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CHERNOBYL'S SUBCLINICAL LEGACY: PRENATAL EXPOSURE TO RADIOACTIVE FALLOUT AND SCHOOL OUTCOMES IN SWEDEN

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Chernobyl's Subclinical Legacy: Prenatal Exposure to Radioactive Fallout and School Outcomes in Sweden
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ABSTRACT

Japanese atomic bomb survivors irradiated 8-25 weeks after ovulation subsequently suffered reduced IQ [Otake and Schull, 1998]. Whether these findings generalize to low doses (less than 10 mGy) has not been established. This paper exploits the natural experiment generated by the Chernobyl nuclear accident in April 1986, which caused a spike in radiation levels in Sweden. In a comprehensive data set of 562,637 Swedes born 1983-1988, we find that the cohort in utero during the Chernobyl accident had worse school outcomes than adjacent birth cohorts, and this deterioration was largest for those exposed approximately 8-25 weeks post conception. Moreover, we find larger damage among students born in regions that received more fallout: students from the eight most affected municipalities were 3.6 percentage points less likely to qualify to high school as a result of the fallout. Our findings suggest that fetal exposure to ionizing radiation damages cognitive ability at radiation levels previously considered safe.

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1 Introduction and Motivation

This paper studies the school performance of Swedish children *in utero* during the Chernobyl (Ukraine) nuclear accident on April 26, 1986.

Japanese A-bomb survivors irradiated *in utero* at post-ovulatory ages 8-25 weeks subsequently suffered reduced IQ: 25-30 points per Gy for those exposed at post-ovulatory ages 8-15 weeks [Otake and Schull, 1998]. Whether these findings generalize to doses less than 10 mGy has not been established [Hall and Giaccia, 2005, BEIR, 2006]. The existence of various sources of very low-level ionizing radiation (e.g., radon) makes this a public health question of general and continuing relevance.

The ideal study of the effects of low dose radiation would assign doses randomly, an approach that is not feasible for ethical and practical reasons, the latter because for low doses, effects are presumably correspondingly small and thus require a large sample size to be detected [Brenner et al., 2003].

The Chernobyl accident provides a nearly ideal natural experiment in radiation exposure. Deposition occurred between April 27 and May 10 in Sweden [Moberg, 1991], creating a pronounced spike in radiation levels. For example, Figure 1 shows measured gamma radiation in Umeå, 400 miles north of Stockholm, which jumped more than ten-fold at the end of April, 1986. Differences in rainfall immediately after the accident caused substantial geographic variation in deposition [Holmberg et al., 1988]. The northern parts of Sweden were virtually spared, while near the cities of Gävle and Sundsvall, located on the Baltic sea about midway between the northern and southern most points of the country, ground deposition of Caesium-137 averaged 44 kBq/m^2 (Table 1, also see Figure 2).[1] This feature of the research design enables us to compare within cohorts, and assess whether regional variation in fallout predicts the magnitude of damage to the cohort between weeks 8 and 25 post-conception at the time of Chernobyl, holding constant other regionally-varying determinants of students outcomes, observed and unobserved (e.g., differences in parents' cognitive skills by county).

We evaluate student outcomes in a comprehensive data set on virtually all Swedes born 1983-1988 – some 562,637 individuals – measuring performance in the final year of compulsory schooling. These data also record the month and place of birth, which we use to link student outcomes to average Chernobyl deposition by region, measured aerially by the Swedish Geological Co. in the accident's aftermath.

We find that the cohort of likely fetal age 8-25 weeks post conception during the accident and born in one of the eight most affected municipalities was 4% less likely to qualify to high school (or equivalently, were 40% more likely to fail middle school). Grade point averages were 5% lower. Moreover, students born in regions with more modest levels of Chernobyl fallout also registered damage (of correspondingly smaller magnitudes) relative to the least-exposed far north of Sweden. These results are robust to family fixed effects, mitigating selection concerns. Those born

[1] Maximum doses for the Swedish population were estimated at 3-4 mSv in the first year Holmberg et al. [1988], Edvarson [1991a]. For gamma radiation, 1 Gy corresponds to 1 Sv.

February-May 1986, and thus outside the period brain development has been deemed particularly radiosensitive, showed no corresponding damage.

To our knowledge, ours is the first large scale study of the effects of fetal exposure to very low-level ionizing radiation – levels hitherto considered safe and/or having undetectable effects – on school performance.

1.1 Literature review

A series of studies by Otake and Schull (summarized in Otake and Schull [1998]) analyzed the effect of *in utero* exposure to radiation after the Hiroshima and Nagasaki atomic bomb explosions in August, 1945. The sample used in these studies contains information on 1,566 individuals (1,242 in Hiroshima and 324 in Nagasaki) who (prenatally) were closer than 2,000 meters from the hypocenter of the atomic bombs. Two control groups from the same areas were matched on to the sample on the basis of age and sex: one from distally exposed survivors (3,000-4,000 meters from the hypocenter) and one of non-exposed survivors ($>$ 10,000 meters). In addition to some anthropometric measures – such as weight, height and head size – these studies also analyzed cognitive ability (IQ) and school records.

The Otake and Schull studies contain several results of relevance for our analysis. First, they established an effect on both IQ and school records for children exposed between week 8 and 25 post-conception. For children exposed earlier or later, no significant effect were found. Second, the effect was estimated to be linearly increasing in the level of exposure. Third, no conclusive evidence on a threshold level for radiation effects was established.

1.1.1 Chernobyl and Cognitive Outcomes

A number of previous studies have found reduced cognitive functions due to prenatal radiation in high fallout areas of Ukraine, Belarus, and Russia, e.g., Nyahu et al. [1998], Kolominsky et al. [1999], Loganovskaja and Loganovsky [1999]. However, these studies have focussed on populations born near the reactor. As a consequence, they suffer from weaknesses related to the comparability of the treatment and control populations. Along with other potential confounders, the physical dislocation (forced evacuations) of the treated population limits the comparability of the treated and control groups. Moreover, sample sizes have been relatively small.

Nyahu et al. [1998] compared 544 children in Ukraine who lived near the Chernobyl reactor and were *in utero* at the time of the accident to Ukrainian children born in "radioactively clean zones". Despite having similar heights and weights at birth as the control group, prenatally exposed children were more likely to be mentally retarded (IQ $<$ 70) less likely to have a high IQ (>110) and reported more emotional and behavioral problems. However, the fact that mothers of prenatally exposed children also had lower IQ scores, as well as worse mental health, than the control parents undermines the internal validity of the study's conclusions. As Kolominsky et al. [1999, p. 304] noted, "Living in contaminated areas, as well as forced resettlement, lead to the growth of emotional tension of parents."

Other studies have found no or small effects. Litcher et al. [2000] found no effect on school performance from Chernobyl fallout. They studied 300 Ukranian children evacuated from the 30-kilometer zone around Chernobyl, comparing them with "same-sex non-evacuee child[ren] selected from the same classrooms as each evacuee. Thus, they had the same teachers and daily schedule, and resided in similar apartment buildings," Litcher et al. [2000, p. 292]. The exposed children were not significantly different along objective measures including school performance, intelligence, attention, or memory. However, the "treated sample" included children up to age 15 months at the time of the meltdown.

Joseph et al. [2004] studied cognitive and behavioral outcomes of 1,629 children from the former Soviet Union who had subsequently migrated to Israel. The immigrants came from areas that ranged in fallout exposure from 'uncontaminated' to 'highly contaminated.' They did not find evidence of impaired cognitive ability. However, their sample included children up to age 4 years at the time of the accident, meaning that only 270 children were *in utero* during the accident and only 98 of these were from areas with Caesium-137 ground deposition in excess of 37 kBq m^{-2}. Hyperactivity and attention deficit disorder were higher among all children *in utero* at the time (irrespective of area of origin or stage of gestation).

Thus, weak or inconclusive results have prompted the conclusion that Chernobyl damage, if any, reflects anxiety or stress brought on by the economic and social upheaval following the evacuation of the Chernobyl vicinity and the fall of the Soviet Union [Joseph et al., 2004, UNDP/UNICEF, 2002, IAEA, 2006].

