop production and had depressed agricultural land values decades following testing.

The paper is divided into five additional sections. The first section provides some historical context behind nuclear testing at the Nevada Test Site from 1951 onwards. This discussion describes why radioactive fallout from atmospheric testing could affect agricultural productivity and the dispersal mechanisms of radioactive pollution that make agricultural exposure plausibly exogenous. In section two, I provide a simple model similar to the one presented in Hornbeck (2012). This model provides testable predictions regarding short term land allocation responses to productivity shocks. I describe how I use agricultural policy changes in the 1950's to test whether farmers treat fallout induced productivity shocks differently from typical productivity shocks. Section 3, presents the empirical strategy employed in this paper. I use within county variation in fallout exposure across years in both reduced form and instrumental variable regression strategies. Section 4 discusses the empirical results. These results reveal that fallout from nuclear testing led to substantial reductions agricultural yields, caused farmers to abandon cultivated acreage, and altered planting behaviors in the years following exposure. The final section concludes with a brief discussion regarding the potential long term consequences of atomic testing for U.S. agriculture and describes the implications for future research on climate change adaptation.

1 Historical and Scientific Background

1.1 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. Prior to 1951, most American nuclear tests occurred in the Pacific Ocean. These tests were logistically complicated, costly, and were slow to implement. 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).

The period of domestic nuclear testing lasted from 1945 until 1992, with the United States conducting 1,030 tests in total. A total of 828 underground blasts and 100 above ground detonations occurred at the NTS (US Department of Energy, 2000). Above ground nuclear testing occurred at the site from 1951 – 1963 and ended with the signing of the Partial Nuclear Test Ban Treaty. Figures 1 and 2 provide county specific radiation deposition maps created from the data used in this paper. The maps report cumulative deposition of I-131 per meter squared for both the 1953 Upshot Knothole and 1957 Plumbbob test series for the continental United States. There is much variation in exposure from 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. The overwhelming majority of the fallout landed in the eastern United States as wet precipitate, far away from the NTS (National Cancer Institute, 1997).

1.2 Fallout Delivery Mechanisms

When an atomic bomb is detonated it releases a tremendous amount of energy which can split the atoms of surrounding material. Atmospheric denotations conducted near the surface of the earth irradiate thousands of tons of material. This material is then drawn up into the mushroom cloud many kilometers up into the atmosphere. Figure 3 provides a diagram describing the 1953 Simon test shot. This figure describes how winds intercept radioactive material. A portion of the radioactive material is intercepted by low altitude winds and deposited in the surrounding area as dry precipitate. In the downwind region this radiation would be carried as radioactive dust blows. The vast majority of the material, however, is carried high up and intercepted by high altitude winds. This radioactive material would travel vast distances and would deposit hundreds to thousands of miles from the test site as wet precipitate. In the days following the test, areas outside of the Downwind region would receive radioactive fallout only if it happens to be raining while the radiation cloud was over head. Rain would scavenge radioactive dust from the cloud and deliver it to the ground. The agricultural regions studied in this paper would only experience fallout exposure as a consequence of wet precipitate. As such, radioactive deposition from atomic testing can be treated as a plausibly exogenous event.

1.3 Biological Effects of Radiation Poisoning

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 (Lee 1959; Kulp and Slatter 1958; Olson 1959 & 1962; and Rivera 1961). The Public Health Service (PHS) and Atomic Energy Commission (AEC) at the time corroborated these findings but downplayed the risks(Flemming, 1959, 1960; Wolff, 1957, 1959). The scientific literature from the period also suggests that fallout exposure may adversely affect agricultural production (Bustad et al., 1957; Garner, 1963; Sparrow et al., 1971).

After radiation dispersed across agricultural fields plants would absorb radioactive material and animals would consume contaminated grass. This radiation then could cause sickness in animals and be secreted in animal milk. Anecdotal and legal evidence suggests that nuclear weapons fallout did harm ranchers and farm animals living downwind of the NTS. 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). The PHS and AEC actively spread disinformation regarding the dangers of radioactive pollution resulting from atomic tests. A Freedom of Information Act request in 1978 brought the dangers and the cover up to national attention (Ball, 1986; LeBaron, 1998; Fradkin, 2004). 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 died during the spring and summer of 1953; with around 12.1% of lambing ewes and 25.4% of new lambs dying (or being born 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) studied 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 and patchy skin/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 generatde from tests by Garner (1963) suggests that radioactive toxicity is greater in sheep than cattle and that relatively low amounts of exposure reduces offspring viability, increases difficulty nursing, and stunts 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. Figure 4 provides a summary of radiation sensitivity for numerous crops from their survey. They found that large radiation doses can lead to diminished yields depending on the time crops are exposed.

According to Sparrow et al. (1971), winter wheat is particularly susceptible to harm. Winter wheat irradiation in field trials failed to survive winter hibernation. This evidence suggests that radioactive exposure to radioactive material may reduce 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 would land on fields when winter wheat is most vulnerable. This radiation may have stunted plants and led to crop failure. If farm fields experienced substantial fallout deposition during the period of above ground nuclear testing, then it is possible that crop yields could diminish substantially. This may have caused farmers to substitute cropland for other uses or let fields fallow.

2 Theoretic Model and Transitory Damages

2.1 Theoretical Model

To motivate and understand the channels through which radioactive pollution could have persistent effects on agricultural production, I provide a simple model similar to that of Hornbeck (2012). In this model the farmer has a single unit of land to allocate between two production technologies, $f(\theta)$ and $g(1-\theta)$. The variable θ denotes the division of this land allocation and takes values between zero and one. Each production technology has a differentiable and concave profit function denoted by π_f and π_g. I consider three possible scenarios in this model. The first is that productivity shocks from radioactive fallout are treated as persistent by farmers. The second is that the productivity shocks from radioactive fallout cause farmers to become liquidity constrained. The third scenario considered is a case where the productivity shock causes a policy constraint to bind. Table 1 summarizes the short run predictions this model has specifically for wheat and corn planting.

In the initial period, the representative farmer is an unconstrained maximizer. He or she maximizes profit such that the marginal profit from technology f equal the marginal profit from technology g.

$$\max_\theta \pi_f(\theta) + \pi_g(k - \theta) \tag{1}$$

$$\frac{d\pi f(\theta^*)}{d\theta} = \frac{d\pi_g(1 - \theta^*)}{d\theta} \tag{2}$$

At some point in the future the farmer receives a productivity shock from radioactive fallout precipitating down on her fields or pasture. Let η denote this shock and have this shock specifically affect the realized productivity of f. If the damage has no persistent effect and is transitory in nature then the equilibrium denoted in Equation 2 holds.

2.2 Mechanism 1: Persistent Damages

If the radioactive fallout has a persistent effect upon agricultural productivity or the farmer believes that the productivity shocks persists then the results from Hornbeck (2012) hold. Let there be a damage variable denoted by δ_η and let this factor affect only the productivity of technology f. This alters the profit function of f to become $\delta_\eta * \pi_f(\theta)$ and Equation 4 describes the new equilibrium conditions in future periods.

$$\max_\theta \delta_\eta * \pi_f(\theta) + \pi_g(k - \theta) \tag{3}$$

$$\delta_\eta * \frac{d\pi f(\theta^*)}{d\theta} = \frac{d\pi_g(1 - \theta^*)}{d\theta} \tag{4}$$

Under this scenario farmers will reallocate resources from f to g as the effect of the productivity shock is treated as persistent.

2.3 Mechanism 2: Liquidity Constraint

If the productivity shock is large enough, the productivity shock might reduce the amount of resources the farmer could allocate to one technology. For simplicity sake suppose that technology f is more profitable than technology g but is also more costly to produce. Assume that g is costless to implement (e.g. leaving the land idle or fallow). The farmer now faces a new constraint $\theta \leq L(\eta)$. If this constraint binds, then the farmer is forced to reallocate resources from f to g.

