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ABSTRACT

Research increasingly shows that differences in endowments at birth need not be genetic but instead are influenced by environmental factors while the fetus is in the womb. In addition, these differences may persist well beyond childhood. In this paper, we study one such environmental factor – exposure to radiation—that affects individuals across the socio-economic spectrum. We use variation in radioactive exposure throughout Norway in the 1950s and early 60s, resulting from the abundance of nuclear weapon testing during that time period, to examine the effect of nuclear exposure in utero on outcomes such as IQ scores, education, earnings, and adult height. At this time, there was very little awareness in Norway about nuclear testing so our estimates are likely to be unaffected by avoidance behavior or stress effects. We find that exposure to nuclear radiation, even in low doses, leads to a decline in IQ scores of men aged 18. Moreover, radiation exposure leads to declines in education attainment, high school completion, and earnings among men and women. These results are robust to the choice of specification and the inclusion of sibling fixed effects.

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Introduction

There is a large literature documenting the substantial persistence in early childhood endowments. Increasingly, the evidence shows that differences in endowments at birth need not be genetic but instead are influenced by environmental factors while the fetus is in the womb. This includes studies on the effects of the 1918 flu epidemic (Almond, 2006), the 1957 Asian flu pandemic (Kelly, 2011), the 1959 to 1961 Chinese famine (Almond, Edlund, Li, and Zhang, 2010), birth weight effects (Black, Devereux and Salvanes, 2007), and the effects of maternal smoking and drinking (Currie, Neidell and Schmieder, 2009; Fertig and Watson, 2009).[2] In this paper, we study one such environmental factor – exposure to radiation. Importantly, unlike other factors that disproportionately affect one part of society, nuclear exposure affects members of all socioeconomic groups.

This paper uses variation in radioactive exposure throughout Norway in the 1950s and early 1960s resulting from the extensive nuclear testing during that time period to examine the effect of nuclear exposure in utero on outcomes such as IQ scores, education, height, and earnings. Norway provides an ideal laboratory; because of its geographical location and topography, with high precipitation in coastal areas, Norway received considerable radioactive fallout from atmospheric nuclear weapons tests in the 1950s and 60s (Storebø, 1958, Hvinden and Lillegraven, 1961). Regional fallout was determined by wind, rainfall, and topography; we use this variation across Norway and over time for identification.

Unlike other environmental factors such as pollution from highways or factories, fallout was relatively evenly spread across socio-economic groups. Therefore, we are able to identify whether the effects of radiation differ by socioeconomic status. Are families with more resources better able to mitigate the negative effects of this early health shock? In addition, by looking

[2] See Currie (2011) for a review.

within families using sibling fixed effects methods, we can also get some indication as to whether, within families, parents engage in reinforcing or compensating behavior towards the children who face this negative endowment shock. We find that sibling fixed effects estimates are generally smaller than cross-sectional estimates, suggesting that parental investments may be compensating rather than reinforcing.

Several studies have examined the impact of the Chernobyl disaster on children who were in utero when it occurred; one important study was by Almond, Edlund and Palme (2009), who find that exposure in utero leads to lower test scores in school. Our paper adds to this literature by focusing on the long-run effects of low doses of radiation from global nuclear fallout resulting from nuclear weapon testing. As a result, we are able to incorporate both cross-sectional as well as time-series variation in exposure over a longer period of time. Also, unlike the Chernobyl nuclear accident in 1986, there was very little public awareness in Norway of the exposure to nuclear fallout in Norway resulting from nuclear testing taking place in foreign countries. Moreover, the first medical studies analyzing the effect of nuclear fallout on cognitive achievement were only published in the 1980s (see, e.g., Otake and Schull, 1984). Therefore, there is no reason to expect that avoidance behavior is important. This additionally implies that, unlike with Chernobyl or the atomic bombs in Japan in 1945, our health effects cannot be explained as resulting from stress due to worry about the effects of radiation.

We find that exposure to nuclear fallout in the air or on the ground, even in low doses, leads to a decline in men's IQ scores at age 18, completed years of education, and earnings at age 35. Among women, radiation exposure leads to declines in educational attainment and high school completion, and lower earnings at age 35. These results are robust to the choice of specification, tests of selection, and the inclusion of sibling fixed effects.

The paper unfolds as follows. Section II describes the relevant history of nuclear testing affecting Norway. Section III describes our empirical strategy and Section IV describes our data. Section V presents the results and numerous robustness tests, and Section VI concludes.

II. Background

Nuclear Testing

There was intensive nuclear weapon testing worldwide in the periods 1952–1954, 1957–1958, and 1961–1962 (see Appendix Figure A1), with deposition rates peaking in 1963.[3] According to the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR), 520 tests were conducted in the atmosphere - most of them prior to 1963. These atmospheric nuclear weapons tests are considered to be the most significant source of radioactive fallout; contamination resulting from underground nuclear weapon testing is, from a global perspective, negligible.

A nuclear weapon test produces about 150 fission products with half-lives long enough to contribute to radioactive fallout. In general, the fallout can be divided into three components: 1. large particles that are deposited from the atmosphere within hours of the test, 2. smaller particles that remain in the troposphere only a few days, and 3. longer-lived particles such as Cesium (CS-137), Strontium (Str-90), Rubidium (Ru-103), Xenon (Xe-133), Iodine (I-131) and Barium (Ba-140), that are injected into the stratosphere (Bergan, 2002). This radioactive debris injected into the stratosphere--so-called "global fallout"--will trickle down slowly to the troposphere; from

[3]On October 10, 1963, a partial test ban treaty came into force, banning nuclear tests in the atmosphere, underwater and in space. The treaty was not signed by France and China; as a result, the last atmospheric explosion was performed by China as late as October 1980. As of January 1999, there were 2,532 known nuclear tests worldwide (UNSCEAR, 2000), see Appendix Table 1. As the number of tests depends on the definition of a test, different sources report different numbers. Here, we adopt the definition used by the United States and the Soviet Union/Russia where a test is defined as a single explosion, or two or more explosions fired within 0.1 seconds within a diameter of two kilometers.

there, the debris is deposited on the ground mainly through precipitation. Differences in the rate of deposition across locations can thus primarily be explained by temporal and spatial variation in precipitation. Because the fallout cloud disperses with time and distance from the explosion, and radioactivity decays over time, the highest radiation exposures are generally in areas of local fallout.[4]

Immediately following a nuclear explosion, the activity of short-lived radionuclides is much greater than that of long-lived radionuclides. However, the short-lived radionuclides decay substantially during the time it takes the fallout cloud to reach distant locations like Norway, and the long-lived radionuclides become relatively more important. In the polar region, radionuclides remain in the stratosphere on average from 3 to 12 months (UNSCEAR, 1982).[5] Bergan (2002) estimates the average age of the fallout in Norway to be between 3 and 5 months during the intensive testing periods.

The western Norwegian coast line was particularly exposed to atomic fallout coming from nuclear testing taking place in Novaya Zemlya in the Russian arctic archipelago, one of the most intense test regions between 1955 and 1962 (see Figure A2). The macro weather system is the primary force that moved long-lived radionuclides from Russian test stations to their ultimate deposition along the Norwegian coast: cold air over the poles creates high pressure zones taking the air to lower latitudes.[6]

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[4] According to UNSCEAR (1993) fallout activity deposited close to the test sites accounts for 12% of total fallout, tropospheric fallout, which is deposited in a band around the globe at the latitude of the test site, for 10%, and global fallout, which is mainly deposited in the same hemisphere as the test site, for 78%. As most tests were carried out in the northern hemisphere, most of the radioactive contamination is also found there.

[5] The polar region is down to the 60 degree latitude (about where Bergen is located in south west Norway), and most of the time the radionuclides from the test sites in Northern Russia were transported in this zone.

[6] Due to the Coriolis forces, the cold dry air moves away from the pole twisting westward resulting in the so-called polar easterlies. Thus, these winds carry air from Northern Russia southwest towards the Norwegian Sea and Iceland. At around 60 degrees north, the airstream enters the low pressure zone and the air is brought eastwards again towards the Norwegian coast (see Figure A3). Moreover, the polar jet streams located right below the stratosphere at around 60 degrees north also distributed long-lived nuclear debris over the globe.

Figure 1 shows estimates of the *in situ* total Beta fallout in each municipality in Norway in 1958, 1960, 1962, and 1964.[7] The activity of fallout in the air or on the ground or other surfaces is measured in becquerels (Bq). This measurement is defined as the number of radioactive disintegrations per second.[8] The fallout varies significantly by municipality and also over time. There was an international moratorium on nuclear testing from November 1958 to September 1961 so Norway received almost no fallout in the second half of 1959, in 1960, and throughout most of 1961. The partial test ban treaty in October 1963 led to very little fallout in 1964 or in subsequent years. However, there is significant fallout in 1957 and 1958 and, even more so, in 1962 and 1963 because the explosions after the expiration of the moratorium were much larger than before. This results in substantial time series variation in addition to that across municipalities.

Prenatal Radiation Exposure and Cognitive Damage

Following the deposition of fallout into the air and on the ground, there are different means by which one can absorb radiation. Irradiation might come from penetrating gamma rays emitted by particles in the air and on the ground. In this case, simply staying inside a building reduces exposure. Moreover, one could inhale fallout or absorb it through skin. A further source is the consumption of contaminated food. Vegetation can be contaminated when fallout is directly deposited on the surface of plants, or when it is deposited on the ground and plants absorb it through their roots. People can also be exposed when they eat meat and drink milk from animals grazing on contaminated vegetation or if they drink contaminated water.

[7] We use the phrase "*in situ*" to denote nuclear fallout that has been deposited to the ground (as distinct from being suspended in the air).

[8] The initial measurements in Norway were made in pikoCurrie. We have converted these into Bq as this is the current standard unit of measurement.

It is well-established that ionizing radiation can lead to molecular, cellular, and tissue damage (see, e.g., Hall, 2009). Importantly, actively dividing cells are known to be more sensitive to ionizing radiation than cells that have completed division (see, e.g., ICRP, 1986). As cell cycling and division occur more rapid early in life, the age at the time of exposure to ionizing radiation is an important factor in determining the damage to the developing brain.

While formation of most human organs is largely complete by the 8th week after conception, the development of the cerebral cortex occurs rapidly from weeks 8 to 15 post-conception. The neocortex is the part of the cerebral cortex that is involved in higher functions such as sensory perception and generation of conscious thought and language, and prenatal exposure to ionizing radiation is particularly harmful if it occurs during this 2-month period of time (see, e.g., Otake and Schull, 1998). By the 16th pregnancy week, the normal number of neurons in the cerebral neocortex of the human adult has been established (see Dobbing and Sands, 1973). During weeks 16 to 25 after conception, the differentiation of cells accelerates, and after the 25th week, the central nervous system becomes quite resistant to radiation. At that point, major fetal brain damage becomes highly improbable (see, e.g. ICRP, 1991; Otake and Schull, 1998).