1.1.2 Chernobyl and Perinatal Outcomes

In contrast to the cognitive studies, perinatal impacts have been evaluated in areas of Europe with substantially lower levels of Chernobyl fallout. Outcomes including conceptions, spontaneous abortion, induced abortion, stillbirth, gestation length, birth weight, and neonatal mortality have each been studied. For each outcome, studies can be found on either side: some find effects and others do not.

Some of the strongest evidence points to compromised outcomes at birth resulting from Chernobyl. Scherb et al. [1999] studied stillbirths in 18 European countries and found elevated stillbirths following Chernobyl in the more eastern countries of Europe: Poland, Hungary, Sweden, and Greece. Lüning et al. [1989] found increased mortality among infants within the first 7 days of life in West Germany in May of 1986, which the authors attributed to Chernobyl fallout in southern Germany.

Increases in Down's syndrome have been reported from a number of countries, e.g., Belarus [Laziuk et al., 2002], Germany [Sperling et al., 1994], and Sweden [Ericson and Källén, 1994], and has lately been acknowledged by the WHO [2006, p. 87] as Chernobyl related. (Irrradiation of the fetus itself cannot cause Down's syndrome.[2] Thus, cognitive per-

[2]Ericson and Källén [1994, p. 153] "If radioactive fallout causes Down syndrome, it must be in pregnancies where conceptions occurred after the accident – or just before

formance of those irradiated weeks 8-25 post conception is not mediated by Down's syndrome.)

A number of studies have documented adverse perinatal and child health outcomes in Scandinavia. Ericson and Källén [1994] studied the universe of Swedish perinatal outcomes for 1985-1989 and found a slight decrease in conceptions in June 1986, and a statistically significant increase in Down's syndrome among those born in 1987 in all areas with more than 5 kBq m^{-2} Caesium-137 ground deposition. They also recorded three cases of childhood leukemia.[3] In addition, Auvinen et al. [2001] found elevated levels of spontaneous abortions in Finland following Chernobyl.

2 Data

2.1 Radiation Data

We use two measures of radiation exposure: aerial and *in situ* measurements, further described below.

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the accident if mosaic cases are considered (which arise by a nondisjunction in an early mitotic division after conception)."

[3]In addition, no effects were found on the likelihood of short gestation or birth weight below 2,500 grams. The likelihood of birth weight below 1,500 grams was higher in July of 1986 than July 1985, which "could well be random" Ericson and Källén [1994]:149. No change in either low birth weight measure (below 2,500 grams or below 1,500 grams) was found for the birth cohorts for whom we find the largest cognitive effects, see Section 3.

Aerial Measurement The Swedish Geological Co. (SGAB) (commissioned by the Swedish Radiation Protection Authority) conducted aerial measurements of ground deposition gamma-radiation of Caesium-134 over the period May-October 1986 and decay corrected to May 1986.

Caesium-134 was measured because of its stable relationship to Caesium-137 (Cs-137/Cs-134=1.7) and its shorter half life (2 years), allowing for the separation of radiation stemming from atmospheric nuclear weapons tests and that from Chernobyl.

These aerial measurements are available for 2,380 parishes (out of 2,517). A parish is a rather small geographical entity, and for most people, everyday activities would involve crossing parish boundaries. Therefore we also aggregate up to both the municipality and county level.[4] The detailed geographic coverage is a strength of these data.

The aerial measurements, however, suffer from two drawbacks. First, they lacked precision at low levels of ground radiation [Edvarson, 1991b]. Second, they only reflect deposition of Caesium isotopes. While its long half life (30 years) makes Caesium-137 an obvious priority, our focus is on the initial spike in radiation following the accident, for which Iodine-131 was an important contributor [Kjelle, 1991]. This motivates our interest in the *in situ* measurements.

[4] The county (*län*) is the first level administrative and political subdivision. There are 21 counties. The second level is the municipality (*kommun*), and there are 290 municipalities.

***In Situ* Measurement** The Swedish Defence Research Agency (FOA) conducted *in situ* measurements at 63 locations. Figure 3 replicates Edvarson [1991b]:table 2, which displays aerial measurements corrected by *in situ* measurements since "It was found that the SGAB measurements in the low-deposition areas (< 2 kBq/m^2 Cs-134) were higher than FOA *in situ* measurements by a factor of 2-3..." Edvarson [1991b, p. 49].

Comparing Figures 3 and 4 it is clear that Iodine was an important source of radiation in the initial aftermath of Chernobyl. Moreover, both data sources show that the north of Sweden (Norrbotten county) had the lowest levels of Caesium-137 ground deposition: 0.3 kBq m^{-2}.

2.1.1 Regional Groups

Based on the information from the aerial and the *in situ* measurements, we classify Sweden into four groups as detailed in Table 1. Classification at the measured extremes is straight-forward. The areas around Gävle and Sundsvall were particularly hard hit, while Norrbotten county was virtually spared. Consequently, we include in the top group Gävle and Sundsvall and six contiguous municipalities. Together, these eight municipalities registered the highest levels of ground deposition of Caesium-137. As for the control group, R0 (Norrbotten county) is motivated by Edvarson [1991b, table 2], where Norrbotten shows the lowest values of Caesium-137 and Iodine-131 ground deposition.

Norrbotten is, however, a relatively sparsely-populated county. Therefore, we also present results from using a broader control group. Based on Moberg [1991, figure 2], replicated in Figure 4, we extend the control group to also include the counties denoted by R1 (Table 1): Stockholm, Örebro and Värmland.

In sum, while data clearly single out our two extreme groups R0 and R3, the division of the "middle" into R1 and R2 may be viewed as exploratory.

2.1.2 Radiation doses

While we believe the above measurements/regional grouping provide a reasonable ordinal proxy for radiation exposure, there are several reasons why the assignment is imperfect. First, we obviously do not know where the expecting mother was at the time of Chernobyl, only where she was registered at the time of giving birth. Second, we compare those *in utero* at the time of Chernobyl to adjacent cohorts. Earlier cohorts were exposed as infants and later cohorts were exposed to radiation stemming from long lived radionuclides (prenatally and postnatally). Thus, any effect we detect that is unique to the cohort *in utero* must be due to the spike in radiation in the days after the accident. Iodine-131, whose release was 20-100 times that of Caesium, was an important contributor to this initial spike [Moberg, 1991], and only proxied by the Caesium-137 estimates. Third, ground depositions are more quickly washed away in urban areas, therefore it is possible that urban areas received more fallout than indicated by the values in the last two column of Table 1. Fourth, the actual dose a person received depends on a number of factors not captured here. Since these radionuclides enter the food chain, internal irradiation may depend on the local food distribution system and dietary habits (e.g., consumption of milk).

Despite these uncertainties, we are clearly evaluating effects of radiation well below what has been deemed a health hazard and/or having a measurable impact. Radiation levels in Sweden, using the UN classification, ranged from negligible to 'contaminated.'[5] While small compared to what the populations in Ukraine, Belarus and Russia suffered, a study of very low-level exposure is of interest in its own right and for what the results may imply for the risk assessment of other low-level radiation sources, notably indoor radon radiation, and radiation in medical use.

2.2 Student Data

We focus on individuals born 1983-1988. That is, students born three years before the accident through two years after.[6]

We have register data on all persons either born in Sweden 1983-1985 or the children of a Swedish-born parent born in the period 1940-1985. As a result, we have almost universal coverage for cohorts born 1983-1985. For the 1986 birth cohort, we capture everybody who had at least one

[5]Maximum Cs-137 over a square measuring 200 by 200 meters was 156.49 kBq m^{-2}(< 5 Ci km^{-2}).

[6]The reason the later window is shorter is that our graduation data ends with the class of 2004. School entry is in the fall of the calendar year the person turns seven, and compulsory schooling ends with grade nine, normally in spring of the year the person turns 16.

Swedish born parent younger than 46 years (in 1986), and for 1987 and 1988 this age is 47 and 48 respectively. Since fertility is complete for nearly all women by age 45, this means that coverage for the later cohorts is also high.

2.2.1 Cohort groups

We focus on three cohorts as described below.

`inutero` Those born May 1986-February 1987 were arguably *in utero* at the time of the accident. This grouping allows for effects in very early pregnancy through late pregnancy. This broad categorization, however, obscures possible gestational-age differences in sensitivity to irradiation.