2.4 Mechanism 3: Policy Constraint

$$\max_\theta f(\theta) + g(k - \theta) + \beta * V(\kappa(\eta, \theta))$$

Another way a transient productivity shock may alter land allocation and investment decisions is through agricultural policy. In the 1950's wheat farmers faced a unique policy restriction. The amount of acreage a farmer could plant and bushels of wheat he or she could sell was a function of past planting and harvesting behaviors. If fallout led farmers to abandon cultivated acreage, farmers who abandoned acreage might face tighter acreage allotments in the future. One way farmers could hedge against this acreage reduction would be to plant more acreage before the policy constraint is enacted. Let $\beta * V(\kappa(\eta, \theta))$ denote the present discounted stream of future profits the farmer will received. Policy restricts the amount of acreage planted in the future with $\kappa(\eta, \theta)$ denoting the restriction on allocation in the future.

$$\frac{\delta f(\theta^*)}{\delta\theta} - \frac{\delta g(k-\theta^*)}{\delta\theta} = \beta * \frac{\delta V(\theta_B(\eta,\theta))}{\delta\kappa(\eta,\theta)} * \frac{\delta\kappa(\eta,\theta)}{\delta\theta}$$

The first order conditions of this value function state that for any optimal allocation the value of any change made in current period has to equal the effect of this decision in future periods. If the farmer experiences a negative draw of η this decreases the partial derivative on the right hand side of the equality such that the previous allocation is no longer optimal. If the farmer decides to allocate more resources to wheat in the current period, this decision increases the value on the right hand side and decreases the value on the left hand side of the equality. The farmer chooses to over allocate resources towards winter wheat production because it offsets the negative effect η has on his or her future stream of profits.

2.5 U.S. Agricultural Policy During the Atmospheric Testing Period

Substantial government intervention into the agricultural sector began with the Agricultural Adjustments Act (AAA) in 1933. This policy was succeeded by the Agricultural Adjustment Acts of 1938, 1948, and 1949. These laws set fixed price supports for crops, land allotments restrictions, and marketing quotas (Rasmussen et al., 1976). Acreage allotments were restrictions on acreage planted and were set according a farm's historical base acreage. Marketing quotas were restrictions on the quantity of crops permitted for sale or on farm use during a specific growing year. Farmers would be eligible for price supports and government aid if they complied with government market quotas and land allotment restrictions. If a farmer failed to abide by market quotas they might receive a per bushel fine on marketed crops. Acreage allotments and farm specific marketing quotas were calculated from a value called base acreage and would be strictly increasing in base acreage (Cochrane and Ryan, 1976). Basic crops of corn, cotton, peanuts, rice, tobacco, and wheat received mandatory price supports.

The historic base acreage of wheat farms was set as a function of the past three year's wheat plantings. The particular language of the 1948 Farm Bill states acreage "planted for harvest" determines base acreage. Farms that did not possess allotments could to request new allotments. The total value of requests could not exceed 3% of the total county allotment. In 1955 this formula switched to using harvested acres rather than planted acreage (Cochrane and Ryan, 1976). Farmers who failed to abide by market quotas or allocation restrictions the years they were in effect would lose access to price supports and face possible fines.

These restrictions create a "use it or lose it" scenario for many wheat farmers. If a farmer reduced planting (or harvesting) of wheat in a single year, it could negatively affect their future base acreage and thus future stream of income. The switch to using harvested acreage to calculate base acreage also introduces an incentive to over plant winter wheat because the farmer can strategically adjust harvesting to comply with allotment mandate and hedge against crop failure (Cochrane and Ryan, 1976). However, if radioactive fallout induced crop failure and led farmers to abandon cultivated acreage, this policy shift magnifies the cost of damage as the radiation shock could affect their base acreage in the future. In years where allotments were not enforced farmers could increase their total wheat acreage and in years where allotments were enforced they would be hesitant to cut wheat acreage because it could result in decreased wheat acreage in the future. From 1940 to 1949 and 1951 to 1953 there were no restrictions on wheat planting. From 1954 to 1972 acreage allotment restrictions for wheat were in effect and became generally more restrictive. Marketing quotas were in effect from 1954 to 1964 (Burt and Worthington, 1988). In practice, it is plausible that farmers would increase wheat acreage in response to radioactive fallout deposition as a hedge against future restrictions on acreage allotments.

An additional policy, the Soil Bank Act, also appears during the testing period and reduces the cost of this hedging. In 1956, the Soil Bank Act was signed into law. This law allowed farmers to place allotted acreages into conservation for payment. The Soil Bank accepted land for short and long term conservation. It accepted land in 1956, 1957, and 1958. This decision would not decrease base acreage for farmers opting into the program. Winter wheat had the unique advantage over other crops in that farmers could observe the productivity of the crop prior to making the allotment decision. This policy would subsidize hedging by farmers as farmers could plant wheat over their allotment and strategically place under performing acreage into the soil conservation program.

3 Empirical Methodology and Data

3.1 Annual County Panel Regression Model

Equation 5 represents the full specification of the regressions employed in measuring how fallout from nuclear tests altered agricultural productivity.

$$
\begin{aligned}
&ln(Y_{it}) = \alpha_i + \beta_0 * X_{it} + \beta_1 * \bar{X_{it-1}} + \beta_2 * \bar{X_{it-2,t-5}} + \beta_3 * X_{it-6,t-10} + \\
&\gamma_t + \lambda_{it} * \phi + T_{st} + \epsilon_{it}
\end{aligned} \tag{5}
$$

Y_{it} denotes the outcome of interest such as the bushels produced per acre planted or harvested in county i at time t for each acre planted. I use yield per acre planted because farmers might opt to only harvest productive acreage in the event of sporadic crop damage. This could lead to yield per acre harvested understating the true magnitude of the productivity shock. This would lead to greater amounts of abandoned acreage and would be reflected in yield per acre planted.[2]

The main variable of interest is X_{it}. This variable measures the total I-131 deposition in County i in Year t, as thousands of nCi per square meter. I exploit variation within counties across time to identify the effects of radiation deposition upon yields. The exposure measure proxies for total fallout deposition resulting from each nuclear test series. I include deposition in the current year and previous year. $\bar{X_{it-1}}$ and $\bar{X_{it-2,t-5}}$ denote average deposition between two to five years ago, and average deposition between six to ten years ago. I pooled averaged exposure to measure the possible medium to long term effects of fallout exposure. λit denotes a vector of crop specific monthly precipitation levels and monthly temperature averages for county i in years t. T_{st} denotes state specific time trends and controls for any underlying trends in productivity or technology within states. Year fixed effects and county fixed effects are represented by γ_t and α_i respectively. ϵ_{it} denotes the heteroskedastic error term which is not observed by the researcher. Errors are clustered at the county level. I also 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 centroid.

[2]The empirical results are robust to specification with county characteristics in 1940 interacted with year indicators. The inclusion of such controls introduces significant collinearity and complicates the calculation of Conley standard errors. As such, these robust control are not reported.