The first studies indicating that iodizing radiation causes cognitive abnormalities were analyses of individuals exposed in utero to diagnostic X-ray procedures in the 1980s (see, e.g., Brent, 1989). Most evidence on the effects of acute exposure to ionizing radiation has, however, been obtained from studies on the survivors of the atomic bombs at Hiroshima and Nagasaki. Different studies using a variety of measures of cognitive function, such as the occurrence of severe mental retardation, the intelligence quotient (IQ) and school performance, find a significant effect on individuals exposed during weeks 8 to 15 and weeks 16 to 25 after conception. However, no evidence of a radiation effect has been seen among children exposed prior to the 8th week or subsequent to the 25th week after conception (see, e.g., Otake and Schull, 1984; Otake, Yoshimaru, and Schull, 1989; Miller and Mulvihill, 1956). Moreover,Otake and Schull (1998) report that the risk of severe mental retardation was 5-times greater for persons exposed during weeks 8 to 15 post-conception than for individuals exposed during weeks 16 to 25 post-conception.

However, these survivor studies are limited in that they analyze the effects of a single, relatively high dose and not of small, intermittent, or continual doses typical of medical, professional, or environmental exposure. Studies evaluating the impact of smaller doses of radiation, such as after the reactor incident in Chernobyl, on health outcomes such as spontaneous abortion, stillbirth, length of gestation, birth weight, and neonatal mortality, are not conclusive. Some find effects after prenatal exposure, while others do not (see, e.g., Lüning *et al*., 1989; Ericson and Källén, 1994; Sperling *et al*., 1994; Scherb, Weigelt, and Brüske-Hohlfeld, 1999; Auvinen *et al*., 2001, Laziuk *et al.*, 2002). However, studies focusing on cerebral dysfunctions do suggest that the prenatal exposure to radioactive fallout after Chernobyl resulted in detectable brain damage or lower schooling performance and fetal death (see, e.g., Nyagu *et al*., 2004; Almond *et al.*, 2009, Halla and Zweimuller, 2012).

The potential to extrapolate the Japanese or Ukrainian findings to those from the nuclear weapon testing fallout is limited. The global fallout from the testing yielded no fatal doses in Norway, but during periods of the 50s and 60s the population was continuously exposed to radionuclides. In contrast, the Japanese population was acutely irradiated by γ-rays and neutrons and the Ukrainian population also received a high dose of radioiodine. As mentioned earlier, another difference between our study and both Chernobyl and the atomic bombing in Japan, is that people in Norway were totally unaware of the potential danger, and thus our estimates should be unaffected by avoidance behavior or by stress. Stress during pregnancy has been linked to poor infant health outcomes (Kuzawa and Sweet, 2009). Because of the different situations, it is not easy to predict the radiobiological effect of the global fallout received by Norway from the Japanese or Ukrainian results.

III. Empirical Strategy

To measure the long-run effects of nuclear fallout on cognitive test scores, height, education and income, we exploit the variation in radioactive fallout in Norway within geographic areas over time. We use a similar approach to that in the Chernobyl study of Almond *et al.* (2009) but incorporate the fact that we have variation over a relatively long period of time as well as across space. The amount of fallout experienced by any individual depends on their month of birth, year of birth, and municipality of birth.

Basic Specification

We estimate the following equation:

$$H_{ict} = \alpha_0 + \alpha_1 F_{ct} + \beta X_{it} + \gamma_t + \lambda_c + \epsilon_{ict}. \quad (1)$$

Here H_{ict} represents outcomes such as education, IQ score, height and earnings for child i born in municipality c at time t. F denotes the nuclear fallout in municipality c at the time the child was in months 3 and 4 (approximately weeks 8 to 16) in utero. We choose the 8-16 week period as our primary specification because evidence from the medical literature suggests that this is when the fetus is most vulnerable to radiation exposure (see, e.g., Otake and Schull, 1984), but we also test the effect of exposure at different points in time. X is a vector of controls that includes parental education, the county level unemployment rate when the child was in utero, and birth order indicators (family size at birth of child). We also include controls for year of birth by month of birth indicators (γ_t) and municipality fixed effects (λ_c).[9] We use OLS estimation; in the case of high school completion, we are estimating a linear probability model.

Specification with Municipality-Specific Trends

One concern might be that our results are driven by different trends in municipalities that are exposed to high doses of radiation relative to those that are not. While we examined this directly and found no evidence of differential trends in the observable control variables during this time period, we also report estimates from a specification that allows for municipality-specific linear trends.[10] These trends are included in addition to the year of birth by month of birth indicators.

Specification with Interactions

As a further robustness check, we also estimate a richer model that adds interactions of the municipality dummies with month of birth (to allow for seasonal factors that differ by area) and interactions of the municipality dummies with year of birth (to allow cohort effects to differ by municipality). Note that we cannot include the interaction of year of birth by month of birth by municipality, as that is our identifying variation. Letting *y* denote year of birth and *m* denote month of birth, we estimate

[9] An alternative to this difference-in-difference type strategy is to use time-series variation in fallout. We have tried this approach by replacing the year of birth by month of birth dummies with a time trend and found effects that have the same sign and statistical significance but smaller magnitudes. Because this is a period of rapid changes in educational infrastructure and in compulsory schooling laws, we have more faith in specifications that include cohort effects.

[10] Results on differential trends for control variables are available from the authors upon request.

$$H_{ict} = \alpha_0 + \alpha_1 F_{ct} + \beta X_{it} + \gamma_t + \lambda_{cy} + \mu_{cm} + \epsilon_{ict}. \quad (2)$$

This model is still well identified as there is much variation in fallout over the course of any particular year that is not driven by seasonal factors but instead by the timing of nuclear tests in the Soviet Union.

Sibling Fixed Effects Model

While exposure is arguably exogenous to family and neighborhood characteristics within municipalities, one might still worry that non-random migration might change the composition of people in the municipality over time. Furthermore, the composition of the sample could be correlated with the fallout if there are changes over time and region in the types of people who give birth and these are, by chance, correlated with fallout levels.[11] While we have no evidence that this is the case, we also estimate a specification that includes sibling fixed effects. Variation is then based on differences in exposure within families across children, thereby differencing out anything that is constant within families such as socio-economic status.[12]

Families with multiple children can offset or reinforce endowment differences at birth by investing relatively more or less in one child compared to the others. If the OLS results without sibling fixed effects are consistent (as we believe), then the comparison of the cross-sectional estimates to the sibling fixed effects estimates can thereby provide some insight into this behavior. If the effects of exposure are larger in the sibling fixed effects specifications (where

[11] In the U.S., birth selectivity by socio-economics status has been found to differ by month of birth (Buckles and Hungerman, 2010) and by economic conditions (Dehejia and Lleras-Muney, 2004).

[12] Because nuclear radiation may affect later fertility, as a specification check, we have estimated the sibling fixed effects model on a subset where the exposed child is not the first-born and compare this child to existing children and find similar results. We also look at fertility directly and find no effects of exposure on later fertility behavior; this is unsurprising, given the lack of knowledge about exposure at the time.

identification comes from within family differences in sibling outcomes), this would be consistent with re-enforcing parental investments.

IV. Data

Data are compiled from a number of different sources. Our primary data source is the Norwegian Registry Data, a linked administrative dataset that covers the population of Norwegians up to 2009 and is a collection of different administrative registers such as the education register, family register, and the tax and earnings register. These data are maintained by Statistics Norway and provide information about educational attainment, labor market status, earnings, and a set of demographic variables (age, gender) as well as information on families.[13] We include data for cohorts born 1956-1966.

Using month and year of birth, and assuming that a pregnancy lasts 266 days, we can identify the period of time in which each individual was in months 3 and 4 in utero.[14] We allocate a municipality to each child born between 1956 and 1964 using the 1960 Census by assuming that the municipality during pregnancy is the mother's municipality of residence in 1960. For individuals born in 1965 and 1966, we are able to use register data on the exact municipality where the mother lived when the child was born.

Military Data

The IQ score and height data are taken from the Norwegian military records that cover all the cohorts we study. Before young men enter the service, their medical and psychological

[13] See Møen, Salvanes and Sørensen (2004) for a description of these data.

[14] This seems appropriate, given the results of Almond *et al.* (2009), who found that the radioactive fallout from Chernobyl had no effect on gestational length in Sweden.

suitability is assessed; this occurs for the great majority between their eighteenth and twentieth birthday. In Norway, military service is compulsory for every male; as a result, we have military data for men only.[15]

The IQ measure is the mean score from three IQ tests -- arithmetic, word similarities, and figures (see Sundet *et al*. [2004, 2005] and Thrane (1977) for details). The arithmetic test is quite similar to the arithmetic test in the Wechsler Adult Intelligence Scale (WAIS) (Sundet *et al.* 2005; Cronbach 1964), the word test is similar to the vocabulary test in WAIS, and the figures test is similar to the Raven Progressive Matrix test (Cronbach 1964). The IQ score is reported in stanine (Standard Nine) units, a method of standardizing raw scores into a nine point standard scale that has a discrete approximation to a normal distribution, a mean of 5, and a standard deviation of 2.[16]

Education

We measure educational attainment in 2009 and use two measures of education achievement. High school graduation is an indicator equal to one if the child obtained a three-year high school diploma. We also consider the years of education completed by the individual. The data are based on school reports sent directly to Statistics Norway by educational institutions, thereby minimizing any measurement error due to misreporting.

[15] Norway has mandatory military service of between 12 and 15 months (fifteen in the Navy and twelve in the Army and Air Force) for men between the ages of 18.5 (17 with parental consent) and 44 (55 in case of war). However, the actual draft time varies between six months and a year, with the rest being made up by short annual exercises.
[16] The correlation between this IQ measure and the WAIS IQ score has been found to be 0.73 (Sundet *et al*., 2004).