`inutero8-25` As mentioned, the literature has identified weeks 8-25 post conception as particularly sensitive to radiation. This motivates singling out those born in the period August through December 1986 as being of a critical age around the time of the accident. The birth interval was determined as follows: Assuming that the radioactive cloud swept Sweden April 27-May 10; and a 38 week post-conception gestation period, this implies that the "treated" group are those born between July 27 and December 13, 1986. Since we only have data on month of birth, we include those born August through December 1986 in our `inutero8-25` cohort.

`inutero0-7` A third group of interest are those born in January and

February 1987. Many of this cohort were 0 to 8 weeks post conception at the time of Chernobyl. We are interested in their school performance since cognitive performance has not been found to be affected by irradiation in this period by previous studies.[7] We will also investigate two other outcomes: cohort size and the sex ratio. Cohort size depends on a number of factors, notably conceptions, term pregnancies and perinatal outcomes. Pre-implantation is the stage most sensitive to the lethal effects of radiation, while irradiation during organogenesis is more likely to result in neonatal death [Hall and Giaccia, 2005, p. 169]. Also, the accident may have influenced fertility decisions both with respect to conceptions and induced abortions. Our interest in the sex ratio is motivated by the observation that the male conceptus and fetus may be more susceptible to radiation, see Schull and Neel [1958], Peterka et al. [2004].

2.2.2 Outcome variables

Qualify HS To qualify to continue to high school, a passing grade is needed in all the core subjects (English, Swedish, and Math). About 90% of students had passing grades in these subjects.

Grade points The sum of grades range from 0 to 320. These are the total grades summed over all subjects in the final year of compulsory school. There are 16 subjects and four grade levels: fail - 0

[7] "Few if any abnormalities are produced by irradiation at this stage" Hall and Giaccia [2005, p. 169].

points, pass - 10 points, pass with distinction - 15 points, and pass with special distinction - 20 points. The mean is approximately 200, and there was a slight positive trend. Grades in core subjects are "curved", that is, reflect relative performance in nationally administered tests. The vast majority of the `inutero8-25` cohort belong to the class graduating in 2002, and this year sees no reduction in average grades.[8]

3 Results

We find damage to cognitive performance as measured by grades in the final year of compulsory education and qualification to continue to high school for those exposed *in utero*. Consistent with the bio-medical literature, we find the effects to be concentrated among those most likely to have been exposed weeks 8-25 post conception. Moreover, the effect is substantially larger in areas with greater Chernobyl fallout.

3.1 Figures

We begin our empirical analysis by presenting the share qualifying to high school by birth cohort in a series of figures. Because there is substantial seasonality in school performance by birth month, we compare those born August-December 1986 against those born in the same months but in adjacent years.

[8]The national averages were 202, 203 and 204 for the classes graduating in 2001, 2002 and 2003 respectively.

Figure 5 compares those in the worst affected area, R3 ("Gävle and Sundsvall", the "treatment group") to the rest of Sweden. The two series track each other fairly closely until 1986, when the share qualifying from R3 drops substantially to produce a 3 percentage point gap.[9] A similar pattern is revealed in Figure 7, where the control group is those born in areas R0 and R1 (Norrbotten, Stockholm, Örebro and Värmland counties). Restricting the control group further to the least affected area, R0 (Norrbotten), shows a qualitatively similar picture, Figure 9. The gap is now larger, at about 5 percentage points, and it is noteworthy that the difference is in part driven by the control group doing better for this particular birth year. We believe this may be related to grades in the core subjects (and thus qualification to high school) being assigned based on nationally standardized test (and a decrease in "raw" scores for most students).

Figures 6, 8, and 10 present the analogous series of figures but for those born between February and May, i.e. cohorts for whom the biomedical literature would <u>not</u> predict effects attributable to radiation. Clearly, the poor performance of the 1986 cohort born in R3 does not extend to the "spring" birth cohort, which reduces the likelihood that geographically-varying effects unrelated to Chernobyl account for the pattern observed for the cohorts exposed between weeks 8 and 25 of gestation.

We now turn to the regression analysis.

[9] The pre-treatment gap in qualification rates in Figure 5 is consistent with the existence of effects on children born prior to Chernobyl and therefore exposed post-natally. We will estimate the *additional* effect attributable to prenatal exposure.

3.2 Regression Analysis

We estimate three basic regression specifications for those born 1983-1988. First, we estimate the departure in school performance for all Swedes *in utero* during Chernobyl:

$$y_i = \beta_0 \times \texttt{I(inutero*)} + \tau_{yob} + \gamma_{mob} + \lambda_{county} + \delta_{sex} + \epsilon_i, \qquad (1)$$

where y_i is the dependent variable of interest, `I(inutero*)` is an indicator variable that takes the value 1 for the cohort of interest (`inutero`, `inutero8-25`) and 0 otherwise; β_0 is the parameter of interest. We include vectors of dummies for year of birth (τ_{yob}), month of birth (γ_{mob}), county of birth (λ_{county}), and gender (δ_{sex}).

Second, we evaluate whether variation in Chernobyl fallout by area within Sweden predicts the magnitude of the departure in outcomes for the exposed cohort:

$$y_i = \beta_0 \times \texttt{I(inutero}*\texttt{)}_i + \sum_{j=1}^{3} \beta_j \times r_j \times \texttt{I(inutero}*\texttt{)}_i + \tau_{yob} + \gamma_{mob} + \lambda_{county} + \rho_{R3} + \delta_{sex} + \epsilon_i, \qquad (2)$$

where y_i is the dependent variable of interest, r_j denotes the three areas exposed to varying degrees by Chernobyl: R1, R2, and R3 (see Table 1). The inclusion of county-of-birth indicators clearly subsumes inclusion of the measured level of Caesium deposition for each county (geographic grouping) along with any other time-invariant county or area-level characteristics. We also include a dummy variable for being born in one of the eight high fallout municipalities, ρ_{R3}. The parameter estimates of interest are $\hat{\beta}_j, j > 0$ and we hypothesize that $\hat{\beta}_3 \leq \hat{\beta}_2 \leq \hat{\beta}_1 < 0$. These parameters measure the extent to which the outcomes for the inutero* children born in the corresponding areas at the time of the accident differ from the inutero* children born in the reference (omitted) area, controlling for all permanent differences between areas.

Our third empirical strategy is to apply the difference-in-differences approach to a sample restricted to siblings (using the unique mother and father identifiers) and compare those presumed exposed to Chernobyl radiation to their siblings.

We focus on the inutero8-25 cohort and estimate equation (2) where we add a vector of indicator variables, one for each family (5,448 in total). (We drop the indicator variable for gender, since we only look at same-sex siblings. County effects are identified by families that report different counties of birth for their children.) We restrict the sample to include only those families with two same-sex full siblings whose fathers were married as of 1990 (to reduce the likelihood that the parents had separated, an event likely to have differential effects on siblings depending on age) where one sibling belonged to the exposed cohort and the other one did not (but was born between 1983 and 1988).

Including these fixed effects is equivalent to differencing the outcomes and regressors of the sibling presumed exposed to Chernobyl fallout from his/her presumed unexposed sibling. Therefore, comparisons of the Chernobyl effect are only made within (and not across) families. As before, if school performance is affected by Chernobyl fallout, we would expect those born between August-December 1986 to perform worse than their siblings, and this difference to be larger for those born in areas that received more fallout.

We estimate equations (1)-(2) for the following two outcomes: (1) whether grades in core subjects (English, Swedish, Math) were sufficient to qualify the individual to continue to high school; and (2) total grades in the final grade of compulsory school.

We employ Ordinary Least Squares (OLS), where standard errors are robust to heteroscedasticity and clustered at the region level.

3.2.1 Regression Results

Table 3 presents estimates of the average departure in outcomes for the cohort *in utero* during the Chernobyl accident, controlling for year, month, and county of birth, and gender (equation (1)). Columns (1) and (3) estimate a "naive" model where we assume that prenatal irradiation affects cognitive development equally irrespective of fetal age. In addition, we consider all Swedes *in utero* during Chernobyl, regardless of place of birth, to be equally exposed. Finally, we consider those not *in utero* to be unexposed. With these assumptions, we find that the probability of qualifying is reduced by 0.2 percentage points for the `inutero` cohort (Column (1)). For grades, we find a 1 unit reduction (Column (3)).