3.2 2SLS Regression Model

In order to isolate how farmers respond to exogenous variation in productivity, I perform 2SLS and instrument for crop yields using weather variables and radiation deposition. Both weather conditions and radioactive fallout affect crop productivity. Variation in productivity due to weather affects both farm income and provides the farmer information about future growing conditions. Furthermore, farm policy took into account weather conditions when determining acreage allotments (Cochrane and Ryan, 1976). Therefore responses to weather induced variation should differe from those caused by fallout.

$$ln(YPA_{it-1}) = \theta_0 * Z_{it-1} + \lambda_{it-1}\phi + \alpha_i + \gamma_t + \epsilon_{it-1} \tag{6}$$

Equation (6) denotes the first stage of the regression the exogenous instrument Z_{it-1} represents radiation deposition. County and year fixed effects are denoted by α_i and γ_t. Monthly precipitation and temperature controls for the previous growing season are denoted by λ_{it-1}.

$$ln(Acres_{it}) = \delta_0 * ln(YPA_{it-1}) + \lambda_{it-1}\beta + \alpha_i + \gamma_t + \mu_{it} \tag{7}$$

The second stage reports the effect of yields in the previous year upon acres of winter wheat planted. A positive coefficient on δ would imply that productivity in one period is positively related to planting in the subsequent period. A positive coefficient would suggest that productivity shocks in one period have persistent effects into the next period. A negative coefficient on δ would imply that an negative productivity shock in the previous period causes farmers to increase planting in the subsequent period. Such a response would be driven by hedging behavior and would be consistent with a scenario where land allocation constraints might become more restrictive in response to adverse productivity events.

3.3 Data and Identification Strategy

I use a balanced panel of counties that are observed for every year from 1945 to 1970.[3] Annual agricultural data on corn, winter wheat, and sheep populations is provided through the National Agricultural Service's Quick Stats program (National Agricultural Statistics Service, 2015). The variables examined and the samples used are summarized in Table 2. Monthly temperature average and precipitation measures are provided by National Oceanic

[3] For sheep the panel is balance based on whether there is an observed quantity of animals reported. For corn and wheat I balance the panel according to whether or not the counties reported acreage planted.

and Atmospheric Administration (2015). Geographic information regarding county centroids comes from the Census Bureau and is used in the application of spatially correlated standard errors following Hsiang (2010).

Annual county level fallout deposition measures are created from data provided by 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 came from the I-131 deposition measures contained in the report.

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. 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 whose number varies across time, but never exceeded 100 stations. Figure 5 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. There are a few potential challenges to this identification strategy. There is the possibility that the radiation measures could be correlated with local weather patterns. Most of the fallout deposition resulting from the tests came down as wet precipitate. This means that radiation would 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 for 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 be depositing in the country. This global fallout would be much smaller in magnitude and 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.

While the location of the site was not random, as 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 would not have knowledge of where a fallout cloud might be traveling or the exact date of nuclear tests. While test planners did avoid meteorological conditions that could result in fallout in the immediate area around the base, they would have been 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 under developed 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 been harmful to the environment as they could visibly link tests with radioactive dust blows. Fortunately, these counties are excluded from my data sample because they are neither corn or wheat producing areas. The public at large became aware of how dangerous atmospheric tests at the NTS were in the late 1970's after 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 would anticipate the dangers of fallout from tests, the position of fallout clouds, or possess knowledge of how fallout precipitates down under various meteorological conditions. Farmers and ranchers whose animals resided in fields also would have been 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 that was contemporaneously being developed by researchers. Even if the exposure variable is correlated with rainfall, monthly precipitation and temperature controls should account for this correlative effect. Simple correlations suggest that cumulative yearly rainfall is relatively uncorrelated with cumulative fallout deposition. Therefore, fallout deposition should be orthogonal the unobserved error term.

3.4 Short Run Effects of Nuclear Testing on Crops

The empirical results from analysis of the annual data suggests that radioactive fallout had a substantial negative effect on crop yields for both winter wheat and corn. Tables 3 and 4 report the effects of radiation exposure on yields. Specifications 1 to 3 report log yield per acre planted and specifications 4 to 6 report log yield per acre harvested. Three different specifications are reported, only fixed effects, fixed effects and weather controls, and finally fixed effects with time trends and weather controls. Tables 5 and 6 report the effects of fallout exposure on harvested acreage and planting in subsequent years. Specifications 1 to 3 relate to wheat and specifications 4 to 6 relate to corn. The discussion of the empirical results interpret coefficients from specifications 3 and 6.

Radioactive fallout deposition in the current year has the greatest effect on wheat yields and is robust to the inclusion of Conley standard errors. I find that a one standard deviation in fallout exposure leads to approximately a 3.9% and 1.9% reduction in winter wheat yield per acre planted and per acre harvested respectively. There is some evidence that yield per acre planted decreased in the year following fallout deposition, and that yields increased on two to five years out from testing but the statistical significance of these results attenuate with the inclusion of Conley standard errors. Yield per acre harvested two to five years out increases substantially and this might be attributed to changes in farmer behavior following the productivity shock. Further out, I find that a one standard deviation increase in average exposure two to five years prior increases yield per acre harvested by 1.5% and a one standard deviation increase in exposure six to ten year prior decreases yield per acre harvested by a little less than 1%.

Corn yields show a greater sensitivity to radioactive fallout. Yield per acre planted decreases substantially in the year of fallout deposition but conversely there appears to be a positive effect on yield per acre harvested. The statistical significance of this positive effect disappears with the inclusion of Conley standard errors while the negative effects of yield per acre planted persists. A one standard deviation increase in fallout deposition in the current year decreases yield per acre planted by 2.69%. This same deposition causes a 6.32% reduction in yield per acre planted in the subsequent year and a 1.2% decrease in yield per acre harvested in the subsequent year. A one standard deviation increase in average fallout exposure two to five years prior reduces corn yields by 7.89% and 2.15% for yield per acre planted and harvested respectively.

There is some discrepancy between yield per acre planted and yield per acre harvested. To further substantiate that radioactive fallout had adverse productivity effects I test whether fallout affects how much planted acreage was harvested. I find the radiation deposition causes farmers to harvest fewer acres of planted wheat and corn. A one standard deviation increase in radiation exposure decreases harvested acreage of winter wheat by approximately 2% in the current year and corn by 3.86%. For corn, radiation exposure causes a persistent reduction planted acres harvested for corn. A one standard deviation increase in the exposure measure causes a 5.3% reduction in acres harvested for corn in the year following deposition. A one standard deviation increase in average exposure causes acres harvested to decrease by 6.63% two to five years following deposition. These effects remain statistically significant after the implementation of Conley standard errors. Together these results suggest that radiation deposition from nuclear tests had a productivity effect on crops and caused farmers to adjust their harvesting behaviors in response to damage.

I find that farmers adjust their planting behavior in the years following fallout exposure. The planting responses with winter wheat suggest that farmers increase the amount of acreage under cultivation in the years following exposure. A one standard deviation increase in deposition increases acres planted by 2.7% in the next year and one standard deviation in fallout exposure two to five years ago increase acreage by 3.6%. These increases are likely driven by the potential of future policy restrictions that wheat farmers faced after abandoning wheat acreage due to fallout exposure after 1955. Farmers could hedge against this risk by over planting acreage and from 1956 to 1958 farmers could strategically divert less productive acreage into soil conservation. To test whether or not these results are driven by policy, I interacted exposure with a post 1955 indicator variable. Table 7 suggests that radiation exposure prior to the policy change does not affect acres planted. After agricultural policy shifted from regulating acres planted to acres harvested, wheat farmers respond to radiation induced productivity shocks. Their responses are consistent with the theoretic prediction that agricultural policy rather than persisted damage or liquidity constraints drove their adjustments.

Corn, unlike winter wheat, was not regulated on the amount of acreage planted or harvested by farmers in previous years. Farmers appear to adjust their planting behavior in response to persistent damages in the years following fallout exposure. I find that a one standard deviation increase in fallout exposure two to five years prior reduces corn acres by approximately 1% and a one standard deviation increase in exposure six to ten years prior reduces acres planted by 2.29%. These small changes in acreage might be driven by either by liquidity constraints or by farmers treating irradiated cropland as less productive.