Earnings

Earnings are measured as annual earnings for taxable income as reported in the tax registry when the individual is aged 35. These are not topcoded and include labor earnings, taxable sick benefits, unemployment benefits, parental leave payments, and pensions.[17]

Data on Nuclear Fallout

In the period from 1956 to 1984, the Norwegian Defense Research Establishment (FFI) monitored radioactivity in the air and on the ground at 13 stations across Norway.[18] They collected two primary measures of radiation: (i) a measure of the total beta radiation in the air expressed as Bq/m^3, and (ii) a measure of the total beta radiation *in situ* (ie on the ground) expressed in Bq/m^2.[19] Radioactivity in the air was measured 2 meters above ground level using air filters, and the filters were changed every 24 hours. The samples were sent to the main laboratory of FFI near Oslo, and a Geiger-Müller counter measured the total beta activity 72 hours after the samples were collected.[20] Precipitation (rain, snow) and dry particles were also collected at each test station for the measure of ground deposition.[21] Beta activity came from many isotopes with half-lives of less than a year such as Rubidium (Ru-103), Xenon (Xe-133),

[17] An individual is labeled as employed if currently working with a firm, on temporary layoff, on up to two weeks of sickness absence, or on maternity leave. We later test the sensitivity of our results to the choice of income measure.
[18] The locations of measurement stations for radioactivity are (from North to South in Norway): Vadsø, Tromsø, Bardufoss, Bodø, Værnes (close to Trondheim in mid Norway), Røros, Ålesund, Bergen, Finse, Sola (close to Stavanger), Gardermoen (close to Oslo), Kjeller (also close to Oslo), Kjevik (close to Kristiansand).
[19] We obtained the raw data collected for deposition in air and ground measured in $pikoCurrie/m^3$ and $pikoCurrie/m^2$, respectively. Bergen digitalized the original protocols to obtain the radiation data (Bergan, 2002, 2010, Bergan and Steenhuisen, 2012).
[20] This implies that the short-lived radioisotopes from the decay of Radon had already died out. This is important since Radon is not randomly distributed across regions and its presence might contaminate our estimates of the effects of the fallout from the nuclear tests.
[21] These samples were sent to the same laboratory and total beta activity was measured with the Geiger-Müller counter. In order to identify the source of the radioactive rays, a gamma ray spectrometer was used to identify the different isotopes. See Bergan (2002) for further details about radiation measurement.

Iodine (I-131) and Barium (Ba-140), and also longer lived ones such as Strontium (Str-90) and Cesium (CS-137), with half-lives of 28 and 30 years respectively.

These two measures of deposition (air and ground) have a correlation coefficient of 0.75, implying that they are highly-- but far from perfectly--correlated. Figures 2a and 2b show the two measures for Oslo and Bergen. One can see that the temporal pattern differs for the two measures. This is not surprising as ground deposition is largely determined by rainfall while fallout in the air is more related to the presence of centers of high air pressure as well as influxes of warm subtropical air (Bergan and Steenhuisen, 2012).

There are 13 test stations and about 730 municipalities in Norway during this period. To minimize the measurement error in our measure of nuclear fallout, we limit our sample to municipalities within 20km of a test station.[22] We have tested the sensitivity of our results to different distance cutoffs and find the results are insensitive to this choice.

For radiation in the air, we estimate the fallout for each municipality in our sample in each month by using the fallout at the geographically closest measuring station. For radiation on the ground, we estimate the fallout for each municipality in each month by using the fallout at the geographically closest measuring station and then weight that by the precipitation in that month in the municipality relative to the precipitation in that month at the measuring station.[23] This is equivalent to:

$$F_{ct} = F_{st}\frac{P_{ct}}{P_{st}}, \quad (3)$$

[22] See Table 1 for a comparison of our sample to the total population.
[23] Hvinden, Lillegraven and Lillesæter (1965) claim that removal of debris from the troposphere is proportional to precipitation in Norway and tropospheric concentration (see also Lillegraven and Hvinden, 1982). Moreover, Bergan (2002) states that "The fallout is correlated to the amount of precipitation and concentration in air, and the deposited radioactivity is proportional to monthly precipitation." (page 206).

where F_{ct} measures the nuclear fallout in municipality c at time t and F_{st} represents the nuclear fallout at the closest test station s at time t. P_{it} measures the precipitation in month t in municipality c or s. The reason for weighting by the precipitation relative to that at the test station is that the measured ground deposition is already affected by the amount of rain in the test station area. The re-weighting implies that there will be more fallout in areas of relatively heavier rain and less in areas of relatively less rain.[24]

The rain measures come from the Norwegian Meteorological Institute and are available by month for each municipality. The precipitation map of Norway (Figure A4) demonstrates that there are large differences in annual precipitation; precipitation is higher along the west and north coast of the country. Some of the measuring stations along the west coast have more than 3000mm average precipitation per year, while other stations measure yearly precipitation of less than 400mm. This massive variation in rainfall (as shown in Figure A4) is due to the mountain range that divides the country; this resulted in large local variations in deposited radioactivity, (see Oftedal, 1989).[25]

In Figure 3a and 3b we present the monthly beta fallout at the measuring stations in or close to 5 Norwegian cities from 1956 to 1975.[26] The figures show substantial variation over time and location.

Summary statistics for the key variables we use are presented in Table 1, along with descriptive statistics for the whole country. Because our sample is disproportionately urban, education levels are higher in our sample than in the country as a whole.

[24] We have also tried using the in situ total beta directly without weighting by the relative rainfall and obtained very similar results. This is unsurprising as we only include municipalities that are within 20km of a test station.
[25] Similarly Mattsson and Vesanen (1988) report that 99% of deposition from Chernobyl in western Sweden was due to rainfall (see Almond *et al*., 2009).
[26] There is a measuring station located within the municipality border of Bergen, Røros (central Norway) and Vadsø (northern Norway). The measuring station close to Stavanger is located in the Sola municipality, a neighboring municipality of Stavanger, and is located about 10km from the city center of Stavanger. The measuring station in Kjeller is the closest to Oslo and it is about 20 km away from the city center.

V. Results

Basic Specification

We present the results for each outcome by sex using two different measures of radiation exposure (in separate regressions), the beta radiation from the air and the in situ, or ground, radiation.

Tables 2 and 3 present the results for men and women using in situ exposure as the variable of interest, and Tables 4 and 5 present the results for men and women using air exposure. In each table, we present the results for two different functional forms (estimated from two different regressions) — the top panel uses the standardized measure of exposure (standardized to mean 0, variance 1) and the bottom panel uses log(exposure).[27] Each cell represents the coefficient from a separate regression.

Each regression also includes individual control variables, including indicators for mother's and father's education, birth order controls, and the unemployment rate in the year of birth in the county of birth. However, the results are insensitive to the inclusion of these controls.[28] As the IQ score and height information is taken from the Norwegian military records and military service is compulsory only for men, that analysis is restricted exclusively to men. We cluster the standard errors by municipality and so allow arbitrary correlations of the error terms for people born in the same municipality.

Column 1 present results from our basic specification that controls for municipality and month of birth by year of birth fixed effects. Column 2 then shows the results when we add municipality-specific time trends. Column 3 includes municipality-specific month of birth and

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[27] In the log specification, we dropped individuals who have zero fallout measures; however, we have only 431 zero observations for air fallout and none for in situ.
[28] For parsimony, we don't report results without controls in the tables. These are available from the authors upon request.

municipality-specific year of birth controls. In all specifications, we find that radioactive exposure, even the relatively small doses from the nuclear testing in the 1950s and 1960s, appears to have a significant negative effect on the IQ score of exposed males. This is true regardless of the measure of exposure that we use. To get a sense of the magnitude from the standardized measure, a one standard deviation increase in ground exposure leads to a decline in the IQ score of about 0.05. Given the standard deviation of the IQ score is 2, this is an effect size of 0.025 of a standard deviation. The effect of air exposure is larger with a one standard deviation increase in exposure leading to about 0.08 of a standard deviation fall in the IQ score. This is equivalent to about 1 IQ point on a standard IQ scale.

When we look at the results for educational attainment and high school completion, we find that radioactive exposure seems to have a negative and statistically significant effect on education among men. Similarly, there is a significantly negative effect of exposure on the educational attainment of women; again, this is robust to the measure of exposure used. The magnitudes suggest that a one standard deviation increase in ground exposure reduces educational attainment by 0.14 years for men and 0.18 years for women with effects on high school completion of about 1 percentage points for men and 2 percentage points for women. We also find statistically significant negative effects on earnings at age 35 for both men and women.

For boys, we can also study height at around age 18. The findings are mixed for this variable in that we find no evidence for effects on height when we used standardized fallout measures but a negative effect on height when we use the log of fallout. This suggests that non-linearities might be important; we examine this is more detail later.

Sibling Fixed Effects

We also estimate a specification that includes sibling fixed effects, restricting the sample to families in which there are at least two children born during the period.[29] The control variables included in these fixed effects estimates are birth order, the unemployment rate, and year of birth by month of birth dummies. These results are presented in the fourth column of Tables 2-5. For comparison, Appendix Table A2 presents OLS results for the sibling fixed effect sample. The OLS results for this sample are generally similar to the original OLS results. The sibling fixed effects results are mostly in line with our earlier findings (although somewhat smaller), again with IQ score at age 18 significantly affected by exposure among men, as is years of education. However, the earnings effects for men disappear when we use sibling fixed effects. Among women, we find a negative effect of exposure on the completion of high school and years of education for both fallout measures. The slight decline in the estimates when we include family fixed effects is consistent with compensating parental investments. However, we would not be able to reject that they are statistically the same in most cases.

Further Robustness Checks

We also conducted a number of further robustness checks. In one case, we include a direct measure of rainfall in addition to the other controls in our regressions. If one worries that it is the rainfall itself, and not the associated fallout, that is driving our results, this would address that concern. (Note that the municipality-specific month of birth effects would likely pick up these effects already, to the extent that this is a seasonal effect.) Not surprisingly, the results are completely insensitive to the inclusion of this variable.

[29] We also restrict the sample to siblings who were born in the same municipality. This restriction affects very few families and has little impact on the results.

We also tested the sensitivity of our results to the choice of income measure. One might be concerned about the arbitrary nature of our choice of income at age 35. As a robustness check, we estimated results with the average income between ages 30 and 35 and average income between 35 and 40. The results are very similar.

Finally, we also tried including both measures of fallout (air and ground) in the same regression. These results are presented in Table 6 using the original specification (with municipality dummies and year of birth by month of birth effects). Surprisingly, given the high correlation between the two measures, we find statistically significant effects for both measures. This suggests that there may be adverse effects both from inhaling radiation from the air, and from ingesting ground radiation through food or water.

Tests for Selection

One possible selection issue arises if fallout exposure leads to miscarriages, stillbirths, or infant mortality. To the extent that the weakest fetuses are affected, this would tend to lead to an underestimate of the negative effect of exposure. Although there are no birth registers for the cohorts we study, we do have some data that allow us to study whether exposure to radiation affected the probability of survival of children in-utero. Using county-level data (there are 19 counties in Norway) from the Norwegian vital statistics, we find no effects of average radioactive fallout in the air or in situ on the live birth/still birth ratio or the gender ratio at birth in that county in that year. This is consistent with the findings of Almond *et al.* (2009), who found that the Chernobyl radiation had no impact on birth outcomes in Sweden.