In Columns (2) and (4), we make use of the finding that fetal irradiation 8 to 25 weeks post conception may be especially damaging to cognitive development, and we find a larger reduction in performance for this subgroup. For qualification, this group was 0.6 percentage points less likely to qualify for high school – three times the "naive" estimate. For grades, we find a similar, albeit less dramatic, increase in effect size.[10]

Table 4 assesses whether the apparent damage to the exposed cohorts in Table 3 varies with geographic variation in fallout. Columns (1)-(3) consider the naive model of exposure – that all those born between May 1986 and February 1987 would be equally affected by a given level of fallout (`inutero`). By contrast, columns (4) to (6) only consider the five last months of birth in 1986 (`inutero8-25`).

First, the R3 municipalities consistently show damage when compared to other parts of Sweden. Column (1) compares the effect in R3 municipalities to the rest of Sweden (i.e., the excluded areas are R0, R1, and R2). In Panel A, we see that the `inutero` cohort born in R3 municipalities experienced a .018 drop in the probability of qualification (or roughly 10 times the effect for Sweden as a whole, Table 3). Column 2 now makes comparisons relative to the two least-exposed areas: R0 and R1. We see that the estimated damage to the `inutero` cohort born in the R3 municipalities increases slightly. In addition, the `inutero` cohort born in R2 is estimated to have a slightly larger decrease in qualification rates but this difference is not significantly different from zero. Column (3) repeats this exercise by benchmarking against R0, the least affected area of Sweden. We now find that the `inutero` cohort born in R3 suffered a .033 reduction

[10]Virtually everybody born in 1986 was conceived prior to the Chernobyl accident, and thus there was little scope for potential behavioral responses to Chernobyl with respect to conception.

in the probability of qualifying. Moreover, the R2 `inutero` cohort shows about half the estimated R3 effect, with a slightly smaller effect for the R1 area. Nevertheless, all three exposed areas showed significant damage compared to R0 (Norrbotten).

Panel B, columns (1) through (3), repeat the above exercise with grades as the dependent variable. When comparing to the rest of Sweden, R3 natives of the `inutero` cohort are found to have lower grades: a drop of 2.2 grade units (column (1)). This estimate triples when we compare R3 to the R0 area (column (3)). Again, we find the estimated effect size to correspond to the ordering of fallout.

Columns (4) through (6) restrict attention to the `inutero8-25` cohort. The qualitative pattern is the same as above, but the estimated magnitudes are generally larger. Note that in column (6), we find that the average decrease in qualification rates in R3 municipalities was .036 or 4% relative to R0. In Panel B, the analogous estimate is 10.6 grade units or 5%.

The magnitude of the results for grades can be interpreted as the average treatment effect for the three different fallout levels relative to the `inutero8-25` cohort born in the omitted area (Norrbotten). A change in five grade points corresponds to the difference between pass and pass with distinction in any of the 16 subjects counted in the final grade and a change in 10 grade points corresponds to a one level change in two subjects, or the difference between pass (10 points) and fail (0 points). To give a sense for the importance of such changes in grades, Table 2 shows the percentiles between 40 and 60 in the distribution of grades for those who graduated in 2003. A change in five grade points corresponds, for example, to a change from percentile 46 to 50 or a change from percentile 53 to 56.[11]

In sum, we are finding substantial across-the-board effects for the cohort likely to have been of post-ovulatory age 8-25 weeks at the time of Chernobyl, and the effect is more severe in more exposed areas.

Table 5 reports results when the aerially measured ground deposition of Caesium-137 is entered as a linear term in equation (2). That is, we replace the $\sum_{j=1}^{3} \beta_j \times r_j \times \texttt{I(inutero8-25)}$ term with $\beta_1 \times \texttt{Caesium}_k \times \texttt{I(inutero8-25)}$, where $\texttt{Caesium}_k$ denotes the population-weighted arithmetic mean of Caesium-137 in area k, and k indexes the county, municipality, or parish, respectively.

Consistent with the Table 4 results, we find that higher local radiation predicts larger deteriorations for the August-December birth cohort. Column (1) assigns the average Caesium-137 level in the county of birth to the `inutero8-25` cohort, finding that a 1 kBq m^{-2} increase in Caesium-137 ground deposition reduces the probability of qualification by .053 percentage points. Column (2) and Column (3) assign the municipality- and parish-level Caesium-137 measures to the exposed cohort, and find

[11] As a comparison, in an evaluation of the STAR project, Krueger [1999] found a gain of 4 percentile points for first year students in "small classes" (13-17 students) compared to "regular classes" (22-25 students) on test scores and subsequently a 1 percentile point gain for each year in a small class.

a smaller (though still significant) effect on qualification. Changes to the administrative division means that we lose 12% and 14% of the sample in columns (2) and (3), respectively.

Columns (4) through (6) repeat the above specifications with grades as the dependent variable. While the estimated β_1 is negative for each geographic unit k, only the parish-level Caesium-137 level is significantly different from 0. Column (6) results imply a 0.058 unit reduction in grades for each kBq m^{-2} unit increase in Caesium-137 deposition.

Table 6. Including fixed effects for each family, we find that those born in the high-Caesium-137 deposition areas and exposed prenatally had worse outcomes than their siblings. The `inutero8-25` cohort in the R3 area had a 3 percentage point decrease in probability of qualifying relative to their (older or younger) sibling when the reference group was the rest of Sweden, Column (1). When the R3 group was compared instead to the least exposed R0 area, the estimated effect almost doubled to 5.6 percentage points. Again, the ordering of effect sizes corresponds to the ordering of radiation fallout.

We repeat this exercise for grades and find an analogous pattern The reduction in grades for the sibling `inutero8-25` during Chernobyl was 16.3 points greater in R3 than the same difference in R0.

The existence of effects within families suggests that selection across families into childbearing is not accounting for the effects found in previous tables. In addition, note that the sibling comparison precludes comparison with those born in the spring of 1986 (or spring of 1987), since one sibling need to be born in the fall of 1986. If indeed the 1986 birth cohort benefited from a relaxation of national standards in benchmarking students, we are no longer able to compare to the spring cohort due to the existence of a minimum in birth spacing, which could bias estimated damage toward zero.

Table 7 presents results when dividing the sibling sample according to father's education. Panel A presents results from the sample where the father had two years of (vocational) high school or less; and Panel B presents results for those whose fathers had three years of high school or more. The education cut-off was chosen so as to create roughly similar sized samples. From this division, it appears that the effect is more pronounced in the group whose fathers had less education.

Table 8 shifts the focus to the cohort conceived in April and May 1986, `inutero0-7`. The biomedical literature suggests that this cohort was too young to suffer cognitive damage from the spike in radiation following Chernobyl. Effects, if any, are believed to be terminal. Therefore, we analyze whether the cohort conceived around the time of Chernobyl is smaller than predicted by seasonality and a linear cohort trend. As expected, we find a fall in cohort size in these two months of 3.4% (276/8083). This can be contrasted with Ericson and Källén [1994] who did not find reduced conceptions or increased adverse pregnancy outcomes for April and May 1986.

Furthermore, consistent with Schull and Neel [1958], Peterka et al.

[2004], the `inutero0-7` cohort is more female. This suggests that the fall in fertility was partially the effect of spontaneous abortions (unless Chernobyl induced abortions were performed disproportionately by those who carried male fetuses – a not very likely scenario). Another possibility is that fertility was negatively selected these two months [Trivers and Willard, 1973]. However, since the estimated effect is rather large, a 1.6 % (0.008/0.488) increase in the probability of a daughter, we believe such selection cannot account for this pattern. (For instance, in the U.S., unmarried mothers were found to be 0.2 % more likely to bear daughters [Almond and Edlund, 2007].)

While these patterns are consistent with the literature, several caveats are in order. First, the geographic variation in Chernobyl fallout within Sweden does not correspond to either the magnitude of the reduction in cohort size or the tendency to be female. This stands in contrast to the results presented in the preceding tables. Second, we would clearly prefer to estimate effects on cohort size and gender using natality data, which we plan to obtain, see Section 4. Finally, the academic outcomes among those born in January and February are conflicting: a higher percentage qualified to high school (Column 1), but grades were lower (Column 2).

4 Summary, Discussion and Future Work

We have studied the school performance in the final year of compulsory school of the Swedish cohort born August through December 1986 – and therefore of likely fetal age 8-25 weeks post conception at the time of the

Chernobyl accident. For this cohort, we estimate that those in the eight municipalities that received the highest levels of fallout were 4% less likely to qualify to high school and had 5% lower grades. Moreover, effects are evident in intermediately affected areas – at correspondingly lower levels.