3.5 2SLS Results: Instrumenting for Productivity's Effect on Planting Decisions

Agricultural productivity measured through yields is both the result of farmers' investment decisions and external factors. These variables likely affect farmers' land allocation decisions. Therefore, it is plausible that the effect of realized yields in one period on planting decisions in the subsequent period is subject to endogeniety bias. To circumvent this endogeniety problem, I perform two stage least squares and instrument for crop productivity using radioactive fallout. Table 8 reports the effects of yields upon planting decisions in the subsequent year. Specifications 1 and 4 report the reduced form panel regressions results for wheat and corn. The coefficients are positive and statistically significant for both wheat and corn. A 10% decrease in yield per acre planted in the previous year 1.3% reduction in wheat acreage and 0.5% reduction in corn acreage in the subsequent year. These results are consistent with the theoretical prediction that agricultural productivity shocks are correlated across years. Both effects are statistically significant at the 1% level.

Specifications 2, 3, 5, and 6 report the 2SLS results. Variation in winter wheat yields from radioactive fallout deposition has the opposite effect on wheat acreage in the subsequent year. This result suggests that if wheat yields decrease, acreage increases in the subsequent year. The effect of fallout induced yield reductions for corn is null. A 10% reduction in wheat yields the previous year increases wheat acreage by 4.7% the subsequent year and is statistically significant at the 1% level. After controlling for weather conditions, the magnitude of the effect increases to 6% but the statistical significants decreases slightly. This evidence suggests that wheat farmers respond differently to a pure output shock when it is separated from an informative signal. This response in planted acreage happens for winter wheat due to policy constraints that regulate base acreage. If a farmer abandons damaged acreage in one year and it is not due to weather, his or her future stream of income might suffer and thus counteracting this negative shock becomes more salient. Corn planting is unaffected in the subsequent year because fallout induced productivity shocks in one period are not treated as persistent when farmers make their planting decisions.

4 Conclusion

Nuclear testing substantially reduced corn and wheat yields during the 1950's. Radioactive pollution resulting from NTS activities deposited on agricultural fields and farmers abandoned cultivated acreage in a response to the damage. The gap between acres planted and acres harvested for grain increased in areas that experienced greater amounts of fallout exposure. Following this fallout induced damage, wheat farmers increased the amount of wheat acreage under cultivation. This hedging behavior was done in response to U.S. agricultural policy in the 1950's which penalized farmers for abandoning planted wheat acreage. Corn, which was not subject to these regulation, weakly decreased in response to persistent yield reductions induced by radioactive pollution.

The instrumental variables approach in this paper isolates the effects of pure productivity shocks on short run planting decisions made by farmers. Variation in output from weather events plausibly provide farmers observable signals about potential growing conditions in the future. Radioactive pollution's invisible and imperceptible nature provides no clear or informative forecast regarding future growing conditions. The climate change and agriculture literature has relied upon finely detailed weather variation to draw insight about the potential consequences of climate change. However, weather variation has a direct effect on agricultural productivity and provides an often unobserved forecast regarding future growing conditions in the near term. This paper finds that the direct effect of a pure productivity shock can differ substantially in magnitude and direction relative to a productivity shock where the source of the variation in known to the agent. This result suggests that observed responses to weather variation might be subject to omitted variable bias and the treatment effect might be different than the explanations posited by researchers. Furthermore, I find that variation in productivity at the county year level causes agricultural policy constraints to bind at the same level of variation as the treatment variable. Weather likely interacts with policy constraints and causes these constraints to loosen and tighten alongside the weather variables of interest. Together these results raise questions about what weather variation identifies and the interpretations drawn regarding climate adaptation.

Nuclear testing during the Cold War provides a unique historical circumstance where policy results in exogenous variation in agricultural productivity. It is likely that other sectors of the economy were directly affected by pollution resulting from NTS activities and the data presented in this paper can provide plausibly exogenous variation for other studies.

It is also important for researchers interested in adaptive responses to adverse events, such as weather shocks, to provide a deeper context surrounding the policies that might shape adaptive responses. The use of time fixed effects and regional time trends might not fully account for the effects these policies. If adaptive behavior to weather shocks are shaped by policy constraints, then interpretations drawn from the climate econometrics literature might understate the importance of policy in guiding future climate adaptation.

