

# Chernobyl's subclinical legacy: Prenatal exposure to radioactive fallout and school outcomes in Sweden\*

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November 6, 2008

## Abstract

We use prenatal exposure to Chernobyl fallout in Sweden as a natural experiment in cognitive ability. Students born in regions of Sweden with higher fallout performed worse in secondary school, Math in particular. Damage is accentuated within families (i.e., siblings comparison) and among children born to parents with low education. In contrast, we detect no corresponding damage to health outcomes. To the extent that parents responded to the cognitive endowment, we infer that parental investments reinforced the initial Chernobyl damage. From a public health perspective, our findings suggest that neural development is compromised at radiation doses currently considered safe.

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\*We would like to thank Leif Moberg (Swedish Radiation Protection Authority) for providing the radiation data and key references. We also thank Johanna Adami, Hoyt Bleakley, David Brenner, Janet Currie, Lucas Davis, Tore Ellingsen, Avraham Ebenstein, Andrew Foster, Michael Greenstone, Eric Hall, Per Hall, Ethan Kaplan, Wojciech Kopczuk, Wilbert van der Klaauw, David Lee, Bhashkar Mazumder, Costas Meghir, Torsten Persson, Cristian Pop-Eleches, Heather Royer, William Schull, David Strömberg, Ezra Susser, Miguel Urquiola, Simon Wright, and Lydia Zablotska for valuable comments. Sarena Goodman provided valuable research assistance. Financial support from the National Science Foundation (grant 0721155) and the Russell Sage Foundation is gratefully acknowledged.

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# I. INTRODUCTION

Empirical studies in the human capital tradition have sought to isolate the role of latent variables – such as ability or family background – from differences in other inputs or production technologies. An obvious challenge for such studies is the lack of exogenous variation in the latent variables, which, in turn may be highly interrelated. For example, children’s cognitive ability may be positively related to family background and this background may affect other human capital investments or their return (or both). Furthermore, parents or education policies may respond to realizations of a latent variable, e.g., compensating children with low innate ability.

A natural experiment in a specific latent factor could help disentangle some of these relationships. First, the magnitude of the reduced form impact on human capital formation could be assessed – e.g., how much does cognitive ability matter? Second, with data on baseline characteristics (e.g., family background), we could observe how predetermined factors interact with the latent input in producing human capital.

The physical environment can provide exogenous variation in latent human capital inputs. Cunha and Heckman [2007] observed that “abilities are susceptible to environmental influences, including *in utero* experiences.” But Tiebout sorting implies that proximity to environmental hazards may be endogenous [Banzhaf and Walsh, 2008]. Therefore, changes to the local environment caused by accidents or pollution might be more compelling empirically, especially when the environmental damage is physically removed from its source. Finally, environmental epidemiology can specify pathways by which the environment affects specific latent inputs, e.g., prenatal famine exposure and adult schizophrenia [Clair et al., 2005].

In this paper, we argue that radioactive fallout from the 1986 Chernobyl accident in Sweden offers a natural experiment in cognitive ability. Although more than 500 miles away from Chernobyl, weather conditions caused Sweden to receive about 5 percent of the accident’s Caesium fallout. Due to variation in rainfall levels while the radioactive plume was over Sweden, there was stark geographic variation in the levels of fallout deposited. Chernobyl fallout is of interest because cognitive development is sensitive to prenatal radiation exposure [Otake and Schull, 1998, Nowakowski and Hayes, 2008].<sup>1</sup>

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<sup>1</sup>Indeed, the link made between prenatal medical radiation and microcephaly (small head circum-

Despite targeting cognitive ability, empirical studies of human capital formation have not previously leveraged radiation damage. Previous epidemiological studies have focussed on radiation exposures where either: (i) the estimated dose was an order of magnitude higher, or; (ii) doses were low but exposures were unlikely to be exogenous, e.g., radiation from radon or medical procedures. Following the findings from studies of A-bomb survivors, we focus on the cohort *in utero* between weeks 8 and 25 of gestation at the time of the accident, and thus born in fall of 1986.

We evaluate Chernobyl’s impact using administrative data on the universe of birth, hospital discharge, and schooling outcomes in Sweden for cohorts born 1983-1988 (it is too early to assess labor market outcomes). In particular, we evaluate: (1) health status as recorded by natality data and the in-patient registry which includes all hospitalizations between 1987-2006; (2) performance in final year of compulsory school (age 16); (3) performance in high school (age 19). Importantly, we observe both the place of birth and parental education. This enables us to compare impact estimates by parental education, as suggested by Currie and Hyson [1999], Case et al. [2002], Currie and Moretti [2007].

We find that the fall 1986 birth cohort performed substantially worse in the final year of compulsory schooling (i.e., middle school). Grades in Mathematics were particularly affected. This cohort was also less likely to graduate from high school (by 2006) and had worse grades conditional on graduating. Furthermore, the magnitude of damage to the fall 1986 cohort corresponds to regional differences in fallout. Projecting forward, we estimate that Chernobyl will cause a 3-percent reduction in annual earnings for the most-exposed Swedes. In contrast, we do not detect corresponding health damage. Neither the birth outcomes (including birth weight) nor the hospital discharge records reveal damage. Thus, we believe Chernobyl fallout in Sweden successfully isolated a latent factor: cognitive ability.

Interestingly, the damage to human capital is highly concentrated in families with low-education parents. This pattern exists both across and within families, i.e., when we compare exclusively among siblings where one was exposed to Chernobyl while *in utero*. This pattern – together with the fact that sibling fixed effects estimates are generally stronger than simple difference-in-differences estimates – suggests that if parents

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ference) in 1929 was the “first indication of malformations induced by an iatrogenic agent in human beings” [DeSantis et al., 2005].

responded with postnatal investments, they were most likely reinforcing, i.e., accentuating differences in birth endowments [Rosenzweig and Schultz, 1982, Loughran et al., 2008, Rosenzweig and Zhang, 2008]. Finally, our impact estimates are strengthened when we instrument for measurement error in fallout deposition with rainfall,<sup>2</sup> suggesting that our OLS damage estimates are conservative. From a public health perspective, because sheltering indoors is highly effective in reducing exposure to radiative fallout [Finck, 1991], our findings suggest that pregnant women in areas with rainfall through the radioactive cloud should remain indoors following nuclear accidents or attacks.<sup>3</sup>

The remainder of our paper is organized as follows. Section II describes the Chernobyl accident, summarizes the literature on prenatal exposure to ionizing radiation, and then describes the Swedish schooling system. Section III describes the radiation, schooling, and health data that we analyze. Section IV presents our main results, followed by an instrumental variables approach using rainfall; we then estimate the accident’s costs. Section V considers whether human capital investments may have responded to Chernobyl damage and interprets the concentration of damage among families with low-education parents. Finally, Section VI discusses the external validity of our results for other various sources of ionizing radiation.

## II. BACKGROUND

### A. *The Chernobyl Accident*

The core meltdown at Chernobyl occurred at 1:24 am April 26, 1986 in Ukraine.<sup>4</sup> News of the accident came from Sweden, where heightened levels of radioactivity set off alarm bells at the Swedish nuclear plant Forsmark, some 680 miles away. During the ten days it took to control the fire, large quantities of radioactive material were released. Europe received the bulk of the fallout, but measurable levels of ground deposition have been

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<sup>2</sup>This IV approach has not previously been employed in any fallout study despite the fact that the first stage is strong and well-known to environmental scientists [Holmberg et al., 1988].

<sup>3</sup>As we will show, this response passes a cost-benefit analysis with conservative assumptions and runs counter to the conclusion of the Swedish Radiation Protection Institute that “there was never any need” to keep people indoors [Moberg, 1991].