The fact that fallout varied distinctly in both time and space has allowed us to make difference-in-difference comparisons, which yielded supportive results. We also estimated effects using same-sex full siblings, one of whom was born in the fall of 1986. This sibling comparison was then compared across areas with differing levels of fallout. Had parental characteristics of those born in the fall of 1986 deteriorated relative to those born in adjacent years, *and* this "negative selection" into child bearing was more pronounced in counties that received more fallout, we might erroneously attribute lower performance to radiation exposure (in the absence of family fixed effects). This situation could arise if better educated or wealthier families temporarily moved from high fallout areas to low fallout areas immediately following the accident. As we find a similar pattern with family fixed effects, we conclude that such parental differences cannot explain out results.

Assuming that the highest dose to the Swedish population was 4 mSv [Edvarson, 1991b], extrapolation of the results of Otake and Schull [1998] of a reduction of 30 IQ points per Gy (assuming a 1:1 conversion to Sv), implies a hardly detectable effect ($4{\times}30/1000{=}0.12$ points maximum). However, while our found effect sizes are greater than reasonably predicted by a no-threshold linear model, the Otake and Schull studies did not conclude against the possibility of stronger results at very low doses, and agnosticism regarding the effects of such low level ionizing radiation characterizes the consensus view [ICRP, 2005, BEIR, 2006].

The magnitude of our findings are, however, consistent with Oftedal's study of school performance and fallout from weapons tests [Oftedal, 1989, 1991]. He found that among Norwegian children born in 1965, those most likely irradiated at post-ovulatory age 8-15 weeks (from U.S. atmospheric nuclear tests) performed worse in grades 7 and 9 in tests of Norwegian, English and Mathematics. The effect size corresponded to about one year's development in 15-year olds. Whereas the dose was not known, Oftedal conjectured that it could be no more than a couple of multiples of normal background radiation, but likely much lower.

Other than the possibility of a stronger dose-response relationship at very low doses [Oftedal, 1991], it can be noted that external radiation was more important in the A-bomb cases, whereas internal irradiation (more noxious, e.g. Busby and Fucic [2006]) is likely to have been more important in the case of fallout from atmospheric nuclear tests and the Chernobyl accident.

Several factors suggest that we may have underestimated the effect. First, our estimated effects are for the initial spike in radiation. Radionuclides lingered in the environment and accumulated in bodies, suggesting that later cohorts (used as controls) may also have been affected. We only estimate the additional damage resulting from exposure weeks 8-25 post-conception to radiation in the immediate Chernobyl aftermath. Second, the areas R0 through R4 serve as ordinal proxies for individual doses. Using aggregates instead of individual doses does not necessarily introduce a bias. However, if there is misclassification, e.g. a mother registered in Gävle was in fact in Stockholm around the time of the accident, this could introduce random misclassification that would bias results towards zero. Third, note that the sibling comparison precludes comparison with those born in the spring of 1986 (or spring of 1987), since one sibling was necessarily born in the fall of 1986. If indeed the 1986 birth cohort benefited from a relaxation of national standards in benchmarking students, we are no longer able to compare to the spring cohort due to the existence of a minimum in birth spacing, which could bias estimated damage toward zero.

Our findings contrast sharply with previous studies where weak or inconclusive results have prompted the conclusion that damage, if any, reflect anxiety or stress brought on by the economic and social upheaval following the evacuation of the Chernobyl area and the fall of the Soviet Union. According to the UNDP/UNICEF, in their report "The Human Consequences of the Chernobyl Nuclear Accident," only the top six municipalities in Sweden would be considered 'contaminated' albeit not at a level associated with any objective health risk: "Radiation does not pose serious health risks to any particular group. Economic activities may be hindered by indirect association with Chernobyl." UNDP/UNICEF [2002]:table 3.4. The International Atomic Energy Agency was equally dismissive of the possibility of radiation related damage: "the mental health impact of Chernobyl is the largest public health problem unleashed by the accident to date." IAEA [2006]:36.

In conclusion, we have documented that the Swedish cohort of gestational age 8-25 weeks post conception at the time of Chernobyl performed worse in the final year of compulsory schooling compared to adjacent cohorts and the effect was more pronounced in areas that received more radioactive fallout. Future studies will investigate whether earlier health manifestations (perinatal outcomes, in-patient records) presaged our found effects; as well as track this cohort as it ages and additional outcomes are realized.

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Table 1: Geographic Classification by Fallout

Area	Description	*N* born: 1983-88	*N* born: Aug.-Dec. 1986	^{137}Cs kBq/m^2
R3	Älvkarleby, Heby, Gävle, Timrå, Härnösand, Sundsvall, Kramfors and Sollefteå (municipalities)	18,478	1,152	44.2
R2	Not R0, R1 or R3	381,804	24,511	4.9
R1	Värmland, Örebro and Stockholm (counties)	144,486	9,842	2.0
R0	Norrbotten (county)	17,869	1,073	0.3[a]
	All Sweden	562,637	36,578	5.7

The radiation values are population weighted. Areas R0-R4 are mutually exclusive and collectively exhaustive.
Caesium values are from the Swedish Radiation Protection Authority, with the exception of
[a] – from Edvarson [1991b].

Table 2: Percentiles 40 to 60 in the grade distribution

Percentile	Grade points
40	190
43	195
46	200
50	205
53	210
56	215
58	220
60	225

Class graduating in 2003.

Table 3: Simple difference

	(1)	(2)	(3)	(4)
	Dependent variable:			
	Qualify to high school		Grade	
mean	0.91		204	
`inutero`	-0.002**		-0.97**	
	[1.96]		[3.20]	
`inutero8-25`		-0.006***		-1.23**
		[3.20]		[1.99]
N	562637	562637	562637	562637
R^2	0.01	0.01	0.04	0.04

All regressions include year of birth, month of birth, county of birth, R3 and gender indicator variables, and a constant.
Robust t-statistics in brackets. * significant at 10%; ** significant at 5%; *** significant at 1%.

Table 4: Effect by Geographic Area

	(1)	(2)	(3)	(4)	(5)	(6)
	Cohort:					
	inutero (born May 1986-January 1987)			inutero8-25 (born August-December 1986)		
Panel A.	Dependent variable: Qualify to high school (mean=0.91)					
cohort×area:						
R3	-0.018***	-0.020***	-0.033***	-0.016***	-0.021***	-0.036***
	[6.97]	[6.50]	[12.21]	[3.78]	[5.06]	[10.12]
R2		-0.003	-0.015***		-0.008***	-0.023***
		[1.43]	[13.74]		[3.04]	[16.35]
R1			-0.014***			-0.017***
			[10.74]			[7.01]
Panel B.	Dependent variable: Grade (mean=204)					
cohort×area:						
R3	-2.222***	-3.260***	-6.755***	-4.169***	-6.206***	-10.633***
	[3.17]	[3.87]	[10.37]	[2.93]	[3.83]	[8.04]
R2		-1.491**	-4.986***		-2.941***	-7.368***
		[2.67]	[29.39]		[3.01]	[23.57]
R1			-3.903***			-4.914***
			[6.89]			[4.40]
Excluded areas:	R0, R1 & R2	R0 & R1	R0	R0, R1 & R2	R0 & R1	R0
N	562,637	562,637	562,637	562,637	562,637	562,637

All regressions include an indicator variable for area R3, as well as year, month, county, and gender indicator variables, and a constant.
Robust *t*-statistics in brackets. * significant at 10%; ** significant at 5%; *** significant at 1%.

Table 5: Continuous Treatment

	Qualify to high school (mean=0.91)			Grade (mean=204)		
	(1)	(2)	(3)	(4)	(5)	(6)
`inutero8-25`	-0.003*	-0.003*	-0.004*	-1.018	-0.796	-0.722
	[1.78]	[1.77]	[1.82]	[1.34]	[1.61]	[1.56]
`inutero8-25`$\times^{137}$Cs:						
County	-5.3×10^{-4}***			-0.044		
	[3.16]			[1.03]		
Municipality		-3.35×10^{-4}*			-0.06	
		[1.88]			[1.40]	
Parish			-2.92×10^{-4}*			-0.058*
			[1.89]			[1.74]
N	558611	492916	478697	558611	492916	478697
R^2	0.01	0.01	0.02	0.04	0.05	0.08

The explanatory variables are mean radiation in kBq m^{-2} from Caesium-137 (estimated from aerial measurements of Caesium-134 by the Geological Survey of Sweden, on behalf of the Swedish Radiation Protection Authority, over the period May-October 1986 and decay corrected to May 1986).