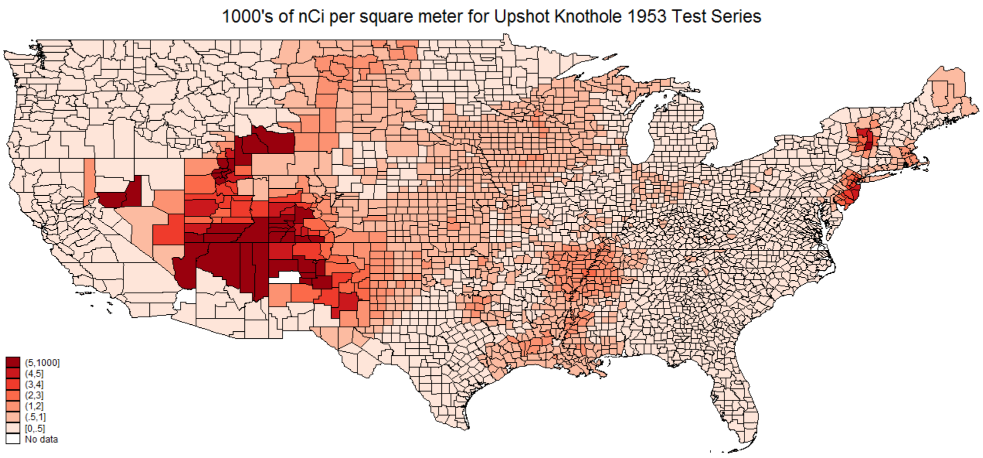

Figure 1: Thousands of nanoCuries of I-131

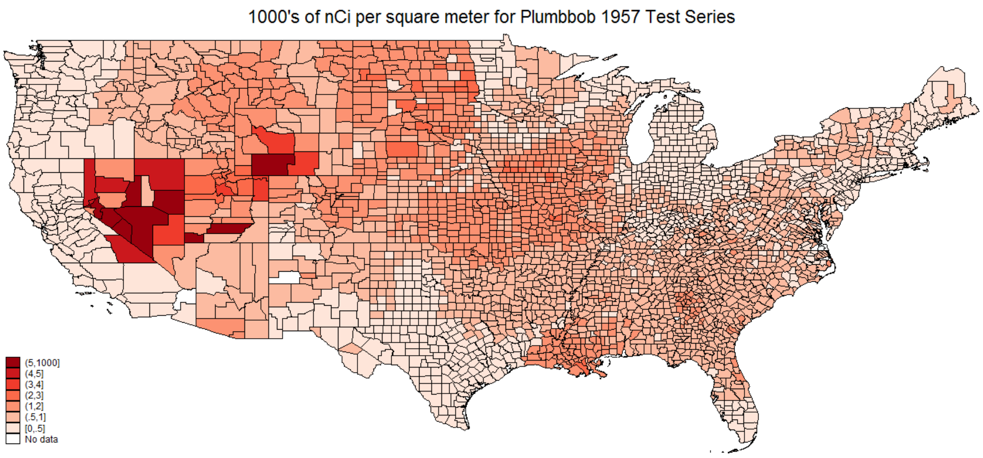

Figure 2: Thousands of nanoCuries of I-131

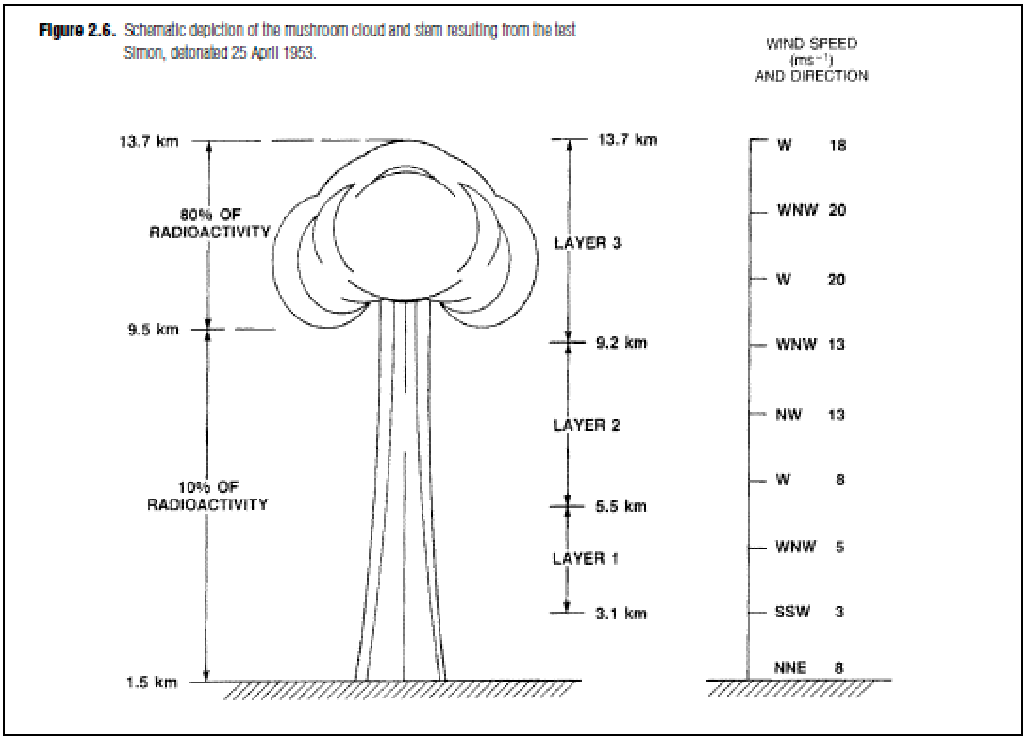

Figure 3: Mushroom Cloud and Wind Patterns. Source: NCI 1997

EFFECTS OF EXTERNAL GAMMA RADIATION FROM RADIOACTIVE FALLOUT 9

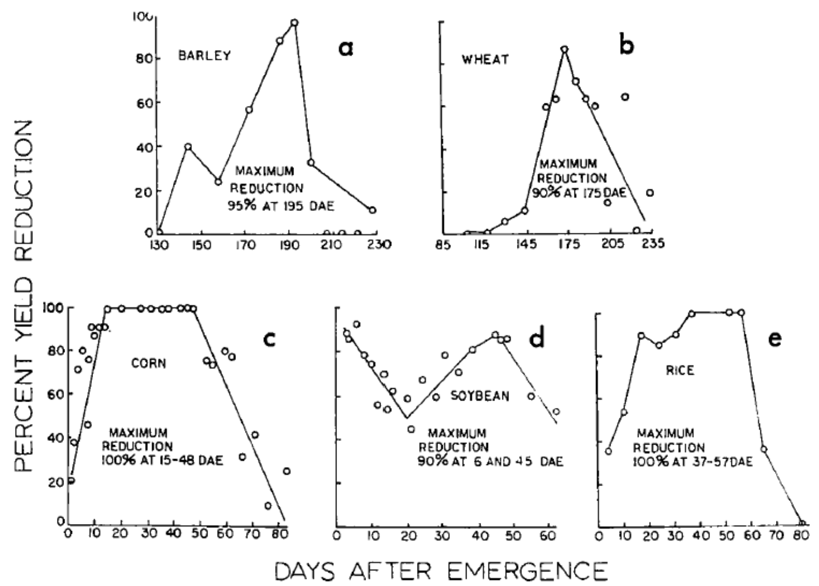

Fig. 4. Seed yield reduction of five crops after exposure to ^{60}Co gamma radiation at different days after seedling emergence. (a) 'Dayton' barley after exposure to 1 kR at 20 R/min (plants irradiated previous to 130 days after emergence did not survive winter conditions); (b) 'Seneca' wheat after exposure to 1·6 kR at 20 R/min (plants irradiated previous to 85 days after seedling emergence did not survive winter conditions); (c) WF-9X38-11 maize after exposure to 2·5 kR at 50 R/min; (d) 'Hill' soybeans after exposure to 2·5 kR at 50 R/min(87); (e) rice (CI 8970-S) after exposure to 25 kR at 50 R/min (redrawn from Siemer *et al.*(65)).

Figure 4: Gamma Radiation Exposure and Crop Yields. Sparrow, Schwemmer, and Bottino (1971)

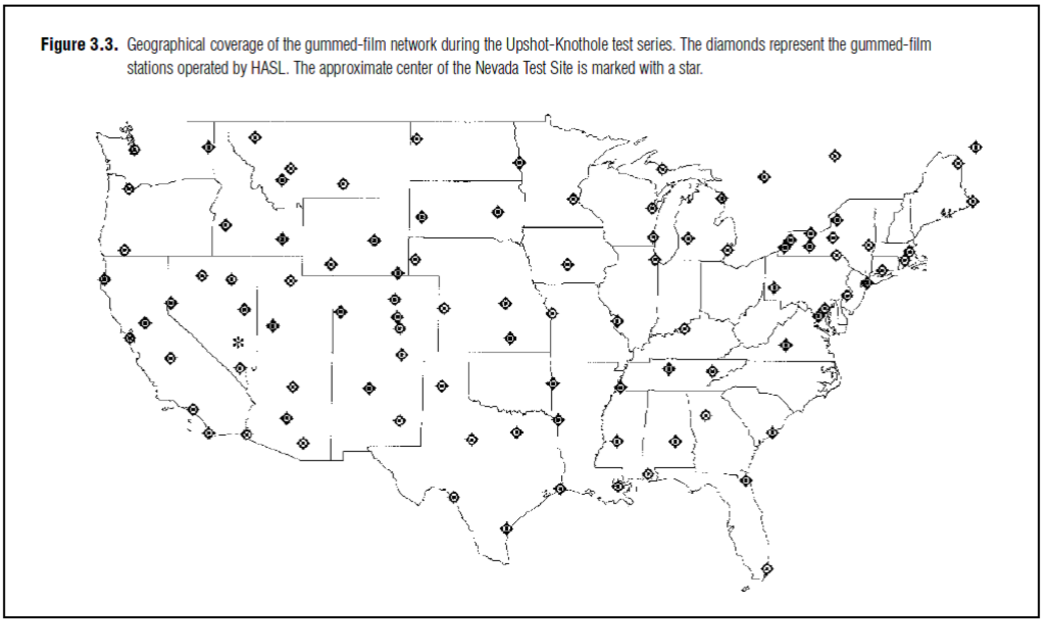

Figure 5: Map of National Radiation Monitoring Stations 1953. NCI (1997)

Table 1: Model Predictions on Short Run Land Allocation

Dominant Channel	Predicted Change in Land Allocation	
	Winter Wheat	**Corn**
Persistent Productivity Reduction	Reduction	Reduction
Liquidity Constraint	Reduction	Reduction
Policy Constraint	Increase	No Change

Table 2: Summary Statistics: Annual Production Data 1945-1970

	Winter Wheat Sample Summary Statistics: CA, CO, DE, ID, KS, MD, MT, OK, OR, SD					**Corn Sample Summary Statistics: DE, IA, MD, MT, ND, NE, SD**				
Variable	Observation	Mean	Std. Dev.	Min	Max	Observation	Mean	Std. Dev.	Min	Max
Exposure, 1000's nCi m^2	11,463	0.112152	0.37814	0	6.579	9120	0.107293	0.313857	0	3.093
Avg. Exp. t-2 to t-5	11,463	0.112152	0.219189	0	2.9395	9120	0.104893	0.166127	0	0.992
Avg. Exp. t-6 to t-10	11,463	0.080108	0.144718	0	1.679714	9120	0.072754	0.109138	0	0.568
Yield Per Acre Planed	11,463	20.46773	10.32357	0.161688	86	9120	38.00004	24.87167	0.0125	120.325
Yield Per Acre Harvested	11,463	22.86997	10.10654	3.23375	86.98876	9120	43.87103	24.25899	3.010204	124.9296