<sup>4</sup>UTC+3 (Moscow time)

detected in all countries in the northern hemisphere [UNSCEAR, 2000].

The Chernobyl accident provides a nearly ideal natural experiment in radiation exposure. Meteorological conditions resulted in Sweden receiving about 5 percent of the Caesium fallout, creating a pronounced spike in radiation levels [Moberg, 1991]. Figure I shows measured gamma radiation in Njurunda in Sundsvall municipality (about 1,000 miles from Chernobyl). Gamma radiation in Njurunda peaked on April 29 at over ten times background levels.

There was also substantial geographic variation in deposition due primarily to differences in rainfall at the time of the accident [Holmberg et al., 1988].<sup>5</sup> Njurunda registered the highest radiation level among Sweden's fixed gamma monitoring stations [Kjelle, 1987]. Ground deposition in the worst affected areas (around Gävle and Sundsvall) equalled those found just outside Chernobyl's 30 km (19 mile) radius exclusion zone, while the northernmost parts of Sweden were virtually spared (see Figure II). In addition to the distinct time and geographic variation, this natural experiment exposed a large number of people, thereby overcoming an important challenge to evaluating effects of low dose radiation (since effect sizes are also presumably small [Brenner et al., 2003]).

## *B. Prenatal Radiation and Cognitive Damage*

It is generally accepted that prenatal radiation exposure causes cognitive damage. However, the best-regarded epidemiological studies considered radiation doses an order of magnitude higher than the maximum dose estimated for Swedes following Chernobyl: 4 mSv in the first year [Edvarson, 1991a].<sup>6,7</sup> Although exposure to low-dose ionizing radiation is common, the low-dose question remains unresolved [DeSantis et al., 2005,

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<sup>5</sup>Daily rainfall data for about 100 weather stations in Sweden 1985-1986 (from the U.S. Dept. of Commerce) reveal that between April 27 and May 30, it rained substantially more near Gävle and Sundsvall. Also, rainfall during this period was uncorrelated with rainfall during the rest of the year (see Section IV part D).

<sup>6</sup>See Section III part A (last paragraph) and Appendix A for summary of radiation measurements and magnitudes.

<sup>7</sup>While controlled laboratory experiments have also been supportive, relative to other endpoints (e.g., lifespan), cognitive function is more difficult to assess using animal subjects. These issues aside, 60 mGy is the lowest prenatal dose for which damage has been observed: brain or behavioral damage in the rat [Hall and Giaccia, 2005, table 12.2]. Gray (Gy) measures absorbed dose and sievert (Sv) the effective dose. For gamma radiation, they are numerically the same.

Peplow, 2006]. Below, the pathophysiologic mechanism for cognitive effects is summarized, followed by the epidemiological studies of medical radiation and the 1945 atomic bombings of Hiroshima and Nagasaki.

Damage to neural development from prenatal irradiation is biologically plausible. Ionizing radiation ejects electrons capable of breaking chemical bonds, those in DNA strands in particular. While there is some ability to repair, improper repair may lead to mutations or cell death.<sup>8</sup> DNA is particularly vulnerable during cell cycling and division, which is more rapid early in life.<sup>9</sup> The brain differs from other epithelial organs in that there is little cell proliferation in the adult brain. This limited renewal means that insults to the developing brain are likely to have permanent effects. Nowakowski and Hayes [2008, p. 527]: “any neural loss sustained during the developmental period is retained for life.” Weeks 8-25 post conception mark a major neurogenetic period of the neocortex. During this period, the neocortex expands more than 100 fold [Nowakowski and Hayes, 2008], and the normal number of neurons in the neocortex in an adult may already have been achieved by week 16 [Otake and Schull, 1998]. Except for the hippocampus, no neuronal stem cell proliferation takes place after birth [Gluckman and Hanson, 2005].<sup>10</sup> Radiation interferes with the two main processes of proliferation and migration to the cortex, and results in fewer and/or improperly wired neurons (the migration is guided by specialized neurons that later self-destruct).

The first indication that radiation exposure during pregnancy caused cognitive damage came from case-studies of children born to women who had been treated with high-doses of medical radiation while pregnant. Prior to the early 1930s, “therapeutic” x-ray and radium irradiation of the maternal pelvis (for cancer of the uterus) was conducted at doses above 100 mGy. Such doses during pregnancy was found to induce microcephaly (small head), and mental retardation in the fetus [DeSantis et al., 2005]. These malformations were restricted to pregnancies at week 20 of gestation earlier, but the small study sample (25 symptomatic children) restricted power.

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<sup>8</sup>While cell death is believed to be roughly proportional to dose rate, the ability to repair and compensate is unknown.

<sup>9</sup>The effect of radiation on DNA and DNA’s vulnerability during cell division is a reason radiation can both cause and treat cancers – cancer cells’ not showing the slow-down in growth typical of normal cells.

<sup>10</sup>The brain continues to grow after birth, but this growth is largely that of myelin, not neurons.

It was the larger-sample studies of atomic-bomb survivors that permitted a finer analysis of when during pregnancy radiation was most damaging. 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 bomb explosion. Two control groups from the same areas were matched 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 non-exposed survivors ( $> 10,000$  meters). In addition to some anthropometric measures (e.g., weight, height and head size) these studies also analyzed cognitive ability (IQ) and school records. The effect on IQ was estimated to be a 25-30 points reduction per Gy (1,000 mGy) for those exposed at post-ovulatory ages 8-15 weeks. A smaller reduction was estimated for those aged 16-25 weeks. For children exposed earlier or later, no significant effect was found.

Irradiation outside the 8-25 week window was not associated with lower cognitive performance among the A-bomb survivors. That is not to say radiation does not have effects outside those ages. In the pre-implantation period (the first two weeks after conception), radiation is believed to result in embryonic death, but conditional on survival, there are no developmental effects. During organogenesis, 2-7 weeks post conceptions, the internal organs are developed, and radiation during this period can lead to malformations and growth retardation including small head size (but without mental retardation). Radiation in the third trimester can heighten the risk of cancer [Hall and Giaccia, 2005]. But insofar as the central nervous system is concerned, the period after the 25th week of pregnancy is “relatively radioresistent” [DeSantis et al., 2005].

Median exposure for A-bomb survivors was estimated to be 40 mGy [Otake and Schull, 1984]. Whether the findings from the A-bomb survivors generalize to doses less than 10 mGy has not yet been established [Hall and Giaccia, 2005, BEIR, 2006].

In light of the effects documented above, both ethical and cost considerations render controlled experiments of low radiation doses infeasible.

### *C. Chernobyl Studies*

A number of previous studies have found reduced cognitive function 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]. These studies have

focussed on populations born near the reactor. As a consequence, they were exposed to much higher levels of radiation than considered here, and sample sizes have been relatively small.

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 [Lüning et al., 1989, Sperling et al., 1994, Ericson and Källén, 1994, Scherb et al., 1999, Auvinen et al., 2001, Laziuk et al., 2002]. For each outcome, studies can be found on either side: some find effects and others do not, and generally the effects have been small.

In the interest of space, we refer the reader to our working paper, Almond, Edlund, and Palme [2007], for a more thorough discussion of these studies.

#### *D. The Swedish Schooling System*

Primary and middle schooling (*Grundskola*), grades one through nine, is compulsory in Sweden (unlike in the United States, where compulsory schooling relates to age). The school year begins in August, and typically, pupils enroll in first grade the calendar year they turn seven.<sup>11</sup> Although some specialization is allowed after sixth grade, students are kept in common classes and the final year grades are set on the basis of the outcomes from national tests.