To the extent that radioactive exposure during one pregnancy changes future fertility decisions, estimates of the effects of radioactive exposure (especially those using sibling fixed effects) may be biased. To test for this, we used administrative registry data to examine whether future childbearing decisions were affected by in-utero exposure of existing children. We found that radioactive exposure of the first or second child has no significant effect on completed family size or on later fertility. It is not surprising that we find no evidence of fertility effects, as, at the time, there was no public awareness of the dangers arising from nuclear testing, particularly testing taking place so far away.

Nonlinearities and Heterogeneous Effects

While we have already estimated specifications with two different functional forms of the fallout measure, we next examine whether there might be other non-linearities in the effects. To do so, we also estimated a specification where we split fallout levels into quintiles. These results are presented in Table 7 using the original specification (with municipality dummies and year of birth by month of birth effects). We find little evidence for non-linearities, in that the estimates are monotonically increasing in magnitude with quintile and it is only for quintiles 3-5 of exposure that there are any significant negative impacts of radioactive fallout. This result is the same for men and women and for both air and ground fallout.

One might expect effects to be larger in months with more sunlight when individuals are more likely to be outside. As another check, we also estimate specifications where we include an interaction indicating whether the exposure occurred during spring or summer months (April-September). Table 8 presents these results. We find statistically significant interaction effects for both ground and air fallout, suggesting that exposure is more harmful during spring and summer months.

Finally, the negative effect of poor childhood health on human capital accumulation is often found to be stronger for individuals growing up in a less educated or low-income family (see, e.g., Currie and Hyson, 1999; Currie and Moretti, 2007; Currie, 2011, Almond and Currie, 2010). When we interact the nuclear fallout measures with an indicator variable equal to one if the individual's mother had a high school degree or more, we find that the interaction term is not statistically significant in most cases and the coefficient on the level effect of exposure is quite similar to the earlier estimates (see Table 9.) Interestingly, the effect of exposure is actually greater for individuals born to more highly educated parents when we look at years of education for both men and women. This is contrary to what the existing literature would suggest but given the general insignificance of the interaction terms we do not put too much weight on this finding.

During what months after conception are fetuses most vulnerable?

As discussed before, the development of the cerebral cortex occurs rapidly from weeks 8 to 15 post-conception, and the medical literature describes a newborn's cognitive ability as most vulnerable during these weeks. However, we are able to test the sensitivity of our results to this assumption. When we include both exposure in months 3 and 4 and exposure in months 5 and 6 in the same regression, it is clear that the exposure in months 3 and 4 is what matters. This is presented in Table 10. This is consistent with the findings of Otake and Schull (1984) that the cognitive development of children in utero during the 1945 Japanese bombings were 5 times more adversely affected if in utero between weeks 8 and 15 compared to being in utero during weeks 16 to 25.

To give a more complete picture, we separately analyze the effect of nuclear exposure on our outcomes of interest for each month of the pregnancy as well as the first three months after birth. Note that, because of the high correlation in exposure across months, exposure in each month is included in a separate regression. Table A3 presents the results for in situ nuclear exposure and Table A4 has the estimates for fallout in the air. Importantly, it is only the fallout measured in months three and four (and sometimes five) after conception that has significant effects on children's outcomes. Thus we conclude that, consistent with the medical literature, the fallout during weeks 8 to 15 post-conception is most important for long-term cognitive outcomes.

Magnitudes

The most important issue for health effects is the estimated dose individuals absorb. The basic unit to characterize this type of radiation dose is the Sievert (Sv), which is designed to measure biological effects of ionizing radiation. Unfortunately, this dose is very difficult to measure. Bergan and Steenhuisen (2012) estimate the annual doses of radiation that resulted from the nuclear fallout in Norway in the 1960s were about 23mSv in Bergen, 5mSv in Stavanger and 4mSv in Oslo. To put this into perspective, the external dose received from natural sources of radiation—from primordial radionuclides in the earth's crust and from cosmic radiation—is of the order of 2 mSv per year. The dose from a whole-body computed tomography (CT) examination is about 10mSv, and the external dose from a mammogram breast X-ray is about 0.4mSv.

To get a sense of how our results compare to the existing research, such as that by Almond *et al.* (2009), it is important to first understand the relative magnitude of the exposure to radioactive fallout. The maximum total beta deposited per month in Norway is lower than the maximum CS-134 fallout in Sweden after Chernobyl. To give a better sense of this: The highest ground deposition Almond *et al.* (2009) report is $54kBq/m^2$. The highest level of monthly total beta fallout reported by the measuring station in Bergen is $32.7kBq/m^2$ in January 1962, $29.9kBq/m^2$ in Kristiansand in October 1961, and $16.3kBq/m^2$ in Trondheim in October 1958. Moreover, the Swedish population was also exposed to other radionuclides in 1986.

While our estimates are not directly comparable to those of Almond et al. (2009), as their main specifications use discrete measures of the degree of exposure of particular regions and they use different measures of radioactive fallout, it is still useful to try to get a sense of relative magnitudes. When they study the effect of log fallout (both air and ground) on compulsory school math scores , they estimate coefficients that are similar in magnitude to the standard deviation of the dependent variable. Our log coefficients for IQ score are about -.15 for ground and about -.3 for air. These are approximately 8% and 15% of a standard deviation of the dependent variable. This suggests that our magnitudes are much smaller than those of Almond et al. (2009). However, they are more precisely estimated.[30]

VI. Conclusion

A large literature has shown that shocks in utero can have lasting effects on children. In this paper, we study one such environmental factor – exposure to radiation—that affects members of all socioeconomic groups. Using variation in radioactive fallout that was generated by nuclear weapons testing in the northern hemisphere and local differences in precipitation and wind patterns in Norway, we find negative long-run effects of exposure to nuclear fallout on cognitive tests, education, and earnings at age 35. While the existing literature has suggested that there are effects on cognitive development, we are the first to show that there are other, persistent effects on children's outcomes. Importantly, it does not seem that high income families are able to offset these negative effects. In addition, our data also allow us to verify the findings in the medical literature that individuals exposed to radiation during weeks 8 to 16 post conception are the most vulnerable. Unlike after the Chernobyl accident, Norwegians were unaware of the fallout that

[30] There are multiple reasons why these differences might arise: first, the age at which the outcome is measured is different, there are differences in the chemical composition of the nuclear fallout, and as people were not aware of the nuclear fallout and its effects in the 50s and 60s, our results should not be affected by stress.

they were exposed to from nuclear tests and, hence, our estimates are unaffected by avoidance behavior or by maternal stress.

While high doses of radiation are rare and confined to persons in the immediate vicinity of nuclear explosions or accidents, lower levels of radiation exposure are more commonplace. Our findings of adverse effects on the fetus--even at radiation levels that are much too low to make the mother sick--have important potential public policy implications. There is a wide range of possible exposure to anthropogenic releases of radioactivity today: A very recent example is the large amount of radioactivity that was discharged after damage to the cooling systems of several reactors in the Fukushima nuclear power plant in March 2011. Our results suggest that the fluctuating levels of radiation near the malfunctioning nuclear reactors may have had long-term effects on children who were in utero in Fukushima and its adjacent prefectures including Tokyo (see, e.g., Yasunari *et al*., 2011). Moreover, the steadily increasing use of radiation in medical treatments or diagnostics also enhances the radiation individuals are exposed to in everyday life.[31] While low dose radiation may be safe for adults, there may be long term benefits from efforts to shield pregnant women from its effects.

[31] In particular, computed tomography (CT) scans are a large source of radioactivity and deliver 100 to 500 times the radiation associated with an ordinary X-ray. The radiation exposure levels of a chest X-ray, for example, are 0.1 mSv, a CT scan of the pelvic or abdomen, however, exposes an individual to about 15 mSv. As the fetus is exposed to the radiation dose during a short time interval when the mother receives a CT scan, the treatment should be more harmful than exposure to similar doses from nuclear fallout from nuclear weapon testing or a power plant accident (Brenner *et al*., 2003). To put this into perspective, the total dose received people living near the Fukushima Daiichi Nuclear Power Station in Japan during the first four months after the reactors were damaged by a devastating tsunami was about 10mSv and the average external exposure in Norway from 1955 to 1975 was about 6mSv. Other possible sources of radiation are cosmic radiation during flights (the annual exposure of an airline crew flying New York to Tokyo polar route is about 9mSv) or also background radiation from radon gas (about 2 mSv per year).

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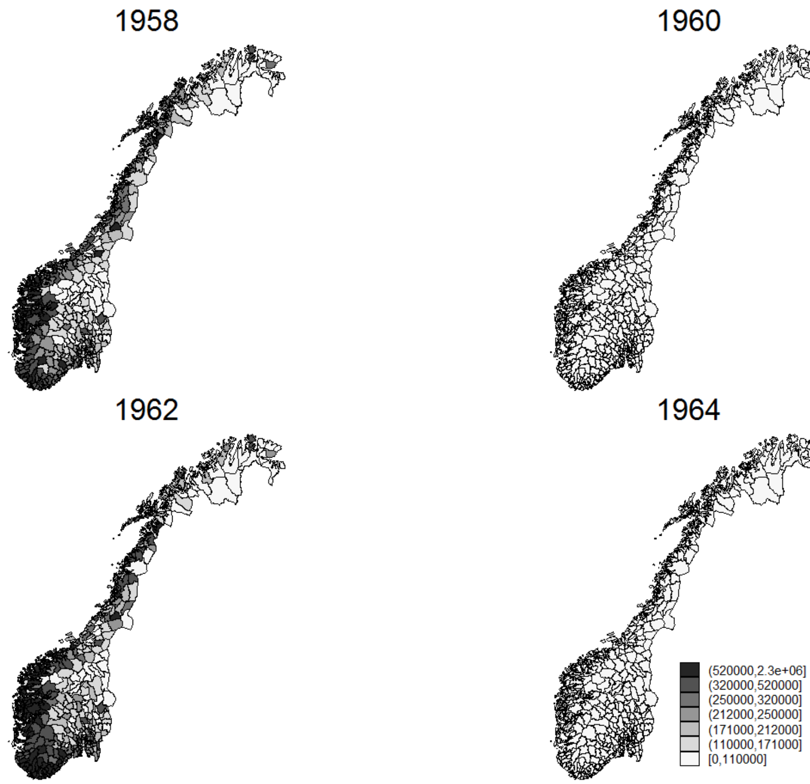
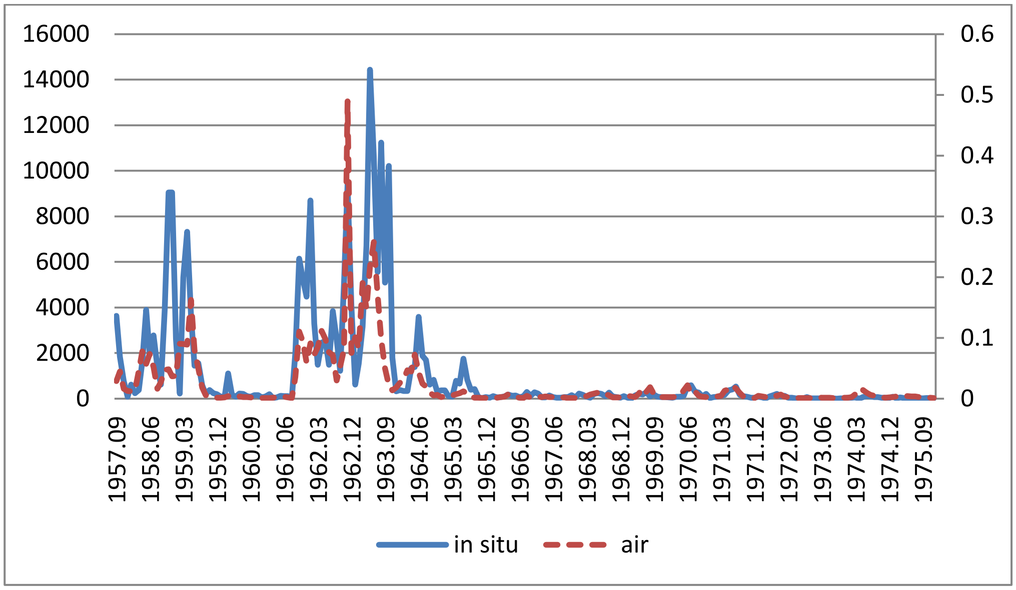
Figure 1: Total Beta Fallout in situ per Community in 1958, 1960, 1962, and 1964