	Number of Sheep in Inventory Jan 1st: NE, SD					**Number fo Sheep Withheld for Breeding Jan 1st, IL, MN, MT, ND**				
Exposure, 1000's nCi m^2	4,056	0.105975	0.306759	0	3.093	7,488	0.087955	0.275463	0	3.136
Avg. Exp. t-2 to t-5	4,056	0.105975	0.166534	0	0.992	7,488	0.087955	0.143646	0	0.81125
Avg. Exp. t-6 to t-10	4,056	0.075696	0.109462	0	0.568	7,488	0.062825	0.094261	0	0.541143
Number of Animals	4,056	13487.52	26885.12	20	322820	7,488	11150.95	17265.76	100	195400

Table 3: Winter Wheat Yields: 1945-1970

	Log Yield Per Acre Planted			Log Yield Per Acre Harvested		
	(1)	(2)	(3)	(4)	(5)	(6)
Exposure	-0.140***	-0.103***	-0.109***	-0.0731***	-0.0497***	-0.0533***
	(0.0231)	(0.0222)	(0.0214)	(0.0116)	(0.0108)	(0.0102)
	{0.0280}	{0.0271}	{0.0265}	{0.0137}	{0.0128}	{0.0124}
Exposure t-1	-0.0122	-0.0246*	-0.0294**	-0.00466	-0.014	-0.0159*
	(0.0148)	(0.0146)	(0.0138)	(0.0102)	(0.00972)	(0.00923)
	{0.0194}	{0.0186}	{0.0179}	{0.0141}	{0.0130}	{0.0126}
Avg. Exp. t-2 to t-5	0.0571*	0.0472	0.0708**	0.0652***	0.0563**	0.0683***
	(0.0315)	(0.0297)	(0.0322)	(0.0236)	(0.0218)	(0.0235)
	{0.0386}	{0.0375}	{0.0376}	{0.0254}	{0.0236}	{0.0237}
Avg. Exp. t-6 to t-10	-0.247***	-0.170***	-0.046	-0.228***	-0.152***	-0.0732**
	(0.0491)	(0.0467)	(0.0429)	(0.0382)	(0.0382)	(0.0341)
	{0.0472}	{0.0461}	{0.0459}	{0.0349}	{0.0345}	{0.0335}
Year FE	Yes	Yes	Yes	Yes	Yes	Yes
County FE	Yes	Yes	Yes	Yes	Yes	Yes
State Time Trends	No	No	Yes	No	No	Yes
Weather Controls	No	Yes	Yes	No	Yes	Yes
N	11463	11463	11463	11463	11463	11463
$Adjusted r^2$	0.524	0.574	0.584	0.619	0.668	0.679

Standard Errors in parentheses are clustered by County. Conley SE in brackets, 100 km cut off. States in sample include CA, CO, DE, ID, KS, MD, MT, OK, OR, and SD.
* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Table 4: Corn Yields: 1945-1970

	Log Yield Per Acre Planted			Log Yield PerAcre Harvested		
	(1)	(2)	(3)	(4)	(5)	(6)
Exposure	-0.221***	-0.172***	-0.0895***	0.0519***	0.0286*	0.0440***
	(0.0454)	(0.0452)	(0.0325)	(0.0178)	(0.0156)	(0.0155)
	{0.0614}	{0.0597}	{0.0463}	{0.0297}	{0.0244}	{0.0236}
Exposure t-1	-0.436***	-0.355***	-0.225***	-0.0921***	-0.0588***	-0.0391***
	(0.0587)	(0.0553)	(0.0404)	(0.0159)	(0.0133)	(0.0129)
	{0.0676}	{0.0628}	{0.0493}	{0.0214}	{0.0174}	{0.0166}
Avg. Exp. t-2 to t-5	-1.398***	-0.900***	-0.645***	-0.315***	-0.193***	-0.139***
	(0.236)	(0.196)	(0.147)	(0.0557)	(0.0500)	(0.0436)
	{0.166}	{0.151}	{0.121}	{0.0626}	{0.0554}	{0.0531}
Avg. Exp. t-6 to t-10	0.154	-0.179	0.418*	0.117	-0.072	0.0566
	(0.394)	(0.348)	(0.224)	(0.0862)	(0.0833)	(0.0661)
	{0.272}	{0.251}	{0.187}	{0.0906}	{0.0886}	{0.0797}
Year FE	Yes	Yes	Yes	Yes	Yes	Yes
County FE	Yes	Yes	Yes	Yes	Yes	Yes
State Time Trends	No	No	Yes	No	No	Yes
Weather Controls	No	Yes	Yes	No	Yes	Yes
N	9120	9120	9120	9120	9120	9120
$Adjusted r^2$	0.611	0.656	0.797	0.811	0.833	0.856

Standard Errors in parentheses are clustered by County. Conley SE in brackets, 100 km cut off. States in sample include DE, IA, MD, MT, ND, NE, and SD.
* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Table 5: Log Acres Harvested Conditioned on Log Acres Planted: 1945-1970

	Log Acres Harvested Winter Wheat			Log Acres Harvested Corn		
	(1)	(2)	(3)	(4)	(5)	(6)
Exposure	-0.0667***	-0.0531***	-0.0548***	-0.280***	-0.209***	-0.131***
	(0.0135)	(0.0136)	(0.0135)	(0.0402)	(0.0386)	(0.0264)
	{0.0167}	{0.0169}	{0.0168}	{0.0517}	{0.0497}	{0.0361}
Exposure t-1	-0.00683	-0.0103	-0.0126*	-0.346***	-0.298***	-0.185***
	(0.00743)	(0.00726)	(0.0072)	(0.0529)	(0.0513)	(0.0367)
	{0.00865}	{0.00870}	{0.00860}	{0.0613}	{0.0595}	{0.0457}
Avg. Exp. t-2 to t-5	-0.00596	-0.00804	0.00467	-1.050***	-0.690***	-0.510***
	(0.0155)	(0.0158)	(0.0163)	(0.21)	(0.181)	(0.136)
	{0.0193}	{0.0204}	{0.0204}	{0.136}	{0.130}	{0.101}
Avg. Exp. t-6 to t-10	-0.0156	-0.0165	0.0287	0.082	-0.0727	0.353*
	(0.0218)	(0.0209)	(0.0206)	(0.357)	(0.321)	(0.212)
	{0.0212}	{0.0213}	{0.0218}	{0.239}	{0.221}	{0.165}
Year FE	Yes	Yes	Yes	Yes	Yes	Yes
County FE	Yes	Yes	Yes	Yes	Yes	Yes
State Time Trends	No	No	Yes	No	No	Yes
Weather Controls	No	Yes	Yes	No	Yes	Yes
N	11463	11463	11463	9120	9120	9120
$Adjusted r^2$	0.988	0.989	0.989	0.888	0.897	0.943

Standard Errors in parentheses are clustered by County. Conley SE in brackets, 100 km cut off. States in wheat sample include CA, CO, DE, ID, KS, MD, MT, OK, OR, and SD. States in corn sample include DE, IA, MD, MT, ND, NE, and SD.
* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Table 6: Log Acres Planted: 1945-1970