Pupils are graded in 16 individual subjects. The grades are set in two stages. In the first stage, each school's average grade is set on the basis of how the school's pupils did in national tests. The specific subject grades we will analyze – Math and Swedish – are both set according to nationally standardized tests. (This national benchmarking would tend to attenuate the cohort main effect below, but not the difference-in-differences estimator.) In the second stage, the individual pupil's grades are set. In addition to his or her performance in the national test, performance in local tests and in the classroom are factored in (which are not nationally standardized). Grades are assigned according to a four-point scale:

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<sup>11</sup>Public, or free, education (all levels) dominates schooling in Sweden. Recently, there has been a growth in private schools that are State financed against not charging tuition. Only a handful tuition charging schools exist.

- “Failed” (0 points)
- “Passed” (10 points)
- “Passed with distinction” (15 points)
- “Passed with special distinction” (20 points)

The grades from the last year in compulsory school (in the spring the pupil turns 16 years old) are used for admission to secondary education. In particular, a passing grade in three core subjects – English, Swedish, and Math – are required for matriculation.

Roughly 90% continue on to Secondary school (Gymnasieskolan), which is elective and divided into two basic tracks: vocational and academic. Within these tracks, there are different programs, most of which last three years. The main programs in the academic tracks are Science, Social sciences, and Business administration. Each program consists of separate courses. Some of these courses are common even between different programs and graded on the basis of results on national tests, using the same grading system for compulsory schools. The grades from secondary school are used for admission to higher education (colleges and universities).

#### *D.1. Municipality Level Clustering*

Beginning in 1989, municipalities assumed responsibility for providing compulsory and secondary education (prior to 1989, school administration was at the county level). Although the schools are regulated in a national curriculum, the political majority in the individual municipalities has discretion over the management of the schools and resources allocated to education. This, in turn, may generate correlation of school performance between individuals within municipalities as well as autocorrelation over time. Our cohorts entered primary education in 1990 and therefore we will cluster standard errors at the municipality level.<sup>12</sup>

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<sup>12</sup>The number of clusters – 286 – is sufficient to avoid downward bias in the estimated standard errors [Angrist and Pischke, 2008]. Furthermore, the most conservative approach, suggested by Donald and Lang [2007], is to use the treatment and control group averages. Our estimated effects are still highly significant using this method (results available from authors).

### III. DATA

Below, we describe the radiation, schooling, and health data that we will analyze. Outcomes data are available for cohorts born 1983-1988. Assuming that the radioactive cloud swept Sweden April 27-May 10; and a 38 week post-conception gestation period, this implies that the those between 8 and 25 weeks gestation are those born between July 27 and December 13, 1986. Thus, we will consider the cohort born between August and December of 1986 the “*in utero*” cohort.

#### A. Radiation Data

Following Chernobyl, ground deposition of Cs-137 fallout (half-life of 30.2 years) was mapped for most of Europe, see UNSCEAR [2000].<sup>13</sup> For Sweden, the Swedish Geological Co. (SGAB) (commissioned by the Swedish Radiation Protection Authority, *Statens Strålskyddsinstitut*) conducted aerial measurements of ground deposition  $\gamma$ -radiation from Caesium-137 over the period May-October 1986 and decay corrected to May 1986.<sup>14</sup>

We have obtained these aerial measurements for 2,380 parishes (out of 2,517). A parish is a rather small geographic unit, and for most people, everyday activities would involve crossing parish boundaries. Therefore we aggregate to the municipality or county level.<sup>15</sup> The aerial measurements of deposition were calibrated against *in situ* gamma-spectrometric measurements using high-resolution Gedetectors at 61 locations covering 48 municipalities [Holmberg et al., 1988, Edvarson, 1991b]. Because of their importance, we focus on Caesium and Iodine-131 (half-life of 8 days).<sup>16</sup>

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<sup>13</sup>“From the radiological point of view, <sup>131</sup>I and <sup>137</sup>Cs are the most important radionuclides to consider, because they are responsible for most of the radiation exposure received by the general population.” UNSCEAR [2000, para. 21]. The release of <sup>131</sup>I and <sup>137</sup>Cs has been estimated at 1,760 pBq and 85 pBq respectively [UNSCEAR, 2000].

<sup>14</sup>In fact, Caesium-134 (half-life of 2.1 years) was measured because of its known relationship to Caesium-137 (a Cs-137/Cs-134 ratio of 1.7) and the fact that, then, radiation from atmospheric nuclear weapons tests stemmed almost exclusively from Caesium-137, rendering the Cs-134 isotope a more accurate indicator of Chernobyl related Caesium fallout.

<sup>15</sup>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 some 286 municipalities. The parish (*församling*) is the third and lowest level.

<sup>16</sup>The other radionuclides measured were: <sup>95</sup>Zr, <sup>103</sup>Ru and <sup>132</sup>Te.

We consider two basic types of radiation measures in this paper. First, there are measures of ground deposition of radioactive Caesium. Second, there are measures of dose, which reflect the energy absorbed by matter. Deposition is more easily measured than dose. Deposition estimates are measured in kilo-becquerels (kBq) per appropriate unit (e.g., per square meter), and doses in millisieverts (mSv), where the sievert refers to the dose equivalent (which for gamma radiation is the numerical equivalent to absorbed dose, denoted in units of gray (Gy)). To give a rough sense of magnitudes, regions with kBq/m<sup>2</sup> above 37 were considered “contaminated,” while 6 mSv is a common estimate of annual dose due to background radiation. These measures are described in greater detail in Appendix A.

### *A.1. Regional Groups*

Based on the information from the aerial measurements and *in situ* measurements, we classify Sweden into four groups as detailed in Table I and mapped in Figure III. 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 eight highest levels of ground deposition of Caesium-137. As for the control group, the choice of R0 (Norrbotten county) is dictated by Edvarson [1991b, table 2] and [UNSCEAR, 2000, figure X], where Norrbotten shows the lowest values of Caesium-137.

Norrbotten is, however, a sparsely-populated county. Therefore, we also present results from using a broader control group. Based on Holmberg et al. [1988, figure 2] replicated in our working paper [Almond, Edlund, and Palme, 2007, Figure 4], we extend the control group to also include the counties denoted by R1 (in Table I): Stockholm, Örebro and Värmland.

In sum, while data clearly single out our two extreme areas – R0 and R3 – the division of the “middle” into R1 and R2 may be viewed as exploratory. However, this categorization will allow us to present results in both figures and regression tables with more than one comparison group.

Table I: Geographic Classification by Fallout – Mapped in Figure III

Area	Description	<i>N</i> born:		Cs-137 kBq/m <sup>2</sup>
		1983-88	Aug.-Dec. 1986	
R3	Älvkarleby, Heby, Gävle, Timrå, Härnösand, Sundsvall, Kramfors and Sollefteå (municipalities)	18,253	1,139	44.1 <sup>a</sup>
R2	Not R0, R1 or R3	375,556	24,094	4.74
R1	Värmland, Örebro and Stockholm (counties)	140,143	9,540	1.93
R0	Norrbotten (county)	17,678	1,061	0.96 <sup>a</sup>
All Sweden		551,630	35,834	5.7

The radiation values are population weighted. Areas R0-R3 are mutually exclusive and collectively exhaustive.

<sup>a</sup> All value from the Swedish Radiation Protection Authority, except *b*, see below.

<sup>b</sup> From Edvarson [1991b].

### A.2. Continuous Measures

We also consider four continuous measures of radiation exposure:

**I-131, in situ, municipality** In the 43 municipalities, the range in I-131 is 3.3-627 kBq/m<sup>2</sup>.

**Cs-134, in situ, municipality** In the 48 municipalities with data, the range is 0.12-54 kBq/m<sup>2</sup>. These values were used to calibrate the aerial measurements, and therefore should coincide (by a factor of 1.7) with the aerial measures for the location in question. We include this measure to allow comparison with the I-131 measures. While there was variation in the nuclide composition, these two radionuclides were highly correlated (correlation 0.97).