The averages are taken over the county, municipality and parish respectively. Changes to county, municipality and parish delineations mean that we can not match all observations to their respective municipality or parish.

The county, municipality and parish means range from 1.6 to 32.3, 0.9 to 64, and 0.4 to 85.3 kBq m^{-2} respectively. Our smallest unit of observation is the parish, and the county and municipality means are population weighted. Values are missing for Gotland and therefore all observations from Gotland are excluded, reducing the sample by 4,026 observations.

All regressions include year of birth, month of birth, county of birth, R3 and gender indicator variables, and a constant.

Standard errors are clustered at the county level. Robust t-statistics in brackets. * significant at 10%; ** significant at 5%; *** significant at 1%.

Table 6: Family Fixed Effects

	Qualify to high school			Grades		
	(1)	(2)	(3)	(4)	(5)	(6)
`inutero8-25`×						
area: R3	-0.030***	-0.041***	-0.056***	-3.925**	-6.759***	-16.278***
	[2.99]	[3.21]	[6.01]	[2.26]	[3.44]	[11.25]
R2		-0.016*	-0.031***		-4.050*	-13.627***
		[1.73]	[6.81]		[1.90]	[8.00]
R1			-0.017*			-10.647***
			[1.94]			[8.40]
N	10,896	10,896	10,896	10,896	10,896	10,896
R^2	0.65	0.65	0.65	0.79	0.79	0.79

The sample includes all singleton children belonging to the `inutero8-25` cohort, i.e., those born in the period August-December 1986, who had one same-sex full sibling born in 1983-1988, and these siblings. The sample is further restricted to those whose father was married in 1990.
R3 has 316 observations, of which 160 belonged to the `inutero0-25` cohort.
The control groups are as in Table 4. Their number of observations are 7441 [3724], 2828 [1410] and 311 [154] in regressions 1 (4), 2 (5), and 3 (6) respectively [the figures in square brackets are the number of individuals belonging to the `inutero0-25` cohort].
All regressions include an indicator variable for area R3, as well as year, month, and county indicator variables, and a constant.
Standard errors are clustered at the county level. Robust t-statistics in brackets. * significant at 10%; ** significant at 5%; *** significant at 1%.

Table 7: Family Fixed Effects by Father's Education

	Qualified HS			Grades		
	(1)	(2)	(3)	(4)	(5)	(6)
Panel A.	Father's education: 2-year HS or less					
inutero8-25×						
area: R3	-0.056***	-0.072***	-0.106***	-4.088	-6.467	-19.253***
	[4.16]	[4.51]	[9.18]	[0.85]	[1.18]	[3.93]
R2		-0.022	-0.057***		-3.304	-16.159***
		[1.58]	[8.30]		[1.06]	[8.87]
R1			-0.039***			-14.496***
			[3.29]			[5.17]
N	6208	6208	6208	6208	6208	6208
R^2	0.64	0.64	0.64	0.77	0.77	0.77
Panel B.	Father's education: 3-year HS or more					
inutero8-25×						
area: R3	0.004	0	0.013***	-2.77	-5.587	-10.164**
	[0.91]	[0.04]	[4.87]	[0.62]	[1.26]	[2.50]
R2		-0.006	0.007		-4.321*	-8.927***
		[0.82]	[1.48]		[2.03]	[4.86]
R1			0.014*			-5.068***
			[1.94]			[3.85]
N	4756	4756	4756	4756	4756	4756
R^2	0.66	0.66	0.66	0.77	0.77	0.77

The sample includes all singleton children belonging to the inutero8-25 cohort, i.e., those born in the period August-December 1986, who had one same-sex full sibling born in 1983-1988, and these siblings. The sample is further restricted to those whose father was married in 1990.
All regressions include an indicator variable for area R3, as well as year, month, and county indicator variables, and a constant.
Standard errors are clustered at the county level. Robust t-statistics in brackets. * significant at 10%; ** significant at 5%; *** significant at 1%.

Table 8: Early Pregnancy Effects

	(1) Qualify to high school	(2) Grade	(3) Cohort size	(4) Female
mean	0.91	204	8083	0.488
`inutero0-7`	0.004**	-1.168***	-276.213***	0.008**
	[2.41]	[3.76]	[7.46]	[2.74]
N	562637	562637	574910	562640
R^2	0.01	0.04	0.97	0

The `inutero0-7` indicator variable is one for January and February 1987. All regressions include a linear year trend, month of birth indicator variables, and a constant.

Regressions 1,2 and 4 include county of birth indicator variables. Regressions 1 and 2 include a gender indicator variable.

Standard errors are clustered at the county level in regressions 1,2 and 4, and at calendar month of birth in regression 3. Robust t-statistics in brackets. * significant at 10%; ** significant at 5%; *** significant at 1%.

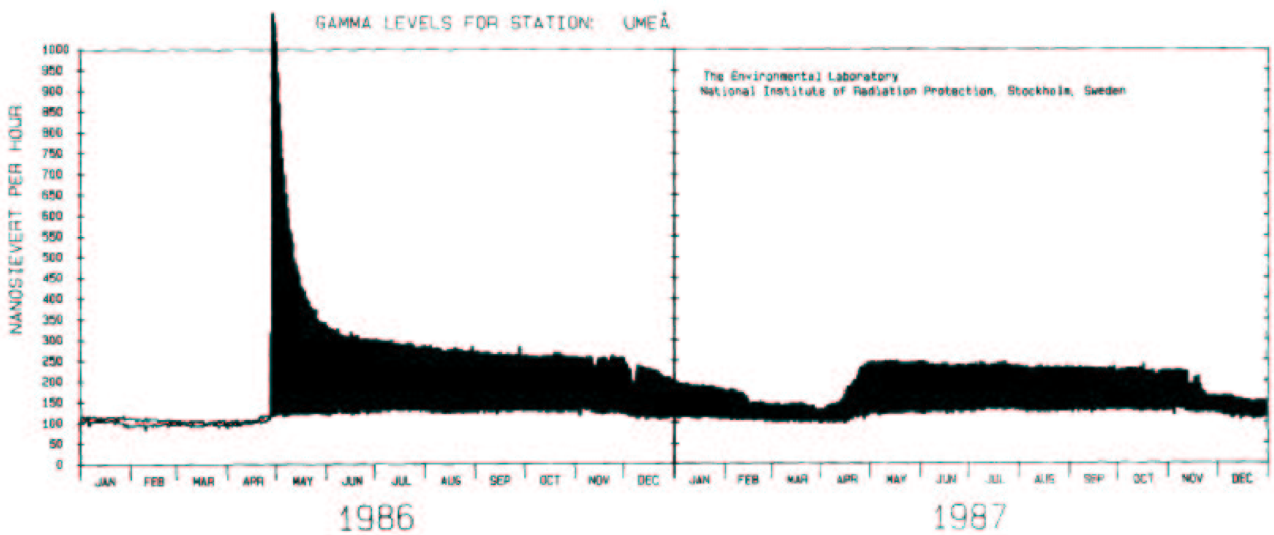

Figure 5. The gamma ambient dose equivalent rate as a function of time for the measuring station in Umeå (Kjelle 1987 and personal communication). The lower curve (with white area below) shows the dose rate from the natural radiation, whereas the dose rate due to the Chernobyl fallout is given by the difference between the upper and the lower curves (black area). The decrease in dose rate between December 1986 and May 1987, and the decrease from November 1987, are due to the shielding effect of snow.

Figure 1: Gamma levels by time – Umeå.

Source: Reproduced from Holmberg et al. [1988]:figure 5.