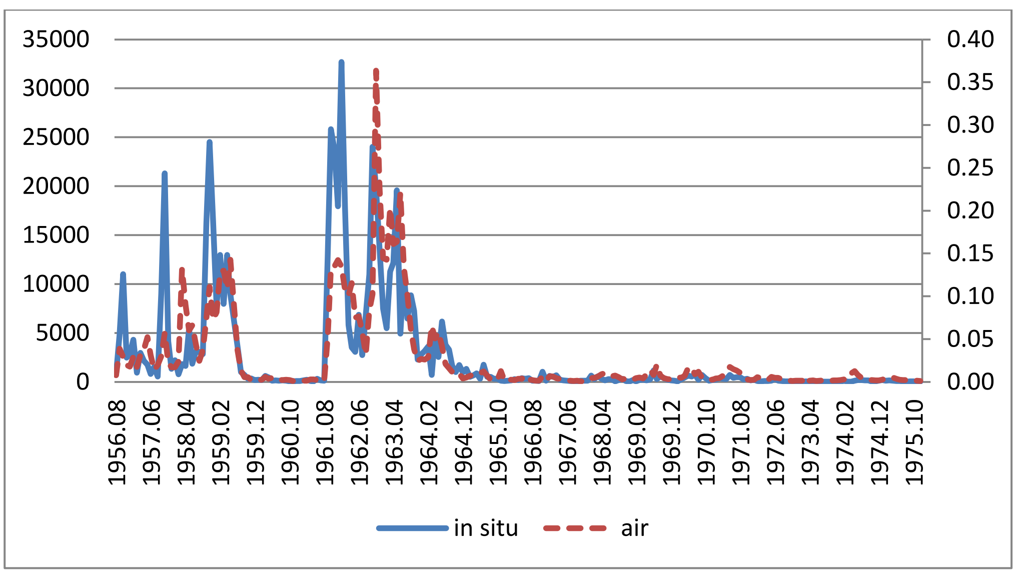
Source: Bergan (2002)

Figure 2a: Monthly Total Beta Fallout in Oslo (in situ and air).



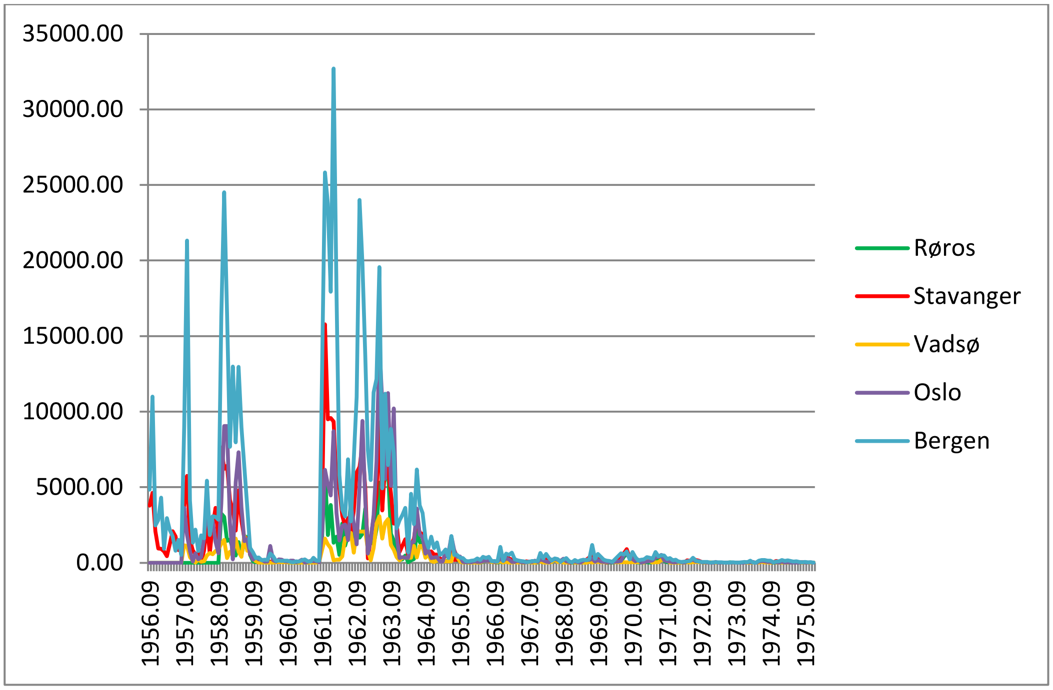
Source: Bergan (2002)

Figure 2b: Monthly Total Beta Fallout in Bergen (in situ and air).



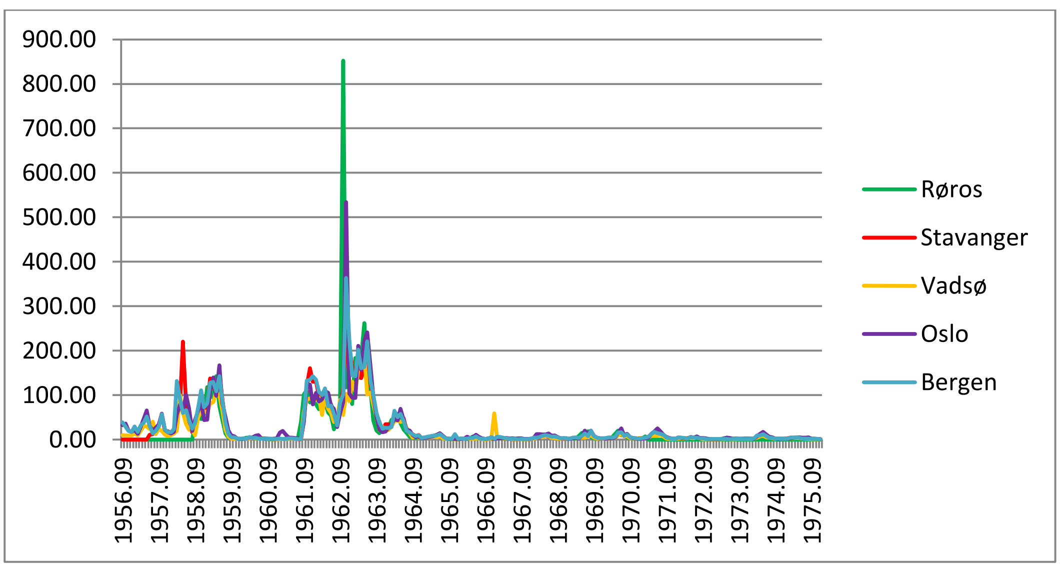
Source: Bergan (2002)

Figure 3a: Monthly Total Beta in situ fallout in 5 Norwegian cities from 1956 to 1975.



Source: Bergan (2002)

Figure 3b: Monthly Total Beta fallout in air in 5 Norwegian cities from 1956 to 1975.



Source: Bergan (2002)

Table 1: Summary statistics

	Men (20km Sample)		Men (All)		Women (20km Sample)		Women (All)	
	Mean	Standard deviation	Mean	Standard deviation	Mean	Standard deviation	Mean	Standard deviation
Control variables								
Father high school degree	0.425	0.494	0.301	0.458	0.417	0.493	0.296	0.457
Mother high school degree	0.326	0.469	0.229	0.420	0.319	0.466	0.225	0.417
Unemployment rate at birth	0.010	0.009	0.013	0.009	0.010	0.009	0.013	0.009
Birth year	1961	3.121	1961	3.152	1961	3.169	1961	3.188
Radioactive fallout								
Mean monthly. Total Beta air (Bq/m^3)	0.042	0.059			0.042	0.059		
Total month. Total Beta ground (kBq/m^2)	2.532	3.789			2.537	3.810		
Outcome variables								
IQ at age 18 (scale: 1-9)	5.264	1.995	5.011	1.999				
Height at age 18 in cm	179.7	6.376	179.4	6.387				
Years of education	12.34	2.609	12.11	2.482	12.36	2.663	12.15	2.591
High school completed	0.731	0.443	0.714	0.452	0.682	0.466	0.653	0.476
Earnings at age 35 in NOK	150146	108704	140258	102672	83191	59831	78658	55350
Number of observations	100354		297947		102373		305347	

Table 2: Effect of Fallout in situ on Various Outcomes for Men

	1	2	3	4
Total beta				
IQ	-0.053**	-0.048**	-0.074**	-0.058**
	0.015	0.014	0.025	0.013
Height	0.012	0.010	-0.066	-0.053
	0.028	0.029	0.041	0.029
ED	-0.136**	-0.135**	-0.213**	-0.097**
	0.036	0.033	0.055	0.031
HS	-0.008**	-0.007**	-0.012**	-0.001
	0.003	0.002	0.003	0.003
Log Earnings	-0.009*	-0.011**	-0.017**	0.008
	0.003	0.003	0.003	0.005
Log (beta)				
IQ	-0.142**	-0.143**	-0.255**	-0.101**
	0.023	0.023	0.032	0.023
Height	-0.022	-0.018	-0.193*	-0.089
	0.058	0.061	0.073	0.063
ED	-0.398**	-0.397**	-0.703**	-0.177**
	0.053	0.054	0.084	0.061
HS	-0.026**	-0.026**	-0.044**	-0.002
	0.005	0.005	0.007	0.005
Log Earnings	-0.024**	-0.024**	-0.041**	0.009
	0.005	0.006	0.008	0.007
Controls				
Muni Dummies	x	x	x	
Yob*mob	x	x	x	X
Municipality-Specific time Trends		x		
Muni * yob dummies			x	
Muni * mob dummies			x	
Family Fixed Effects				X

The sample includes persons born between 1956 and 1966 and includes municipalities within a radius of 20km of the test stations. Total beta in situ refers to ground deposition measured in kBq/m^2 during months 3 and 4 in utero (the average value over the two months). The fallout measure is standardized to mean zero and standard deviation 1.