**Cs-137, aerial, municipality** Full coverage, municipality averages range from 0.3 to 64 kBq/m<sup>2</sup>. We have made the following substitutions. In accordance with Edvarson [1991b, table 2], we assign value 0.3 kBq/m<sup>2</sup> to all but four coastal municipalities in Norrbotten county, and a value of 4.1 kBq/m<sup>2</sup> to Gotland county. The geographic variation at the municipality level is shown in Figure II.

**Cs-137, aerial, county** These are the municipality values aggregated to the county level. County averages range from 1 to 32 kBq/m<sup>2</sup>.

The *in situ* measurements come from [Edvarson, 1991b, table 7] where we assign the measured value to the municipality of the measuring station. There were 61 stations, covering 48 municipalities.<sup>17</sup> Iodine (I-131) readings were missing from some stations, so for Iodine we only have readings for 43 municipalities. While the *in situ* readings may be more reliable than the aerial measurements, there is a steep tradeoff in efficiency as we can match these monitors to less than one-third of the student sample.<sup>18</sup>

## B. School Outcomes

Below we describe the schooling data. These data are matched to the radiation measures above based on the mother’s parish of residence at the time of birth. As a result, we have a fairly good measure of the mother’s likely location in Sweden during pregnancy.

### B.1. Compulsory Schooling

Compulsory school records for cohorts born 1983-1988 come from two sources. The first data set consists of all persons who were either born between 1983 and 1985 or the children of Swedish-born parent born between 1940 and 1985. As a result, this data set has almost universal coverage of the cohort born 1983-1985. For the 1986 birth cohort, we capture everybody who had at least one Swedish born parent younger than age 46 (in 1986), and for 1987 and 1988 this age is 47 and 48, respectively. Since fertility is nearly complete for women by age 45, this means that coverage for the later cohort is also almost universal.

To this data set we have matched on final grades from the last year of compulsory school (typically obtained at age 16), as well as individual information from the National Birth Register and from the National In-patient Register, containing diagnosis codes for all admissions to Swedish hospitals. Altogether, we have 551,630 complete observations. Appendix Table XI contains descriptive statistics.

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<sup>17</sup>For three stations, we could not locate the position with enough precision to identify a unique municipality and we resorted to assigning the measured radiation readings to adjacent municipalities.

<sup>18</sup>As the aerial measurements were calibrated using the *in situ* readings, an instrumental variables approach to correct for measurement error is not feasible. See Section IV part D.

In addition to the individual grades in the subjects Mathematics and Swedish, we focus on the following outcome variables:

**Qualify to High School** As noted in Section II part D, one must pass English, Swedish, and Mathematics in the 9th grade in order to be eligible to attend high school.

**Average Grade** The average grade in 16 subjects, with a maximum of 20 points. It is used for application to secondary education.

### *B.2. High School*

We obtained high school records through 2006 for all students born in Sweden. Students typically graduate the year they turn 19, and therefore we restrict our sample to those born between 1983 and 1987. For this data set we have 444,583 complete observations and descriptive statistics are provided in Appendix Table XII.

We focus on whether the person have graduate from high school (73 percent), their average grades, and individual grades in Mathematics and Swedish.

### *C. Control variables*

**Parental education** We obtained information on parental education as of 1990, the earliest year available. Parental education comes from the National Education Register, obtained from the *LISA* database, which we merged to the schooling records using a unique personal identifier. We will include dummy variables for the education level (two sets, of for each parent). This variable indicates the highest schooling attained: compulsory education (old system), 9 years primary education, vocational high school, academic high school, some college (but not graduate from 3-year program), college graduate (3-year program or more), or graduate degree. Ideally, we should have parental education before the Chernobyl accident in 1986, we note that average age of first birth was 26 years in 1985, an age at which we expect education to be completed or close to completed.

**Local labor market conditions** Employment and unemployment rates are available from Statistics Sweden by quarter and county for those aged 16-64 years. Dehejia and Lleras-Muney [2004] highlighted the effect of the business cycle on the average

characteristics of parents who conceived children. We therefore consider labor market conditions lagged three quarters. For example, if a student was born in the fourth quarter, the unemployment rate in her county of birth during the first quarter is applied.

Means of the control variables (by region) are reported in Appendix Table XIII.

#### *D. Birth Outcomes*

The Swedish Birth Register contains information on pregnancies and deliveries for all births in Swedish hospitals since 1973. This provides date of delivery, information on previous pregnancies, gestation length, clinic, mode of birth, length, weight, as well as diagnoses of the mother and the child (ICD-7 codes). There are between 85,000 and 120,000 births per year in Sweden. The annual information loss ranges between 0.5 and 3 percent.

We focus on the following outcome variables:

**Birth Weight** Weight measured in grams immediately after birth.

**Gestation length** Gestation length measured in days on the basis of last menstrual period or clinical estimates (using ultra sound exam during pregnancy).

**Apgar score** Apgar score from test conducted 5 minutes after birth. The Apgar score is the sum of the scores 0, 1 or 2 for five criteria (heart rate, respiratory effort, muscle tone, reflex irritability, and color). The minimum score is 0 and the maximum (indicating no problems) is 10.

#### *E. Hospitalizations During Childhood*

Sweden's in-patient hospital register contains one record for each hospital admission. The register was started in 1964 and has covered all Swedish hospitals since 1987. The register includes ICD-7 codes for up to eight diagnoses, the date of admission, number of days in hospital care and mode of discharge. Coverage is very close to universal.<sup>19</sup>

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<sup>19</sup>The annual loss of information is estimated to be less than 1 percent, the information loss on main diagnosis and person identifier is about 1 percent each.

Using a unique person identifier, we matched these data set to our Compulsory Schooling data set, and thereby assign likely exposure to Chernobyl radiation based on parish and date (month) of birth. Since we are interested in evidence of radiation damage, we focus on the following outcomes:

**Malformations** Hospital care caused by congenital malformations is identified by ICD-7 diagnosis codes 750-759 (these include congenital malformations of various organs, monstrosity, congenital hydrocephalus, cleft palate and harelip). Since our cohort of interest was likely exposed during the fetal period, and thus past the organogenesis period when radiation has been showed to cause malformations, we do not expect to detect effects. Cohorts at greater risk are part of our reference group (born in January and February 1987), and to the extent that there were teratogenic effects, this would tend to attenuate our results. Still, the fact that Ericson and Källén [1994] did not find increases in malformations suggests that such effects are minimal.

**Mental, nervous and sensory disorders** We consider hospitalizations with diagnoses related to mental health, diseases of the nervous system, and diseases of the sensory organs (ICD-7 codes 300-398). These conditions may be related to development of the brain and nervous system.

**Neoplasms** Most research on the health effects of ionizing radiation focuses on cancer. We consider cancers such as cancer of the thyroid and leukemia, as well as non-malignant tumors (ICD-7 codes 140-239).

**Days Hospitalized** This is a summary measure that may proxy for aggregate health care expenditures.

## IV. RESULTS

Our analysis exploits variation in the timing (Figure I) and geography (Figures II & III) of radioactivity from Chernobyl. We estimate three basic specifications, described below.