	Log Acres Planted Winter Wheat			Log Acres Planted Corn		
	(1)	(2)	(3)	(4)	(5)	(6)
Exposure t-1	0.0754***	0.0621***	0.0740***	0.00143	0.00263	0.0177
	(0.0176)	(0.0182)	(0.0183)	(0.0189)	(0.0178)	(0.0184)
	{0.0177}	{0.0184}	{0.0190}	{0.0242}	{0.0227}	{0.0224}
Avg. Exp. t-2 to t-5	0.218***	0.227***	0.184***	-0.174***	-0.110*	-0.086
	(0.0567)	(0.0600)	(0.0554)	(0.0645)	(0.0633)	(0.0618)
	{0.0371}	{0.0392}	{0.0367}	{0.0467}	{0.0467}	{0.0434}
Avg. Exp. t-6 to t-10	0.307**	0.333**	0.109	-0.288**	-0.267**	-0.237*
	(0.133)	(0.132)	(0.107)	(0.135)	(0.133)	(0.123)
	{0.0689}	{0.0729}	{0.0652}	{0.0963}	{0.0966}	{0.0847}
Year FE	Yes	Yes	Yes	Yes	Yes	Yes
County FE	Yes	Yes	Yes	Yes	Yes	Yes
State Time Trends	No	No	Yes	No	No	Yes
Weather Controls	No	Yes	Yes	No	Yes	Yes
N	11466	11466	11466	9412	9412	9412
$Adjusted r^2$	0.933	0.935	0.943	0.953	0.954	0.96

Standard Errors in parentheses are clustered by County. Conley SE in brackets, 100 km cut off. States in sample include CA, CO, DE, ID, KS, MD, MT, OK, OR, and SD. States in corn sample include DE, IA, MD, MT, ND, NE, and SD.

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

Table 7: Log Acres Planted Winter Wheat: Testing Weather Behavior is Driven by AG Policy Change

	(1)	(2)	(3)	(4)	(5)	(6)
Exposure, t-1	0.00478	0.00166	0.0322	0.00478	0.00166	0.0322
	(0.0203)	(0.0197)	(0.0197)	(0.0234)	(0.0220)	(0.0229)
post55*Exposure, t-1	0.136***	0.119***	0.0932***	0.136***	0.119***	0.0932***
	(0.0274)	(0.0294)	(0.0292)	(0.0320)	(0.0339)	(0.0336)
Year FE	Yes	Yes	Yes	Yes	Yes	Yes
County FE	Yes	Yes	Yes	Yes	Yes	Yes
State Time Trends	Yes	Yes	Yes	Yes	Yes	Yes
Weather Controls	Yes	Yes	Yes	Yes	Yes	Yes
Conley SE	No	No	No	Yes	Yes	Yes
N	11466	11466	11466	11466	11466	11466
$Adjusted r^2$	0.933	0.934	0.943	.	.	.

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

Table 8: 2SLS Regressions: Short Term Planting Responses to Fallout Induced Productivity Shocks

	(1)	(2)	(3)	(4)	(5)	(6)
	Log Wheat Acres Planted			Log Corn Acres Planted		
log Wheat Yield, t-1	0.120***	-0.440***	-0.554**			
	(0.0176)	(0.154)	(0.237)			
log Corn Yield, t-1				0.0447***	-0.133	-0.151
				(0.0119)	(0.136)	(0.178)
Year FE	Yes	Yes	Yes	Yes	Yes	Yes
County FE	Yes	Yes	Yes	Yes	Yes	Yes
Weather Controls	No	No	Yes	No	No	No
N	11462	11462	11462	8788	8788	8788
$Adjusted r^2$	0.935	0.922	0.918	0.955	0.946	0.946

All Standard Errors are Clustered by County.

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

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A Appendix

A.0.1 Effect of Fallout Exposure on Sheep

The productivity effect of radioactive fallout is not limited to crops. Table 9 reports the effect of fallout upon animal populations. I find that radiation deposition causes substantial reductions in reported sheep inventories in SD and NE. The implementation of Conley standard errors increases the statistical significance of these results. Radiation also causes farmers to withhold greater numbers of sheep from market in the year following fallout deposition. This results suggests that farmers' flocks suffered from the adverse effects of radiation poisoning. Farmers sought to mitigate some of the damage by withholding greater numbers of animals from market.

Table 9: Sheep Population: 1945-1970

	Log Number Sheep			Log Number of Sheep Held for Breeding		
	(1)	(2)	(3)	(1)	(2)	(3)
Exposure, t-1	-0.0749**	-0.0560	-0.0563	0.0699***	0.0744***	0.0649***
	(0.0365)	(0.0372)	(0.0372)	(0.0175)	(0.0176)	(0.0170)
	{0.0378}	{0.0381}	{0.0379}	{0.0190}	{0.0208}	{0.0205}
Avg. Exp. t-2 to t-5	-0.367***	-0.256*	-0.259*	0.102	0.0589	0.00967
	(0.139)	(0.150)	(0.151)	(0.0777)	(0.0782)	(0.0761)
	{0.0828}	{0.0841}	{0.0841}	{0.0445}	{0.0473}	{0.0469}
Avg. Exp. t-6 to t-10	-0.499*	-0.332	-0.335	0.134	0.0992	0.0528
	(0.258)	(0.284)	(0.286)	(0.120)	(0.119)	(0.115)
	{0.129}	{0.137}	{0.138}	{0.0734}	{0.0770}	{0.0784}
Year_FE	Yes	Yes	Yes	Yes	Yes	Yes
County_FE	Yes	Yes	Yes	Yes	Yes	Yes
State_Time_Trends	No	No	No	No	No	No
Weather_Controls	No	Yes	Yes	No	Yes	Yes
N	4056	4056	4056	7488	7488	7488
r2_a	0.904	0.905	0.905	0.943	0.944	0.946

Standard Errors in parentheses are clustered by County. Conley SE in brackets, 100 km cut off. States in number of sheep sample include NE and SD. States in sheep held for breeding sample include IL, MN, MT, and ND.
* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

A.1 Empirical Model: Long Run Effects of Nuclear Testing

$$ln(Y_{it}) = \alpha_i + \Sigma_{j=0}^{J}\beta_j * Average.Exposure_{it-j} + \chi_{it} * \theta_t + \lambda_{it} + \epsilon_{it} \quad (8)$$

Equation 8 seeks to measure changes in long run agricultural production using a panel constructed from U.S. Agricultural Census data for the years 1940 to 1997. The outcomes, denoted by $ln(Y_{it})$, include number of farm operations, average farm acreage, land value per acre, % of farmland as cropland, and % of farmland as pastured cropland. The model is a distributed lag model with J lags and time and county fixed effects. $Average.Exposure_{it-j}$

measures the average annual cumulative deposition of I-131 for the five year periods between Census years. In the analysis I show the impact of deposition for the half decades from 0-5, 6-10, 11-15, 16-20, and 21-25 years earlier.

In some specifications I include state specific time trends and Census year fixed effects. In other specifications I utilize a specification similar to that of Hornbeck (2012). I include values of 1940, 1945, and 1950 Census variables, denoted by χ_i, that are not on the right hind side of the regression and interact these pre-test period controls with Census year indicator variables. This specification controls for potential underlying county specific characteristics that might by influencing the outcome of interest over time and are more flexible than time trends. Additional weather controls, denoted by λ_{it}, include monthly temperature and precipitation averages between Censuses. α_i, denotes county fixed effects. ϵ_{it} is the heteroskedastic error term clustered at the county level.

In order to control for potential biases from unaccounted factors related to urbanization, I follow the example set by Deschênes and Greenstone (2007). I restrict the sample to non urban counties with less than 200,000 residents in 1990 or 400 people per square mile in 1990. In some specification I restrict the sample to counties west of the 100th Meridian. Agricultural counties east of the 100th Meridian depend on rainfall while those west have much greater access to irrigation (Schlenker et al., 2006; Burke and Emerick, 2016). I include this sample restriction to test whether or not counties with different agricultural production technologies responded differently to radioactive fallout.