Norwegian Sea
NORGE
SVERIGE
NMARK
Baltic Sea
LATVIJ
LIETUVA
EE

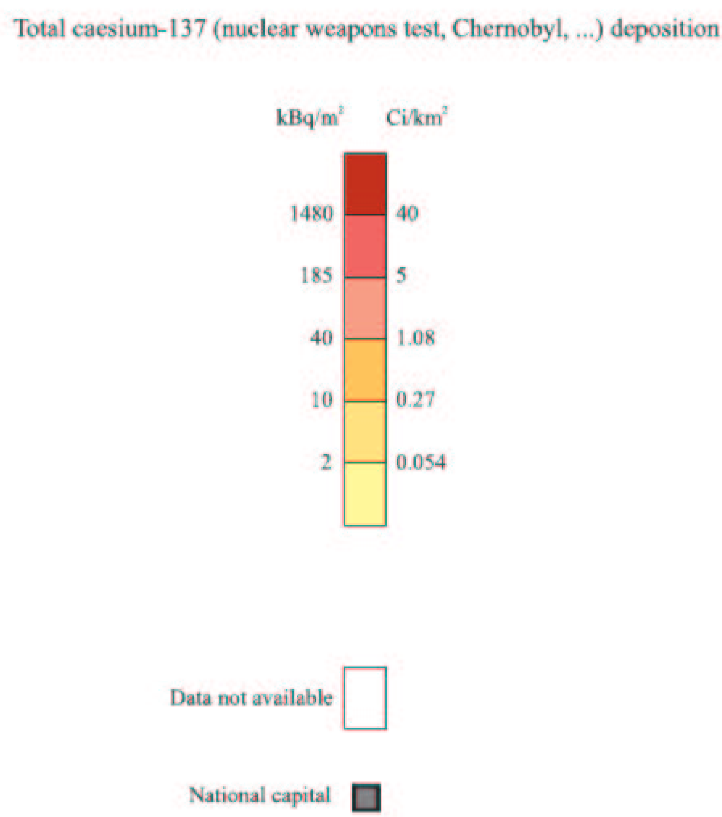

Figure 2: Caesium-137 ground deposition in kBq/m^2.
Source: UNSCEAR [2000].

Deposition of ^{137}Cs in kBq/m^2.													
	120	125	130	135	140	145	150	155	160	165	170	175	180
740							0.3	0.3	0.3	0.3	0.3	0.3	0.3
735							0.3	0.3	0.3	0.3	0.3	0.3	1.4
730						5.2	3.8	2.7	0.8	0.3	0.3	2.7	3.5
725						14.7	7.3	8.2	3.5	0.3	0.3	0.3	1.4
720					43.0	45.2	20.9	9.2	4.4	0.3	0.3	0.3	0.3
715					43.8	45.2	41.1	33.2	19.3	11.7	4.9	3.8	
710					16.3	23.1	20.7	35.6	29.6	22.8	12.2	5.4	
705			5.4	6.3	5.2	10.3	26.9	35.9	53.0	35.1	22.8		
700			6.3	3.8	4.1	8.2	36.7	50.3	43.0	38.9			
695			4.1	2.4	1.4	8.2	16.9	42.4	39.2				
690			3.8	1.9	0.3	5.2	11.4	43.2	56.6				
685			4.1	1.6	1.9	2.7	9.2	31.6					
680			2.7	1.4	1.9	2.4	7.9	23.9					
675			2.7	1.1	0.5	1.6	4.9	39.7					
670			2.7	0.8	1.6	1.1	6.3	65.3	23.7				
665			0.0	1.9	2.4	2.7	8.7	46.5	14.1				
660		0.0	0.0	1.6	2.7	1.4	10.3	28.3	7.3				
655		2.7	2.7	1.1	2.4	2.7	6.8	8.2	0.8				
650	1.9	1.9	0.8	0.8	0.8	1.4	5.4	1.9	0.8				
645	1.9	1.9	1.4	1.4	1.4	1.4	2.7	2.7					
640		1.4	1.4	1.4	1.4	1.9	2.7			4.1			
635		1.4	1.4	1.4	1.4	1.4	1.4		4.1	4.1			
630		1.4	1.4	1.4	1.4	1.4	1.4	2.7	5.4	4.1			
625			1.4	1.4	1.4	1.4	1.4						
620			0.8	0.8	0.8	0.8	2.7						
615					1.6	1.1	1.1						
610					1.1	0.3							

Figure 3: Caesium-137 ground deposition in kBq/m^2.

Aerial measurements corrected by FOA *in situ* measurements.
Source: Reproduced from Edvarson [1991b]:table 2.

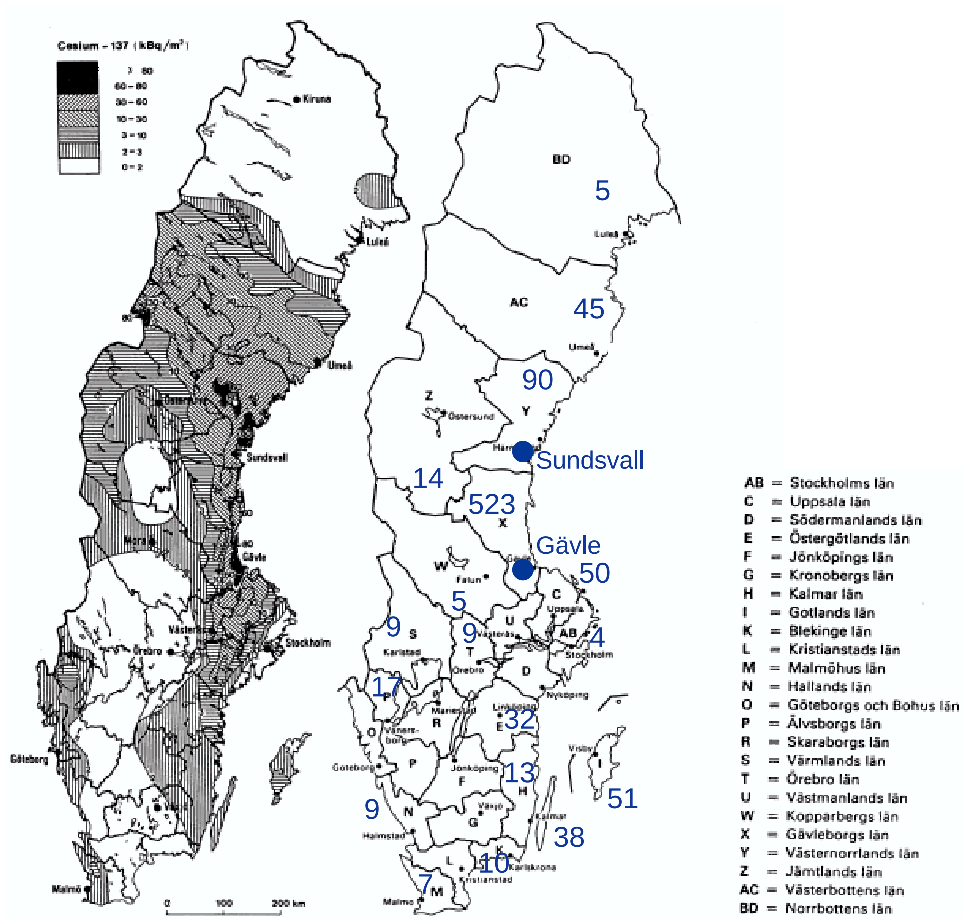

Figure 4: Caesium-137 (left) and Iodine-131 (right) ground deposition in kBq/m^2.
Notes: Caesium-137 figures pertain to aerial measurements by SGAB. Iodine figures from FOA *in situ* measurements, numbers pertain to average for measuring stations in the county.
Source: Adapted from Moberg [1991]:figure 2; and Edvarson [1991b]:table 7.

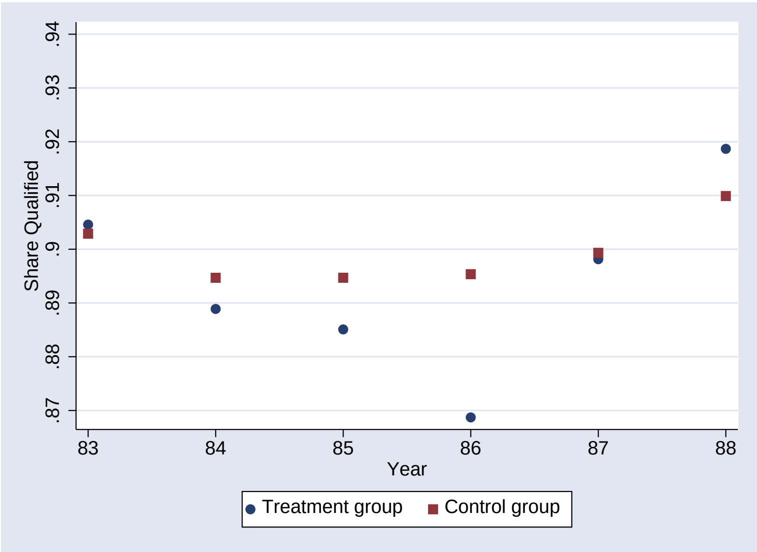

Figure 5: August-December births. Fraction qualified to high school by year of birth. Treatment group: R3 ("Gävle-Sundsvall") – Control group: Rest of Sweden.