Each estimate comes from a separate regression. Also included in each specification are controls for parental education, birth order, and the municipality unemployment rate.

Standard errors are clustered at the municipality level.

** implies significant at the 1% level. * implies significant at 5% level

Table 3: Effect of Fallout in situ on Various Outcomes for Women

	1	2	3	4
Total beta				
ED	-0.175**	-0.175**	-0.248**	-0.140**
	0.043	0.041	0.067	0.032
HS	-0.015**	-0.015**	-0.023**	-0.013**
	0.005	0.004	0.006	0.004
Log Earnings	-0.024**	-0.023**	-0.028**	-0.035**
	0.005	0.005	0.007	0.008
Log (beta)				
ED	-0.448**	-0.448**	-0.762**	-0.238**
	0.043	0.045	0.076	0.053
HS	-0.035**	-0.035**	-0.059**	-0.018**
	0.005	0.005	0.008	0.005
Log Earnings	-0.046**	-0.047**	-0.071**	-0.049**
	0.006	0.006	0.008	0.008
Controls				
Muni Dummies	x	x	x	
Yob*mob	x	x	x	X
Municipality-Specific time Trends		x		
Muni * yob dummies			x	
Muni * mob dummies			x	
Family Fixed Effects				X

The sample includes persons born between 1956 and 1966 and includes municipalities within a radius of 20km of the test stations. Total beta in situ refers to ground deposition measured in kBq/m^2 during months 3 and 4 in utero (the average value over the two months). The fallout measure is standardized to mean zero and standard deviation 1.

Each estimate comes from a separate regression. Also included in each specification are controls for parental education, birth order, and the municipality unemployment rate.

Standard errors are clustered at the municipality level.

** implies significant at the 1% level. * implies significant at 5% level

Table 4: Effect of Fallout in the Air on Various Outcomes for Men

	1	2	3	4
Total beta				
IQ	-0.160**	-0.156**	-0.190**	-0.121**
	0.044	0.043	0.059	0.028
Height	-0.056	-0.057	-0.094	0.001
	0.044	0.046	0.066	0.067
ED	-0.393**	-0.389**	-0.489**	-0.323**
	0.091	0.090	0.125	0.067
HS	-0.029**	-0.028**	-0.034**	-0.019**
	0.006	0.006	0.008	0.006
Log Earnings	-0.011	-0.012	-0.019*	-0.006
	0.007	0.007	0.008	0.006
Log (beta)				
IQ	-0.295**	-0.298**	-0.447**	-0.237**
	0.036	0.035	0.067	0.026
Height	-0.277**	-0.270**	-0.410**	-0.235*
	0.075	0.075	0.085	0.111
ED	-0.874**	-0.882**	-1.338**	-0.706**
	0.095	0.094	0.195	0.069
HS	-0.064**	-0.064**	-0.091**	-0.043**
	0.005	0.004	0.010	0.006
Log Earnings	-0.038**	-0.039**	-0.070**	-0.013
	0.009	0.009	0.012	0.011
Controls				
Muni Dummies	x	x	x	
Yob*mob	x	x	x	x
Municipality-Specific time Trends		x		
Muni * yob dummies			x	
Muni * mob dummies			x	
Family Fixed Effects				x

The sample includes persons born between 1956 and 1966 and includes municipalities within a radius of 20km of the test stations. Total beta in air refers to air deposition measured in kBq/m^3 during months 3 and 4 in utero (the average value over the two months). The fallout measure is standardized to mean zero and standard deviation 1.
Each estimate comes from a separate regression. Also included in each specification are controls for parental education, birth order, and the municipality unemployment rate.
Standard errors are clustered at the municipality level.
** implies significant at the 1% level. * implies significant at 5% level

Table 5: Effect of Fallout in the Air on Various Outcomes for Women

	1	2	3	4
Total beta				
ED	-0.369**	-0.371**	-0.466**	-0.284**
	0.106	0.106	0.142	0.086
HS	-0.033**	-0.032**	-0.040**	-0.028**
	0.010	0.010	0.012	0.009
Log Earnings	-0.029**	-0.029**	-0.030**	-0.033**
	0.010	0.009	0.011	0.009
Log (beta)				
ED	-0.839**	-0.852**	-1.320**	-0.675**
	0.106	0.105	0.216	0.067
HS	-0.070**	-0.071**	-0.113**	-0.057**
	0.007	0.007	0.013	0.008
Log Earnings	-0.055**	-0.055**	-0.089**	-0.067**
	0.008	0.009	0.014	0.012
Controls				
Muni Dummies	x	X	x	
Yob*mob	x	X	x	X
Municipality-Specific time Trends		X		
Muni * yob dummies			x	
Muni * mob dummies			x	
Family Fixed Effects				X

The sample includes persons born between 1956 and 1966 and includes municipalities within a radius of 20km of the test stations. Total beta in air refers to air deposition measured in kBq/m^3 during months 3 and 4 in utero (the average value over the two months). The fallout measure is standardized to mean zero and standard deviation 1.
Each estimate comes from a separate regression. Also included in each specification are controls for parental education, birth order, and the municipality unemployment rate.
Standard errors are clustered at the municipality level.
** implies significant at the 1% level. * implies significant at 5% level

Table 6: Controlling for Both Fallout Types

	Men					Women		
	(1) IQ	(2) Height	(3) Years of education	(4) High school completed	(5) Log earnings 35	(6) Years of education	(7) High school completed	(8) Log earnings 35
Total Beta in situ	-0.037**	0.018	-0.098**	-0.005**	-0.007*	-0.140**	-0.012**	-0.022**
	0.012	0.028	0.025	0.002	0.003	0.039	0.004	0.005
Total Beta in Air	-0.151**	-0.061	-0.367**	-0.028**	-0.009	-0.337**	-0.031**	-0.024**
	0.041	0.045	0.079	0.006	0.007	0.093	0.009	0.009
Obs	88446	92793	93275	93723	86544	95781	96288	83509

The sample includes persons born between 1956 and 1966 and includes municipalities within a radius of 20km of the test stations. Total beta in air refers to air deposition measured in kBq/m^3 during months 3 and 4 in utero (the average value over the two months). Total beta in situ refers to ground deposition measured in kBq/m^2 during months 3 and 4 in utero (the average value over the two months). The fallout measures are standardized to mean zero and standard deviation 1.

Each set of estimates (column) comes from a separate regression with controls for municipality dummies and year of birth by month of birth dummies. Also included in each specification are controls for parental education, birth order, and the municipality unemployment rate.

Standard errors are clustered at the municipality level.

** implies significant at the 1% level. * implies significant at 5% level

Table 7: Quintile of Fallout, in situ and in air

	Men					Women		
	(1) IQ	(2) Height	(3) Years of education	(4) High school completed	(5) Log earnings 35	(6) Years of education	(7) High school completed	(8) Log earnings 35
Total Beta in situ								
Quintile 2	-0.112	0.012	-0.187	-0.015	-0.022	-0.122	-0.022	-0.019
	0.059	0.110	0.106	0.009	0.019	0.125	0.012	0.015
Quintile 3	-0.116	-0.065	-0.422**	-0.029**	-0.028	-0.271	-0.039	-0.023
	0.059	0.150	0.132	0.011	0.015	0.239	0.020	0.030
Quintile 4	-0.264**	-0.163	-0.560**	-0.034**	-0.046*	-0.610**	-0.054**	-0.073**
	0.059	0.194	0.125	0.011	0.018	0.215	0.020	0.028
Quintile 5	-0.373**	-0.060	-0.992**	-0.069**	-0.053*	-1.005**	-0.081**	-0.091**
	0.045	0.210	0.096	0.011	0.021	0.201	0.021	0.036
Total Beta in air								
Quintile 2	-0.090	-0.101	-0.192	-0.021	-0.024	-0.145	-0.039	-0.033
	0.046	0.136	0.118	0.013	0.014	0.119	0.029	0.020
Quintile 3	-0.160	-0.296	-0.469**	-0.043*	-0.048	-0.308	-0.043*	-0.046
	0.090	0.178	0.218	0.021	0.028	0.239	0.021	0.025
Quintile 4	-0.279**	-0.446	-0.636**	-0.067**	-0.069*	-0.780**	-0.077**	-0.058*
	0.116	0.243	0.308	0.027	0.030	0.310	0.028	0.029
Quintile 5	-0.504**	-0.678*	-1.097**	-0.109**	-0.083*	-1.176**	-0.111**	-0.101**
	0.164	0.302	0.423	0.030	0.037	0.439	0.039	0.034
N	94649	99367	99850	100332	92778	101783	102343	88633

The sample includes persons born between 1956 and 1966 and includes municipalities within a radius of 20km of the test stations. Total beta in air refers to air deposition measured in kBq/m^3 during months 3 and 4 in utero (the average value over the two months). Total beta in situ refers to ground deposition measured in kBq/m^2 during months 3 and 4 in utero (the average value over the two months). The fallout measures are standardized to mean zero and standard deviation 1.
Each set of quintile estimates comes from a separate regression with controls for municipality dummies and year of birth by month of birth dummies. Also included in each specification are controls for parental education, birth order, and the municipality unemployment rate.
Standard errors are clustered at the municipality level.
** implies significant at the 1% level. * implies significant at 5% level

Table 8: Interaction with Season of Exposure (Summer: April - September)

	(1) IQ	(2) Height	(3) Years of education	(4) High school completed	(5) Log earnings 35	(6) Years of education	(7) High school completed	(8) Log earnings 35
Total Beta in situ								
Total beta in situ	-0.041**	0.029	-0.105**	-0.006**	-0.006	-0.131**	-0.010**	-0.019**
	0.011	0.030	0.022	0.002	0.004	0.024	0.003	0.004
Summer	0.196	0.040	0.135	0.025	0.025	-0.076	0.022	0.074
	0.117	0.476	0.104	0.024	0.048	0.126	0.021	0.054
Interaction term	-0.106**	-0.154*	-0.276**	-0.018**	-0.020	-0.402**	-0.044**	-0.040**
	0.020	0.072	0.060	0.005	0.011	0.047	0.006	0.014
Total Beta in air								
Total beta in air	-0.113**	0.001	-0.234**	-0.018**	0.002	-0.220**	-0.019**	-0.021*
	0.037	0.045	0.065	0.006	0.006	0.077	0.007	0.009
Summer	0.140	0.062	-0.291	-0.039	0.026	-0.030	-0.003	-0.017
	0.111	0.521	0.252	0.048	0.047	0.206	0.021	0.060
Interaction	-0.238**	-0.283*	-0.794**	-0.055**	-0.065**	-0.814**	-0.077**	-0.043*
	0.068	0.118	0.173	0.014	0.021	0.149	0.009	0.021
N	94649	99367	99850	100332	92778	101783	102343	88633