In order to test whether or not fallout from nuclear testing had persistent effects on the agricultural sector, I create a panel of comparable variables from Historical U.S. Agricultural Censuses for the years 1940 to 1997 Haines et al. (2015). This Census data comes from the most comprehensive surveys of agriculture in the United States that ranges back to 1840. Starting in 1920, the Agricultural Census started conducting bidecennial surveys. I use this data to explore the effects on radioactive fallout deposition on long run outcomes and agricultural development at a national level.

A.2 Long Run Effects of Nuclear Testing

The results using Agricultural Census data suggest that more irradiated counties developed differently relative to less irradiated counties. Table 10 reports the effects of average radiation deposition between Censuses on the number of farm operations and farm size. It appears that more irradiated counties had fewer farm operations sixteen to twenty five years following fallout exposure. This could be evidence that environmental degradation or the productivity shocks from nuclear testing has long term consequences for agriculture. It appears the farms in more irradiated counties grew in size relatively to less irradiated counties. This result suggests that the farms which remained in irradiated counties expanded their overall sizes. This might be evidence that farmers adjusted their production decisions in response to fallout induced productivity shocks.[4]

Table 11 suggests that radioactive fallout has persistent effects for agricultural land values and the share of agricultural land dedicated towards crop production.[5] There is some evidence that radioactive fallout affects land value per acre for the continental U.S., but this effect appears strongest in counties to the west of 100th Meridian. I find evidence that productivity shocks from radioactive fallout were internalized into agricultural land values in the Western U.S. and in counties where crops tend to be produced using irrigation. It is plausible that transitory shocks from fallout caused farmers to permanently reallocate resources away from crop production and decrease investments that would increase the value of agricultural land. There is evidence that more irradiated counties across the continental U.S. shifted land away from crop production. Crop production is a higher value use of land than pasturing and this change could be reflected in land values. Such changes in land allocation also might be more permanent in the western U.S. than the eastern U.S. due to the west's reliance on irrigation.

[4]These results are preliminary. Future results will incorporate weighted least squares with Conley Standard errors.

[5]Not reported is the log share of pastured cropland as there was no effect. This is the only measure of pasture which is consistent from 1940 to 1997.

Table 10: Long Run Effects of Radiation Deposition on Number of Farms and Average Farm Size: 1940 - 1997

	log Number of Farms				Log Avg. Farm Size, Acres			
	(1)	(2)	(3)	(4)	(1)	(2)	(3)	(4)
Avg Exp, t-0 to t-5	-0.00915	-0.0152	-0.0116	-0.0205	0.0805***	0.0431**	0.101***	0.0745***
	(0.0144)	(0.00988)	(0.0175)	(0.0135)	(0.0219)	(0.0196)	(0.0278)	(0.0190)
Avg Exp, t-6 to t-10	-0.0271	-0.00246	-0.0281	-0.0122	0.104***	0.0788***	0.101***	0.0840***
	(0.0166)	(0.00933)	(0.0212)	(0.0141)	(0.0189)	(0.0128)	(0.0240)	(0.0160)
Avg Exp, t-11 to t-15	-0.0204	-0.0189	-0.0396	-0.00448	0.0987***	0.0798***	0.104***	0.0884***
	(0.0166)	(0.0157)	(0.0252)	(0.0119)	(0.0201)	(0.0173)	(0.0241)	(0.0168)
Avg Exp, t-16 to t-20	-0.0302**	-0.0442***	-0.0518***	-0.00708	0.0893***	0.0822***	0.0868***	0.0735***
	(0.0118)	(0.0130)	(0.0153)	(0.0112)	(0.0216)	(0.0179)	(0.0268)	(0.0151)
Avg Exp, t-21 to t-25	-0.0280**	-0.0204	-0.0363**	0.0139	0.0820***	0.0720***	0.0568***	0.0485***
	(0.0112)	(0.0157)	(0.0149)	(0.00998)	(0.0217)	(0.0182)	(0.0218)	(0.0141)
Census_YR_FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
County_FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
State_Time_Trends	Yes	No	Yes	No	Yes	No	Yes	No
Weather_Controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Census_Controls	No	Yes	No	Yes	No	Yes	No	Yes
West_Counties	No	No	Yes	Yes	No	No	Yes	Yes
N	35554	35361	6717	6562	35220	35052	6594	6464
r2_a	0.947	0.954	0.960	0.972	0.963	0.968	0.956	0.964
F_Stat	2.57	3.93	2.57	2.28	8.14	8.87	5.83	8.94
F_Test_Pvalue	0.02	0.00	0.03	0.05	1.20	0.00	0.00	0.00

All Standard Errors are Clustered by County. Average Exposure denotes 1000's nCi of I-131 per m2 .

Exposure measure cumulative I-131 deposition in a county over a year.

Samples are restricted to balance panels for the outcome of interest. Excluding urban counties.

Weather Controls are average monthly temperature average and precipitation controls between each census.

Western counties are west of of the 100th Meridian.

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

Table 11: Long Run Effects of Radiation Deposition on Agricultural Land Values and Share of Cropland: 1940 - 1997

	Log Land Value Per Acre				Log Share Cropland			
	(1)	(2)	(3)	(4)	(1)	(2)	(3)	(4)
Avg Exp, t-0 to t-5	-0.00900	-0.0346*	-0.0972***	-0.0862***	-0.0754**	-0.0491*	-0.0875**	-0.0606*
	(0.0295)	(0.0201)	(0.0196)	(0.0228)	(0.0346)	(0.0298)	(0.0421)	(0.0363)
Avg Exp, t-6 to t-10	0.0142	-0.0218	-0.0834***	-0.0752***	-0.125***	-0.106***	-0.132***	-0.0998***
	(0.0305)	(0.0211)	(0.0201)	(0.0210)	(0.0268)	(0.0264)	(0.0369)	(0.0266)
Avg Exp, t-11 to t-15	-0.0484*	-0.0484*	-0.116***	-0.0736***	-0.0535***	-0.0546***	-0.0940***	-0.0471***
	(0.0263)	(0.0272)	(0.0185)	(0.0154)	(0.0176)	(0.0160)	(0.0214)	(0.0166)
Avg Exp, t-16 to t-20	0.0164	0.0137	-0.0629***	-0.0368***	-0.0118	0.00947	-0.0397	-0.0229
	(0.0248)	(0.0255)	(0.0133)	(0.0140)	(0.0196)	(0.0186)	(0.0305)	(0.0221)
Avg Exp, t-21 to t-25	0.00451	-0.00842	-0.0215	-0.00661	-0.0699***	-0.0719***	-0.0794**	-0.0541**
	(0.0266)	(0.0258)	(0.0167)	(0.0173)	(0.0202)	(0.0236)	(0.0314)	(0.0224)
Census_YR_FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
County_FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
State_Time_Trends	Yes	No	Yes	No	Yes	No	Yes	No
Weather_Controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Census_Controls	No	Yes	No	Yes	No	Yes	No	Yes
West_Counties	No	No	Yes	Yes	No	No	Yes	Yes
N	35011	34842	6568	6425	33967	33889	5712	5660
r2_a	0.976	0.978	0.973	0.977	0.937	0.943	0.936	0.947
F_Stat	3.49	2.95	12.15	6.14	13.61	13.07	11.75	5.89
F_Test_Pvalue	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00

All Standard Errors are Clustered by County. Average Exposure denotes 1000's nCi of I-131 per m2 .

Exposure measure cumulative I-131 deposition in a county over a year.

Samples are restricted to balance panels for the outcome of interest. Excluding urban counties.

Weather Controls are average monthly temperature average and precipitation controls between each census.

Western counties are west of of the 100th Meridian.

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