### A. *Econometric Specification*

We begin by grouping regions of Sweden into four areas according to fallout – R0 (lowest) through R3 (highest) – as detailed in Table I and Figure III.

$$y_i = \alpha_0 \times \mathbf{I}(\mathbf{inutero})_i + \sum_{j=1}^3 \alpha_j \times R_j \times \mathbf{I}(\mathbf{inutero})_i + \beta X_i + \tau_{yob} + \gamma_{mob} + \lambda_{muni} + \epsilon_i, \quad (1)$$

where  $y_i$  is the dependent variable of interest.  $\mathbf{I}(\mathbf{inutero})$  is an indicator variable that takes the value 1 for the cohort born August-December 1986 and 0 otherwise.  $\alpha_0$  is the “main effect,” and we expect  $\alpha_0 < 0$ . If Chernobyl fallout affected the developing brain, we also expect lower performance in areas that received more fallout. Therefore, we interact the  $\mathbf{inutero}$  indicator variable with indicator variables  $R_1, R_2, R_3$  for the three areas R1, R2 and R3 exposed to varying degrees to fallout.  $X_i$  is a vector of controls for gender, parental education (seven education levels, mother and father separately) and county labor market conditions around the time of conception (employment and unemployment rates) to control for selection into fertility.  $\tau_{yob}$  a vector of year of birth indicators.  $\gamma_{mob}$  a vector of month of birth indicators.  $\lambda_{muni}$  a vector of municipality of birth indicators.

Parameters  $\alpha_j, j = 1, 2, 3$  allow for differential effects by region and we hypothesize that  $\hat{\alpha}_3 \leq \hat{\alpha}_2 \leq \hat{\alpha}_1 < 0$ .

These parameters measure the extent to which the outcomes for the  $\mathbf{inutero}$  children born in the corresponding areas at the time of the accident differ from the  $\mathbf{inutero}$  children born in the reference area, controlling for all permanent differences between areas, i.e., we assume that:

$$\text{cov}(\epsilon_i, R_j \times \mathbf{I}(\mathbf{inutero}) | X_i, \tau_{yob}, \gamma_{mob}, \lambda_{muni}) = 0, j = 1, 2, 3.$$

To the extent that parents or schools responded to cognitive damage, this would tend to attenuate the observed damage if the response was compensatory. (We discuss this issue in greater detail in Section V.)

Our second strategy uses the continuous measures of radioactive fallout at the municipality or county level in place of the regional grouping to estimate a model of the form:

$$y_i = \alpha_0 \times \text{I}(\text{inutero})_i + \alpha_1 \times \log(\text{FALLOUT}_r) \times \text{I}(\text{inutero})_i + \beta X_i + \tau_{yob} + \gamma_{mob} + \lambda_{region} + \epsilon_i, \quad (2)$$

where  $\text{FALLOUT}_r$  measures average fallout in region (municipality or county)  $r$ , for example, municipality-level Cs-137 kBq/m<sup>2</sup>. An advantage of this method is that it avoids re-categorizing municipalities into regional groups. However, functional form assumptions become more important.<sup>20</sup> Again, our identifying assumption is independence between the disturbances and the measure of exposure conditional on permanent differences between the areas with different exposure and the other control variables.

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 *in utero* during Chernobyl to their siblings.

That is, we estimate equation (1) with family fixed effects:

$$y_i = \alpha_0 \times \text{I}(\text{inutero})_i + \sum_{j=1}^3 \alpha_j \times R_j \times \text{I}(\text{inutero})_i + \pi_{family} + \tau_{yob} + \gamma_{mob} + \lambda_{muni} + \epsilon_i, \quad (3)$$

where  $\pi_{family}$  is a vector of indicator variables, one for each family (5,547 in total). Municipality fixed effects are identified by families who report different municipalities of birth for their children. We restrict the sample to those families with two same-sex full siblings with married fathers (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 born between 1983 and 1988).

Including these fixed effects is equivalent to differencing the outcomes and regressors of the sibling *in utero* during Chernobyl fallout from his/her sibling. Therefore, comparisons identifying 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. This approach controls for all unobserved heterogeneity at the family level.

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<sup>20</sup>Although similar results are obtained when  $\text{FALLOUT}_r$  is not logged.

## *B. Health*

Before considering school performance, we evaluate health in the universe of birth records and hospitalizations through 2006. Sweden has universal health insurance, and fees, when charged, are nominal and therefore unlikely to deter low income families from using health care.<sup>21</sup>

Table II reports results from estimating equation (1) on our natality and In-patient data. Estimates in column 1 reveal no significant effects for birth weight; nor do the magnitudes of point estimates correspond to geographic variation in fallout levels. The largest difference (for R2) indicates a less than .3% mean difference in birth weight. Nor do we detect significant differences in APGAR score (column 2) or gestation length (column 3). And again, the ordering of the point estimates does not correspond to variation in fallout.

Turning to the universe of hospitalizations through 2005 (i.e., during the 19 years after the accident), we again find no systematic pattern or statistically significant differences for the cohort born in fall of 1986. This cohort was no more likely to be diagnosed with a congenital malformations (column 4), mental or nervous system problems (column 5), or to be hospitalized more days (column 6). There is no systematic ordering of the magnitude of point estimates.

We also studied the occurrence of neoplasms and diseases of the blood. However, the low risk of these diseases made them unsuitable for regression analysis, and we report instead the actual occurrence and the predicted occurrence based on the sample means. For neoplasms (tumors), we found 6 cases for those born in R3, August-December 1986, against a predicted number of 6.82 ( $1154 \times .0059175$ ). For diseases of the blood and blood forming organs, the corresponding figures were 0 actual cases, against a predicted number of 0.32.

In summary, we can detect no significant aberration in the universe of births and hospitalizations for those born in August-December 1986.

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<sup>21</sup>Private health care exists in Sweden but is rare.

Table II: Health

	(1)	(2)	(3)	(4)	(5)	(6)
	Nativity data			In-patient data		
	Birth weight	Apgar<10	Gestation	Malformation	Mental	Hospitalization
mean	3,484 (grams)	0.175	280 (days)	0.021	0.068	5.6 (days)
<b>inutero</b> × area:						
R3	-4.32 [15.85]	-0.015 [0.014]	-0.371 [0.318]	-0.007 [0.005]	-0.012 [0.011]	-0.143 [0.853]
R2	-9.37 [15.79]	-0.021 [0.014]	-0.284 [0.322]	-0.002 [0.001]	-0.002 [0.002]	0.025 [0.656]
R1	-0.057 [19.10]	-0.015 [0.022]	-0.343 [0.383]	0 [0.002]	-0.002 [0.002]	-0.328 [0.670]
$N$	584,014	595,354	586,139	551631	551631	551632
$R^2$	0.001	0.011	0.001	0	0	0

Apgar<10 – dummy, equals 1 if the five-minute Apgar score was below 10.

The in-patient data are through 2005.

Malformation – dummy, equals 1 if any of the diagnoses codes (up to eight for each in-patient record) indicated congenital malformations (ICD-7 codes 750-759).

Mental – dummy, equals 1 if any of the diagnoses codes (up to eight for each in-patient record) indicated mental, psychoneurotic, and personality disorders or disease of the nervous system and sense organs (ICD-7 codes 300-398) in any of the in-patient records for a person.

Hospitalization – Sum of days in hospital, mean=5.6 and median=1.

## C. School Performance

### C.1. Graphical Results

We begin by presenting the share qualifying to high school, average grades, and average math grades in a series of figures.

Figure IV shows the fraction of each birth cohort qualifying to high school. Because there is substantial seasonality in school performance by birth month, we compare those born August-December 1986 to those born August-December in adjacent years in the left two panels. In the upper left panel, we compare annual qualification rates for those born in R3 (highest fallout) to the rest of Sweden (R0-R2). 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. The lower left panel again plots the R3 means, but now against the lowest fallout region of Sweden: Norrbotten (R0). 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.<sup>22</sup> This is consistent with grades in the core subjects (and thus qualification to high school) being assigned in part based on nationally standardized test (see Section II D) where the national standard was temporarily relaxed.