The sample includes persons born between 1956 and 1966 and includes municipalities within a radius of 20km of the test stations. Total beta in air refers to air deposition measured in kBq/m^3 during months 3 and 4 in utero (the average value over the two months). Total beta in situ refers to ground deposition measured in kBq/m^2 during months 3 and 4 in utero (the average value over the two months). The fallout measures are standardized to mean zero and standard deviation 1.
Each set of estimates comes from a separate regression with controls for municipality dummies and year of birth by month of birth dummies. Also included in each specification are controls for parental education, birth order, and the municipality unemployment rate.
Standard errors are clustered at the municipality level.
** implies significant at the 1% level. * implies significant at 5% level

Table 9: Interaction with Mother's Education

	Men					Women		
	(1) IQ	(2) Height	(3) Years of education	(4) High school completed	(5) Log earnings 35	(6) Years of education	(7) High school completed	(8) Log earnings 35
Total Beta in situ	-0.050**	0.021	-0.111**	-0.008**	-0.007	-0.164**	-0.015**	-0.023**
	0.013	0.031	0.032	0.002	0.004	0.040	0.005	0.005
Mother has	1.019**	1.006**	1.362**	0.144**	0.106**	1.470**	0.178**	0.164**
high school	0.021	0.036	0.044	0.005	0.005	0.025	0.004	0.008
Interaction term	-0.010	-0.033	-0.096**	-0.003	-0.006	-0.045*	0.000	-0.001
	0.009	0.057	0.026	0.003	0.005	0.022	0.002	0.004
Total Beta air	-0.158**	-0.053	-0.371**	-0.029**	-0.008	-0.363**	-0.034**	-0.030**
	0.042	0.047	0.084	0.006	0.007	0.104	0.010	0.011
Mother has	1.017**	1.004**	1.355**	0.144**	0.105**	1.468**	0.177**	0.165**
high school	0.022	0.036	0.049	0.005	0.005	0.029	0.004	0.008
Interaction term	-0.007	-0.010	-0.079*	0.001	-0.010	-0.024	0.001	0.005
	0.015	0.039	0.030	0.004	0.006	0.022	0.002	0.007
Observations	89892	94339	94827	95280	88024	95781	96288	83509

The sample includes persons born between 1956 and 1966 and includes municipalities within a radius of 20km of the test stations. Total beta in air refers to air deposition measured in kBq/m^3 during months 3 and 4 in utero (the average value over the two months). Total beta in situ refers to ground deposition measured in kBq/m^2 during months 3 and 4 in utero (the average value over the two months). The fallout measures are standardized to mean zero and standard deviation 1.
Each set of estimates comes from a separate regression with controls for municipality dummies and year of birth by month of birth dummies. Also included in each specification are controls for parental education, birth order, and the municipality unemployment rate.
Standard errors are clustered at the municipality level.
** implies significant at the 1% level. * implies significant at 5% level

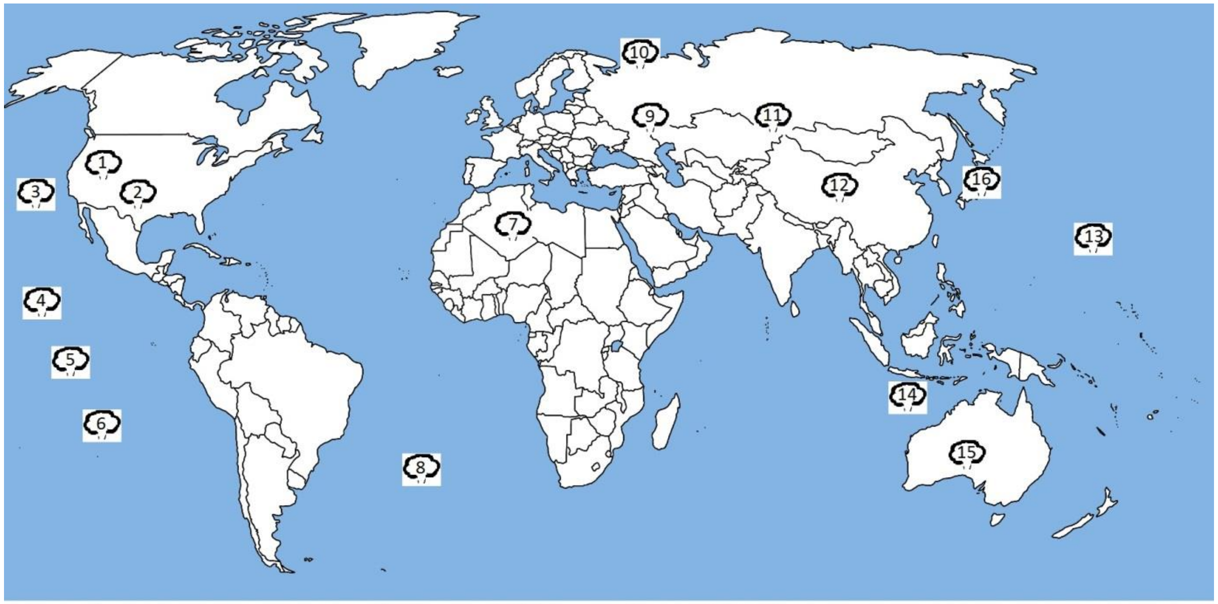
Table 10: Effects of Fallout Including Multiple Months at Same Time

	Men					Women		
	(1) IQ	(2) Height	(3) Years of education	(4) High school completed	(5) Log earnings 35	(6) Years of education	(7) High school completed	(8) Log earnings 35
Beta in situ								
Total Beta in situ 3&4	-0.060**	-0.011	-0.164**	-0.010**	-0.010**	-0.198**	-0.018**	-0.027**
	0.016	0.031	0.038	0.002	0.003	0.052	0.006	0.006
Total Beta in situ 5&6	0.018	0.055	0.029	0.002*	0.003	0.057	0.006	0.007
	0.018	0.030	0.024	0.001	0.005	0.035	0.004	0.004
Beta in air								
Total Beta air 3&4	-0.163**	-0.066	-0.398**	-0.029**	-0.010	-0.376**	-0.034**	-0.029**
	0.044	0.045	0.092	0.007	0.008	0.106	0.010	0.010
Total Beta air 5&6	-0.021	-0.083	-0.035	-0.002	0.010	-0.049	-0.006	-0.001
	0.015	0.044	0.023	0.003	0.008	0.030	0.004	0.008
Observations	89892	94339	94827	95280	88024	95781	96288	83509

The sample includes persons born between 1956 and 1966 and includes municipalities within a radius of 20km of the test stations. Total beta in air refers to air deposition measured in kBq/m^3 during months 3 and 4 (or 5 and 6) in utero (the average value over the two months). Total beta in situ refers to ground deposition measured in kBq/m^2 during months 3 and 4 (or 5 and 6) in utero (the average value over the two months). The fallout measures are standardized to mean zero and standard deviation 1.
Each set of estimates comes from a separate regression with controls for municipality dummies and year of birth by month of birth dummies. Also included in each specification are controls for parental education, birth order, and the municipality unemployment rate.
Standard errors are clustered at the municipality level.
** implies significant at the 1% level. * implies significant at 5% level

Appendix

Figure A1: Location of Atmospheric Nuclear Test Sites



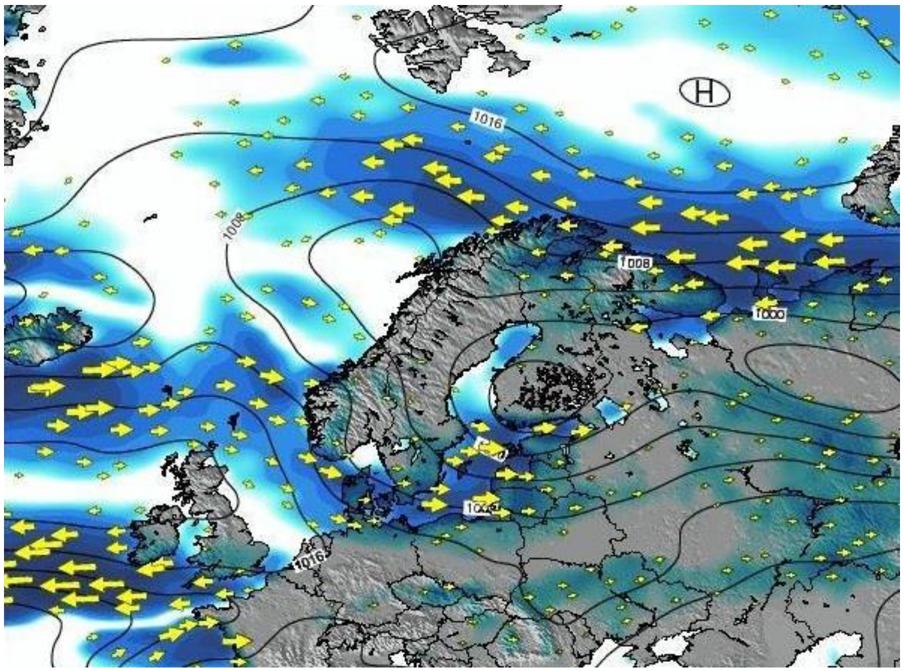
1 Nevada, USA 1951-62
2 New Mexico, USA 9145
3 Pacific, USA 1955-62
4 Johnson Island, USA 1958-62
5 Malden Island & Christmas Island, UK 1957-58 & USA 1962
6 Fangataufa & Mururoa, France 1966-74
7 Algeria, France 1950-61
8 Atlantic, USA 1958
9 Aralsk & Kapustin Yar, USSR 1957-62
10 Novaya Zemlya, USSR 1955-62
11 Semipalatinsk, USSR 1947-62
12 Lop Nor, China 1964-80
13 Bikini & Eniwetak, USA 1946-58
14 Monte Bello Island, UK 1952-56
15 Emu & Maralinga, UK 1963
16 Hiroshima & Nagasaki, USA 1945 (Combat)

Source: Bergan, 2002

Figure A2: Test Site in Novaya Zemlya (Russia)