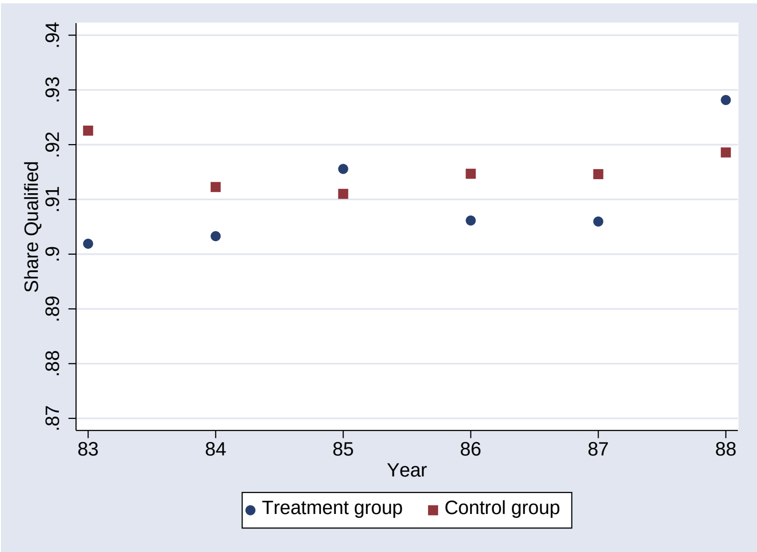

Figure 6: February-May births. Fraction qualified to high school by year of birth. Treatment group: R3 ("Gävle-Sundsvall") – Control group: Rest of Sweden.

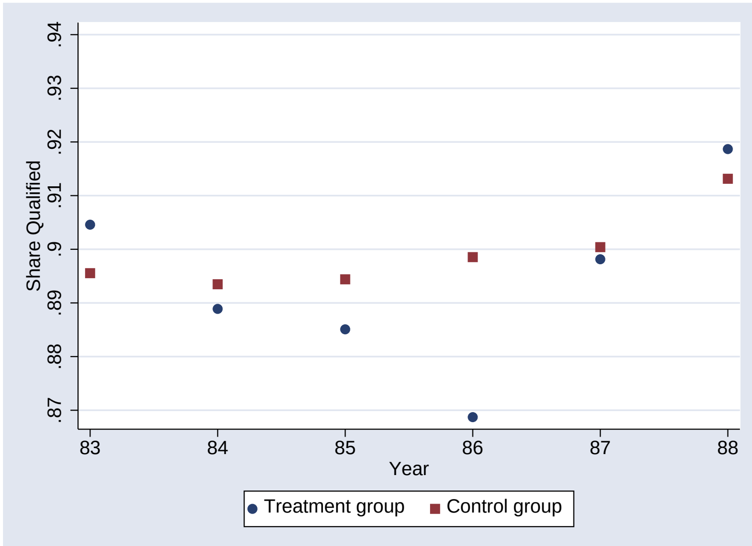

Figure 7: August-December births. Fraction qualified to high school by year of birth. Treatment group: R3 ("Gävle-Sundsvall") – Control group: R0 & R1.

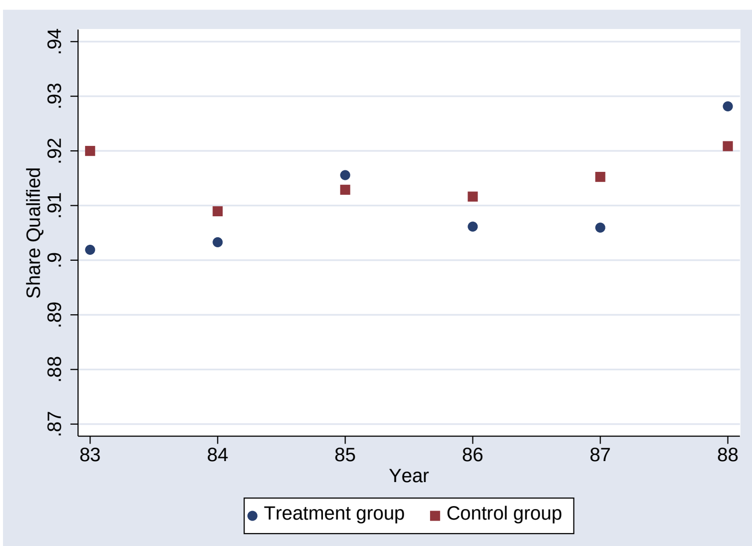

Figure 8: February-May births. Fraction qualified to high school by year of birth. Treatment group: R3 ("Gävle-Sundsvall") – Control group: R0 & R1.

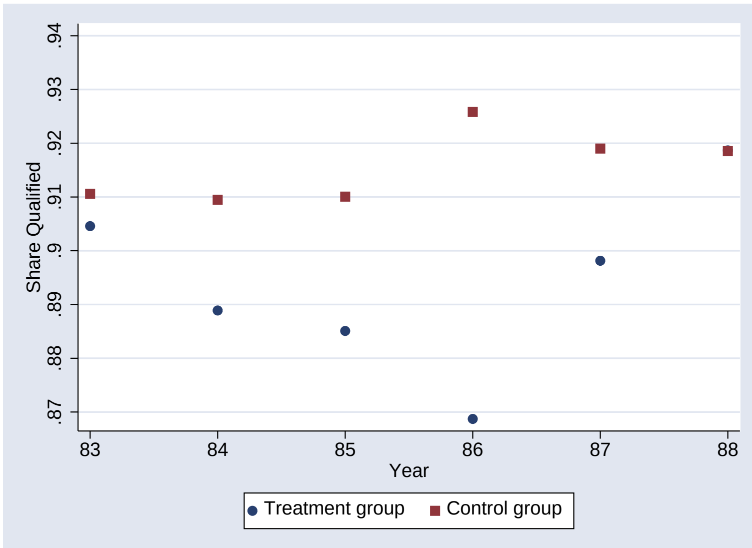

Figure 9: August-December births. Fraction qualified to high school by year of birth. Treatment group: R3 ("Gävle-Sundsvall") – Control group: R0 (Norrbotten).

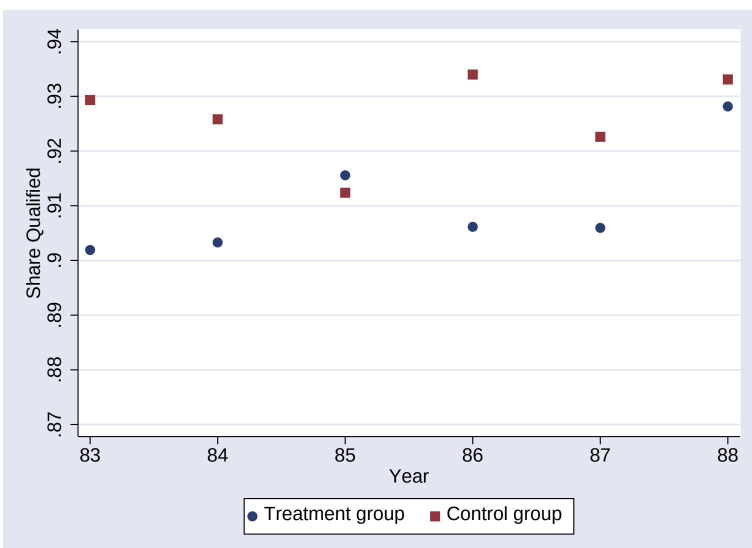

Figure 10: February-May births. Fraction qualified to high school by year of birth. Treatment group: R3 ("Gävle-Sundsvall") – Control group: R0 (Norrbotten).