As a falsification exercise, the right panels of Figure IV make the same regional comparisons for those born between February and May, i.e., cohorts for whom the studies of A-bomb survivors do not predict effects attributable to radiation. Clearly, the poor performance of the R3 cohort does not extend to those born just prior to the accident and exposed to the radiation spike in Figure I as neonates. This finding reduces the likelihood that geographically-varying effects unrelated to Chernobyl account for the pattern observed for the cohorts most likely exposed between weeks 8 and 25 of gestation.

Next, we present grades by month of birth. Figure V plots the difference between the

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<sup>22</sup>The “pre-treatment” gap in qualification rates in the bottom left panel of Figure IV is consistent with effects on children born prior to Chernobyl and therefore exposed post-natally. To the extent that this cohort gap is due to Chernobyl, our regression estimates may be interpreted as the *additional* effect attributable to prenatal exposure. However, corresponding “pre-treatment” gaps are not apparent in Figures V & VI.

mean grade sum in R3 and R0, and Figure VI does the same for the mean Mathematics grade. While generally slightly negative, there is a pronounced dip in this difference for the cohort born in the fall of 1986. We do not observe larger regional gaps for those born before Chernobyl (e.g., aged 2 years during the accident) than those conceived after the radiation spike. This suggests that not only were cohorts exposed at weeks 8 to 25 more affected, but also that children exposed postnatally were not particularly affected (consistent with Otake and Schull [1998]).

### *C.2. Regression results*

Tables III-VI present our primary regression estimates, where standard errors are clustered at the municipality level (as discussed in Section D.1). With the exception of Table VI, outcomes in compulsory school are reported. (As described above, for compulsory schooling we analyze cohorts born 1983-1988, and for high school outcomes we consider cohorts 1983-1987, since the 1988 cohort would only have completed two years of high school in 2006, the last year of our high school data.)

First we present results from estimating (1) without the region interaction terms. This amounts to only exploiting the time variation and the estimated effect is negative for all of the four outcomes, albeit not statistically significant, Table III, columns (1) and (5). Next, we turn to our difference-in-differences estimation where we exploit both the time and the regional variation. The regional interaction terms are entered sequentially to allow for different base groups in the regressions, Table III, columns (2)-(4) and (6)-(8). First, the worst affected area, R3, is compared to the rest of Sweden; then to R0 and R1; and finally to R0. Consistent with radiation related damage, the estimated effect is negative and the magnitude increases with the difference in fallout, and the ordering corresponds to the ordering of fallout. For the average grade, we estimate a reduction of 0.54 points, or a roughly 2.5 percentile drop in the grade distribution for the `inutero` cohort from R3.<sup>23</sup> We also find this group to be 3 percent less likely to qualify to high school. As for Mathematics, the `inutero` cohort in the most exposed area is estimated to have a 0.67 point lower grade, or a six percent reduction (0.67/11.9). The effect

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<sup>23</sup>For average grades, qualification, and Math, the estimated  $\alpha_j$ 's in (1) are significantly different for R3 versus R2 and the R3 versus R1 at at least the 5% level.

size is comparable to the estimated effect of a full year’s delay in school entry (from month of birth dummies, not reported, available on request). The results for Swedish are qualitatively similar, albeit smaller in magnitude.

Table IV repeats the analysis using four different continuous measures of fallout (in logs). The first two are the *in situ* measures of Cs-134 and I-131, which were aggregated to the municipality level as described above. Since there were only 61 monitoring sites, our sample size is reduced accordingly. The last two regressions use aerial measurements of Cs-137 at the municipality and the county level respectively, and here we have full coverage. The reduction in Math grades is statistically significant for all radiation measures, and for qualification to HS, the county-level aerial measurement is significant. The estimated relationship between grades and exposure is negative in ten out of the 11 remaining cases, but fails to be statistically significant.

A violation of our identifying assumption for equations (1) and (2) would occur if the unobservable characteristics of families from high radiation areas of Sweden with children born in the fall of 1986 deteriorated. First, we note that controlling for observable background characteristics (e.g., parental education) does not substantially change our damage estimates.<sup>24</sup> This possibility motivates our sibling fixed effects estimation, the strongest test of our hypothesis. Table V presents the results. The within sibling comparison confirms the findings in the cross section, reducing the likelihood that the found evidence of damage is driven by systematic heterogeneity across families. Moreover, the effect sizes are larger than in the cross-section. For example, the effect on math scores of being prenatally exposed to Chernobyl is over 10%. The strengthening of damage estimates suggests that to the extent that parents responded to the cognitive endowment, such responses may have been reinforcing [Rosenzweig and Schultz, 1982, Loughran et al., 2008, Rosenzweig and Zhang, 2008].

Finally, we repeat the basic analysis for those who graduated from high school. Table VI presents results from estimating (1) for graduation, average grades, mathematics and Swedish. Significant effects are found for average grades, with the expected ordering of point estimates for other outcomes. With the exception of graduation, however, the estimated effect size is smaller than those we found for compulsory schooling. This is

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<sup>24</sup>For example, see the unadjusted estimates for qualification in Table 4 of Almond, Edlund, and Palme [2007].

Table III: Compulsory School Grades – Effect by Geographic Area

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	Grade Average (mean=12.78)				Qualify to HS (mean=0.912)			
<b>inutero</b>	-0.028 [0.026]	-0.023 [0.037]	0.125** [0.053]	0.367*** [0.139]	-0.003 [0.002]	-0.003 [0.002]	0.003 [0.003]	0.015** [0.007]
<b>inutero</b> × area:								
R3		-0.153 [0.113]	-0.301** [0.119]	-0.543*** [0.176]		-0.012 [0.008]	-0.018** [0.008]	-0.030*** [0.010]
R2			-0.213*** [0.054]	-0.456*** [0.140]			-0.009*** [0.003]	-0.020*** [0.007]
R1				-0.269* [0.147]				-0.013* [0.007]
<i>N</i>	551630	551630	551630	551630	551630	551630	551630	551630
<i>R</i> <sup>2</sup>	0.2	0.2	0.2	0.2	0.05	0.05	0.05	0.05
	Mathematics (mean=11.96)				Swedish (mean=12.73)			
<b>inutero</b>	-0.026 [0.032]	-0.02 [0.040]	0.128*** [0.046]	0.470*** [0.104]	-0.034 [0.031]	-0.031 [0.035]	0.082 [0.055]	0.303** [0.141]
<b>inutero</b> × area:								
R3		-0.184** [0.093]	-0.333*** [0.097]	-0.674*** [0.133]		-0.084 [0.158]	-0.198 [0.164]	-0.418** [0.209]
R2			-0.214*** [0.047]	-0.555*** [0.103]			-0.163*** [0.059]	-0.384*** [0.142]
R1				-0.380*** [0.106]				-0.245 [0.151]
<i>N</i>	551630	551630	551630	551630	551630	551630	551630	551630
<i>R</i> <sup>2</sup>	0.13	0.13	0.13	0.13	0.2	0.2	0.2	0.2

Standard errors clustered at the municipality level in brackets.

Table IV: Compulsory School Grades – Continuous measure of exposure

(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	Municipality	Grade Average	County		Municipality	County	County
					Qualify to HS		
Cs-134	-3.400			-0.053			
	[2.548]			[0.125]			
I-131	-0.249			-0.003			
	[0.254]			[0.016]			
Cs-137		-2.740			-0.241		
		[2.483]			[0.182]		
Cs-137			-2.921			-0.522***	
			[2.781]			[0.171]	
N	181258	169659	551630	181258	169659	551630	551630
R <sup>2</sup>	0.2	0.2	0.2	0.05	0.05	0.04	0.05
Mathematics							
Cs-134	-4.087**			-1.306			
	[1.949]			[3.693]			
I-131	-0.540***			0.190			
	[0.190]			[0.252]			
Cs-137		-4.491*			-2.436		
		[2.354]			[3.466]		
Cs-137			-6.185*			-2.369	
			[2.968]			[2.830]	
N	181258	169659	551630	181258	169659	551630	551630
R <sup>2</sup>	0.14	0.14	0.13	0.2	0.2	0.19	0.2

Standard errors clustered at the level of treatment aggregation (municipality or county) in brackets.