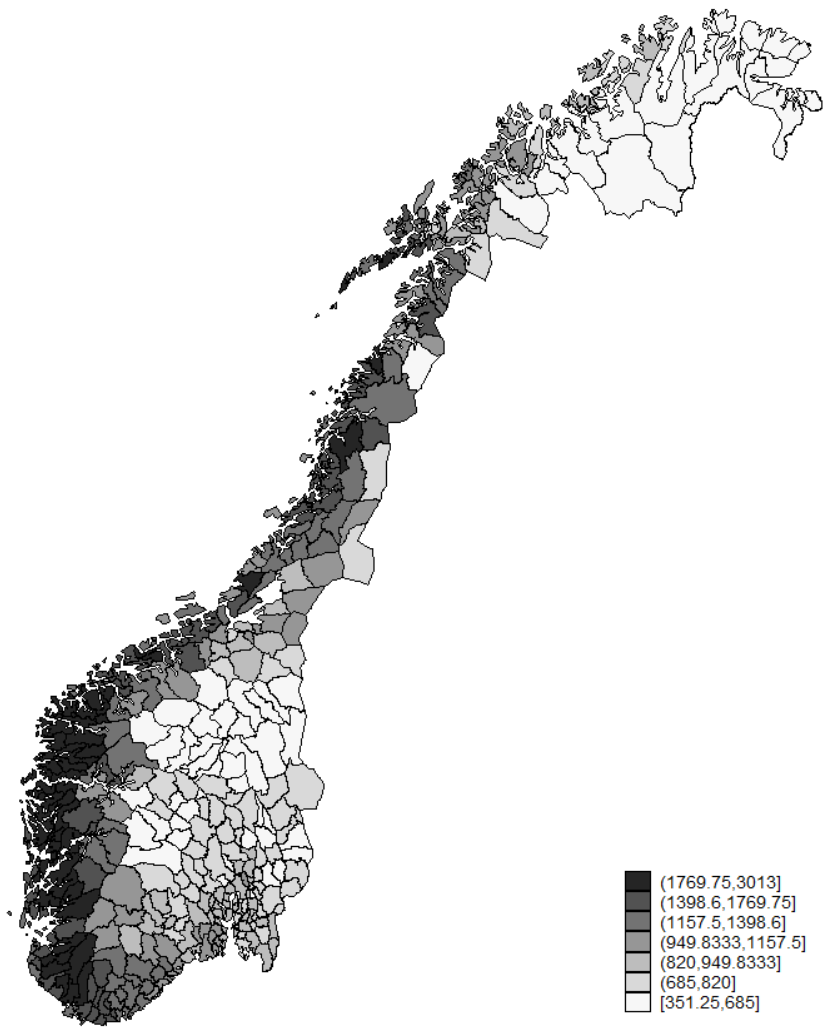
Source: Google Earth

Figure A3: Macro Weather System



Source: www.weather-forecast.com

Figure A4: Annual Precipitation per Municipality



Source: Norwegian Meteorological Institute

Appendix Table A1: Atmospheric nuclear weapon tests

Country	Time period	Atmospheric	Total tests
France	1960-1974	45	205
China	1964-1980	22	44
Soviet	1949-1962	216	1093
Great Britain	1952-1953	21	45
USA	1945-1962	192	1132

Table A2: OLS Results on Fixed Effects Sample

	Men					Women		
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	IQ	Height	Years of education	High school completed	Log earnings 35	Years of education	High school completed	Log earnings 35
Total Beta in situ	-0.051**	-0.014	-0.144**	-0.009**	-0.007	-0.165**	-0.013**	-0.024**
	0.012	0.022	0.029	0.002	0.005	0.038	0.005	0.006
Total Beta in Air	-0.147**	0.040	-0.376**	-0.025**	-0.009	-0.322**	-0.031**	-0.028**
	0.034	0.067	0.073	0.006	0.007	0.091	0.010	0.009
Observations	54164	56968	57225	57523	53308	57812	58139	50543

Table A3: Total Beta Fallout (in situ) by Month

	Men					Women		
	(1) IQ	(2) Height	(3) Years of education	(4) High school completed	(5) Log earnings 35	(6) Years of education	(7) High school completed	(8) Log earnings 35
Pregnancy month 1	-0.0030	-0.0135	0.0018	-0.0005	-0.0008	-0.0067	0.0012	0.0040
	0.0035	0.0257	0.0078	0.0015	0.0022	0.0055	0.0016	0.0029
Pregnancy month 2	-0.0087	-0.0110	-0.0060	-0.0013	0.0013	-0.0008	-0.0060	0.0045
	0.0064	0.0203	0.0122	0.0015	0.0026	0.0076	0.0019	0.0028
Pregnancy month 3	-0.0135*	-0.0089	-0.0096**	-0.0019	-0.0083**	-0.0181**	-0.0076**	-0.0076*
	0.0052	0.0252	0.0033	0.0011	0.0024	0.0049	0.0018	0.0036
Pregnancy month 4	-0.0159**	-0.0066	-0.0103**	-0.0041**	-0.0040*	-0.0129*	-0.0027**	-0.0073*
	0.0045	0.0353	0.0036	0.0016	0.0020	0.0053	0.0019	0.0032
Pregnancy month 5	-0.0161**	-0.0277	-0.0096	0.0003	0.0033	-0.0212	-0.0001	-0.0036
	0.0068	0.0164	0.0108	0.0012	0.0031	0.0120	0.0010	0.0046
Pregnancy month 6	-0.0087	0.0107	0.0056	-0.0001	-0.0009	-0.0085	-0.0023	-0.0060
	0.0064	0.0168	0.0068	0.0013	0.0030	0.0073	0.0018	0.0041
Pregnancy month 7	0.0015	0.0044	0.0044	-0.0002	0.0010	-0.0101	-0.0016	0.0015
	0.0055	0.0178	0.0055	0.0019	0.0027	0.0091	0.0012	0.0032
Pregnancy month 8	-0.0029	0.0077	0.0083	-0.0002	0.0020	-0.0081	0.0004	-0.0004
	0.0067	0.0168	0.0066	0.0011	0.0020	0.0046	0.0012	0.0044
Pregnancy month 9	0.0081	0.0148	-0.0009	-0.0007	-0.0012	-0.0155	-0.0019	0.0003
	0.0046	0.0206	0.0062	0.0009	0.0031	0.0067	0.0014	0.0021
Month of birth	0.0115	0.0203	-0.0018	0.0001	-0.0018	-0.0130	-0.0019	0.0058
	0.0066	0.0216	0.0083	0.0015	0.0021	0.0044	0.0016	0.0030
After pregnancy 1	-0.0042	-0.0037	-0.0023	0.0020	0.0006	-0.0105	-0.0003	-0.0018
	0.0086	0.0129	0.0049	0.0018	0.0020	0.0074	0.0016	0.0031
After pregnancy 2	-0.0118	0.0133	-0.0137	-0.0001	0.0002	-0.0019	-0.0005	-0.0039
	0.0067	0.0195	0.0073	0.0008	0.0025	0.0039	0.0015	0.0023
After pregnancy 3	-0.0126	-0.0077	-0.0041	-0.0014	-0.0017	-0.0046	-0.0012	-0.0009
	0.0072	0.0147	0.0049	0.0009	0.0019	0.0046	0.0009	0.0024
Observations	89892	94339	95280	95280	88024	95781	96288	83509

* p<0.05, ** p<0.01

Table A4: Total Beta Fallout (Air) by Month

	Men					Women		
	(1) IQ	(2) Height	(3) Years of education	(4) High school completed	(5) Log earnings 35	(6) Years of education	(7) High school completed	(8) Log earnings 35
Pregnancy month 1	-0.0110	0.0113	0.0019	-0.0018	-0.0017	-0.0004	-0.0005	0.0017
	0.0049	0.0332	0.0123	0.0013	0.0033	0.0007	0.0014	0.0041
Pregnancy month 2	-0.0090	-0.0147	-0.0103	0.0014	0.0027	-0.0043	-0.0006	0.0004
	0.0076	0.0199	0.0075	0.0022	0.0021	0.0048	0.0012	0.0024
Pregnancy month 3	-0.0165*	0.0234	-0.0144**	-0.0044**	-0.0054*	-0.0133**	-0.0049**	-0.0078*
	0.0069	0.0201	0.0045	0.0016	0.0026	0.0057	0.0013	0.0036
Pregnancy month 4	-0.0197*	0.0320	-0.0244**	-0.0053**	-0.0076**	-0.0145**	-0.0062**	-0.0075*
	0.0082	0.0207	0.0074	0.0013	0.0029	0.0063	0.0019	0.0033
Pregnancy month 5	-0.0134**	0.0281	0.0026	-0.0010	0.0022	-0.0022	-0.0004	-0.0013
	0.0081	0.0356	0.0065	0.0012	0.0026	0.0049	0.0015	0.0030
Pregnancy month 6	0.0072	-0.0468	-0.0012	-0.0003	-0.0026	-0.0056	-0.0011	0.0042
	0.0086	0.0333	0.0075	0.0009	0.0025	0.0057	0.0012	0.0040
Pregnancy month 7	0.0032	-0.0577**	0.0115	-0.0002	-0.0035	0.0008	-0.0016	-0.0023
	0.0094	0.0178	0.0087	0.0019	0.0027	0.0064	0.0012	0.0037
Pregnancy month 8	-0.0006	-0.0048	0.0083	-0.0017	0.0010	-0.0064	0.0023	-0.0059
	0.0060	0.0251	0.0066	0.0016	0.0020	0.0074	0.0012	0.0030
Pregnancy month 9	-0.0040	0.0608	-0.0058	0.0031	-0.0002	-0.0062	-0.0013	0.0003
	0.0063	0.0280	0.0087	0.0017	0.0031	0.0116	0.0022	0.0046
Month of birth	-0.0083	-0.0380	0.0010	0.0012	-0.0013	-0.0115	-0.0025	0.0026
	0.0087	0.0224	0.0081	0.0020	0.0025	0.0007	0.0024	0.0050
After pregnancy 1	-0.0016	-0.0023	-0.0069	-0.0021	0.0061	-0.0114	-0.0004	-0.0006
	0.0071	0.0158	0.0050	0.0011	0.0022	0.0078	0.0016	0.0037
After pregnancy 2	-0.0131	0.0128	-0.0148	-0.0011	0.0030	-0.0006	-0.0008	-0.0033
	0.0080	0.0339	0.0075	0.0010	0.0051	0.0103	0.0017	0.0044
After pregnancy 3	-0.0125	-0.0072	-0.0078	-0.0022	0.0020	-0.0066	-0.0004	-0.0079
	0.0073	0.0204	0.0080	0.0013	0.0034	0.0125	0.0018	0.0048
Observations	94649	99367	99850	100332	92778	94018	94511	88633

* p<0.05, ** p<0.01