Table V: Compulsory Schooling – Sibling Fixed Effects

	(1)	(2)	(3)	(4)
	Grade Average	Qualify HS	Math	Swedish
<i>inutero</i> × area:				
R3	-0.935** [0.427]	-0.049 [0.044]	-1.439*** [0.503]	-0.733 [0.541]
R2	-0.795** [0.374]	-0.028 [0.041]	-1.417*** [0.472]	-0.843* [0.434]
R1	-0.617 [0.382]	-0.009 [0.044]	-1.215** [0.486]	-0.679 [0.435]
<i>N</i>	11094	11094	11094	11094
<i>R</i> <sup>2</sup>	0.8	0.66	0.73	0.76

Standard errors clustered at the municipality level in brackets.

presumably due to the fact that high school graduates are positively selected, and high school attendance is not compulsory.

#### D. Measurement Error

The aerial measurement of Caesium deposition over Sweden did not begin until May, 9, 1986 [Isaksson et al., 2000], two weeks after the accident. Iodine was believed the largest single contributor to radiation doses initially, but due to its relatively short half-life (8 days), was outstripped by other longer-lived radionuclides during the summer of 1986. For example, gamma radiation levels in Njurunda had already dropped to half their April 29 peak when flights began on May 9 (See Figure I and Kjelle [1987]). While our *in situ* data indicate that the correspondence between Iodine and Caesium was high, this relationship weakens over time. Thus, we expect some slippage between the magnitude of the initial radiation spike and subsequent aerial measurement of Caesium (measurement error).

We may be able to improve measurement of geographic differences in the initial radiation spike by using rainfall patterns. As noted above, the Chernobyl accident generated “a highly nonuniform distribution of ground deposition produced by rainout” [Hohenemser, 1988]. Devell [1991] noted:

Rainfall at locations which were passed by the plume washed-out significant amounts of the radioactive materials, where were deposited on the ground.

Table VI: High School Outcomes – Effect by Geographic Area

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	Graduate (mean=0.732)				Grade Average (mean=14.2)			
inutero	-0.004 [0.003]	-0.003 [0.003]	0.006 [0.005]	0.015 [0.020]	-0.025 [0.024]	-0.021 [0.024]	0.014 [0.029]	0.132*** [0.048]
inutero × area:								
R3		-0.016 [0.014]	-0.026* [0.014]	-0.035 [0.024]		-0.138 [0.165]	-0.173 [0.166]	-0.291* [0.169]
R2			-0.014*** [0.005]	-0.023 [0.020]			-0.05 [0.033]	-0.168*** [0.049]
R1				-0.01 [0.020]				-0.131** [0.052]
N	444583	444583	444583	444583	325255	325255	325255	325255
R <sup>2</sup>	0.05	0.05	0.05	0.05	0.18	0.18	0.18	0.18
	Mathematics (mean=13.3)				Swedish (mean=13.9)			
inutero	-0.034 [0.040]	-0.03 [0.041]	0.054 [0.051]	0.173 [0.160]	-0.024 [0.031]	-0.024 [0.032]	-0.075 [0.048]	0.057 [0.137]
inutero × area:								
R3		-0.108 [0.164]	-0.193 [0.168]	-0.312 [0.225]		0.019 [0.232]	0.07 [0.235]	-0.062 [0.268]
R2			-0.120** [0.061]	-0.24 [0.161]			0.072 [0.054]	-0.059 [0.138]
R1				-0.133 [0.165]				-0.147 [0.143]
N	324285	324285	324285	324285	323879	323879	323879	323879
R <sup>2</sup>	0.11	0.11	0.11	0.11	0.17	0.17	0.17	0.17

Standard errors clustered at the municipality level in brackets.

The wash-out is dependent on total rainfall or rainfall intensity

One study of Chernobyl fallout in Göteborg (in western Sweden) found that 99% of Chernobyl deposition was due to rainfall. [Mattsson and Vesanen, 1988].

Daily precipitation data from 94 weather stations across Sweden are available from the National Climactic Data Center of the US Department of Commerce.<sup>25</sup> Rainfall in the 10 days after the Chernobyl accident (while the plume was over Sweden) is indeed strongly predictive of deposition –  $R^2$  of .77.<sup>26</sup> As wet deposition is a well-known physical process [Holmberg et al., 1988], a strong first stage is to be expected. Rainfall in the Chernobyl aftermath is only weakly (and negatively) correlated with rainfall during the rest of the year.<sup>27</sup> Thus, deposition was not in the “rainy” parts of Sweden. As aerial measurement of deposition did not begin until May, 9, 1986, i.e., four days after the end of the 10-day rainfall window [Isaksson et al., 2000], confounding of radiation measures by weather conditions is unlikely.

We instrument for measurement error in Caesium deposition using a well-specified physical process. Unfortunately, few of the the *in situ* radiation monitoring stations were located near the separate set of rainfall monitors. Therefore, we instrument for the *aerial* radiation measurements (at the county level).

Table VII reports OLS and IV coefficient estimates for county-level measures of Caesium deposition (logged) interacted with weeks 8 to 25 gestation during Chernobyl. Because we do not have rainfall measures for Södermanland county, we begin with OLS estimates for the sample with this county dropped; these are trivially different from Table IV estimates in the paper.<sup>28</sup> Instrumenting for deposition with rainfall in the 10 days following Chernobyl, we find larger point estimates – roughly double the OLS estimates. The pattern of increased point estimates suggests we indeed had a measurement error problem. Standard errors are also substantially larger, but the IV estimate for qualifying

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<sup>25</sup>[www.ncdc.noaa.gov/oa/ncdc.html](http://www.ncdc.noaa.gov/oa/ncdc.html)

<sup>26</sup>Population weighted county-level regression of Caesium deposition on precipitation, precipitation squared, and a constant.

<sup>27</sup>For the 84 individual rainfall monitors, slope coefficient on the coefficient on rainfall during the rest of the year is -0.0017 with a standard error of 0.033 (*t-stat* = -.51). Similar results are obtained in a county-level specification (as in footnote 26).

<sup>28</sup> $N=535,954$ , or 97% of the Table IV sample.

	(1)	(2)	(3)	(4)
Outcome	Grade	Qualify	Math	Swedish
Cs-137	-2.92	-0.526***	-6.19**	-2.63
<i>OLS</i>	[2.78]	[0.171]	[2.95]	[2.86]
Cs-137	-14.0	-0.909**	-10.9	-11.2
<i>IV</i>	[10.3]	[0.340]	[7.76]	[9.72]
Cs-137	-25.0	-1.84**	-11.1	-25.1
<i>IV, sibling fixed effect</i>	[23.9]	[0.827]	[19.4]	[26.5]

to high school is significant at the 5% level.<sup>29</sup> Finally, we report the IV estimates for the sibling comparisons – i.e., where sibling differences are identified by county-level rainfall differences. These point estimates are substantially larger than the basic IV results (with the exception of Math). Standard errors are again larger, but qualification remains significant at the 5% level. Thus, the consistent increase in point estimates suggests our results are robust to improvements in measurement of radiation exposure where the source of variation is plausible and clearly defined.

## E. Projected Wage Effects

### E.1. Sweden

Lower school performance may translate into lower productivity and earnings as these cohorts enter the work force. To that end, we study the cohort born 1972, the oldest cohort for which we can match individual school and earnings records (the latter from the *LISA* data base). The earnings data is pre-tax labor income in 2003 (when the cohort is 31 years old). The 1972 cohort was graded on a different scale. For comparability, we convert the grades to grade percentiles.

We regress log earnings (top panel) or percentile in the earnings distribution of this cohort (lower panel) on grades in compulsory schooling (Table VIII, columns 1 and 2) and

<sup>29</sup>Here, we cluster standard errors at the county level because the rainfall instrument only varies at this level.

level of completed education (Table VIII, column 3) and a gender dummy.<sup>30</sup> We find that a 1 percentile move within the grade distribution is associated with a 0.6 percent change in earnings, or a 0.25 change in the percentile distribution.<sup>31</sup> For the *inutero* cohort in the worst affected area, we estimated that Chernobyl fallout reduced Mathematics grades by, on average, -.67 (Table III), or a 2.2 percentile reduction.<sup>32</sup> Plugging in these numbers, we obtain a Chernobyl damage of about 1.3 percent of earnings, or a 0.55 drop in the percentile earnings distribution, for the worst affected cohort. For those in least affected area (outside Norrbotten), R1, the corresponding numbers are a 1.3 percentile reduction in the Mathematics grade, implying a 0.8 percent reduction in earnings, or a 0.3 percentile drop in the earnings distribution.

If, instead, we used the grade average, the estimated damage was a reduction in about 6 percentiles, which predicts an earnings reduction of 3.3 percent or a drop of 1.5 percentiles in the earnings distribution.

As for high school graduation, Table VIII, column 3, we find that high school graduates earned, on average, 19 percent more than those without a high school degree, or in terms of position in the earnings distribution, a 5.6 percentile difference. Taking our estimated reduction in probability of obtaining a high school degree of 2.9 percent, this alone would predict a 0.5 percent reduction in this cohort's earnings. This estimate is lower than that predicted by differences in Mathematics grades, which may derive from the fact that it ignores the possibility that there is also an effect on continuation to college (an outcome that is too early for us to measure).

As mentioned earlier, another way to quantify the damage is to note that for Mathematics, the estimated reduction in performance for the worst affected cohort corresponded to a full year's delay in school entry (calculated using the coefficients on the month of birth dummies, not reported).

## *E.2. Europe*

Most of Europe received fallout at or above the level of R1. Or, more precisely, the area between 5 and 50 degrees east, and 45 and 65 degrees north, plus most of Europe east of

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<sup>30</sup>Unfortunately, we do not have parental characteristics matched to this sample.

<sup>31</sup>Estimating men and women separately, we find a slightly larger effect for women.

<sup>32</sup>Assuming that the observed grades are the midpoints in uniform distributions (within observed bins).

Table VIII: Returns to Education, 1972 birth cohort

	(1)	(2)	(3)
	log(2003 Earnings)		
Grade Percentile: <sup>a</sup>			
Math	0.0058*** [0.0001]		
Sum		0.0063*** [0.0001]	
Completed Education: <sup>b</sup>			
High School			0.187*** [0.014]
College			0.353*** [0.144]
$R^2$	0.103	0.106	0.09
	Earnings distribution (percentiles)		
Grade Percentile: <sup>a</sup>			
Math	0.235*** [0.003]		
Sum		0.259*** [0.003]	
Completed Education: <sup>b</sup>			
High School			5.58*** [0.35]
College			14.59*** [0.36]
$R^2$	0.21	0.219	0.186
$N$	85,706	85,706	85,706

<sup>a</sup> – Compulsory school.

<sup>b</sup> – As of 2003. The (mutually exclusive, collectively exhaustive) education categories are: High school drop out or less, High school Graduate, Some college or more.

Regressions include a dummy for female and a constant.

Italy [UNSCEAR, 2000, Figure X]. This area is home to about 410 million people.<sup>33</sup> If we assume the 1986 birth cohort to be 1/100th of the total population, and the August-December births to account for 5/12 of those births, we arrive at 1.7 million children affected. Assuming a 1 percent loss in productivity and annual income at 30,000 USD, this translates into half a billion USD ( $30,000 \times 1.7\text{M}/100$ ) in lost productivity annually when these cohorts reach prime working age.

## V. COMPENSATORY RESPONSES?

A complete accounting of Chernobyl damage in Sweden would include the cost of avoidance behavior and responsive investments. The fact that we find stronger effects when we compare exclusively among siblings (Tables V and VII) underscores the potential importance of behavioral responses to a negative health or endowment shock. In our context, these behaviors would occur primarily in the postnatal period, as it was not known at the time of the accident that the level of radiation exposure would generate damage, let alone disproportionate damage to the fetuses between 8 and 25 weeks gestation.<sup>34</sup> In the case of the observed cognitive damage, investments could respond to damage regardless of whether damage was attributed to Chernobyl. Such investments might include changes in parental time and schooling inputs. Failing to account for remedial investments in early childhood, should they exist, would lead to an underestimate of costs, see Harrington and Portney [1987] and Deschnes and Greenstone [2007].<sup>35</sup>

In Section A, we proceed to evaluate the most *readily measured* potential responses to

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<sup>33</sup>For this calculation, we subtract from Europe's population of 728 million, 22 percent of Russia's population (of 142 million), the populations of the UK, the Netherlands, Belgium, France, Spain, Portugal, Italy and Turkey. Turkey (70 million people) is excluded for lack of fallout data.

<sup>34</sup>Nor do we find any evidence of avoidance behavior in our data with respect to place of birth. For example, there was no change in the tendency for high education mothers to give birth in high radiation areas of Sweden in the months after Chernobyl accident.

<sup>35</sup>An alternative approach to estimating costs of nuclear accidents/safety might consider housing prices near nuclear reactors before and after the Chernobyl accident relative to farther removed areas, as suggested by Chay and Greenstone [2005] and Davis [2008].

radiation-induced cognitive damage.<sup>36</sup> In Section B, we consider parental responses and what can be inferred from our data about the process of human capital formation. We have no measures of parental investments and therefore resort to an indirect approach: we split the sample by parental education and find damage to be concentrated among low-education families.

### A. *Schooling Expenditures*

A possible way to compensate for negative effects on school performance is through extra municipality resources during primary education. To evaluate such a response, we consider two schooling inputs: (i) the average municipality school expenditures per pupil during the nine years when the children are in the comprehensive school financed by the municipalities, and; (ii) the average teacher-pupil ratio. We use the following empirical specification:

$$y_{it} = \sum_{i=1}^3 \gamma_i \times R_i \times \text{I}(86) + \sum_{i=1}^3 \delta_i \times R_i + \tau_t + \epsilon_{it}, \quad (4)$$

where the indices  $i$  and  $t$  represent municipality and year, respectively;  $\text{I}(86)$  is a dummy variable that equals 1 for the years the 1986 cohort is of compulsory school age;  $\tau_t$  is a vector of year indicators.

We include years of schooling data for cohorts born between 1983 and 1988 (as in the compulsory schooling results). For example, the 1983 cohort enters compulsory school in 1990 and leaves in 1999, while the 1986 cohort enters in 1993 and leaves in 2002. Thus, annual municipality-level school data cover 1990-2004 and the  $\text{I}(86)$  dummy is one for the years 1993-2002 and zero otherwise.

Table IX presents the results when this model is estimated on data from all Swedish municipalities, and none of the coefficient estimates are significant. That is, we do not detect evidence of compensatory (or reinforcing) behavior through municipality school resources.

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<sup>36</sup>We also explored whether the likelihood and timing of subsequent children varied with prenatal exposure to Chernobyl fallout changed – i.e., to run the “quantity-quality” experiment in reverse. In contrast to Rosenzweig and Wolpin [1988], we did not detect a systematic gradient between the birth endowment and subsequent fertility behavior.

Table IX: Municipality school expenditures, 1990-2004

	School Expenditures/Pupil	Pupil-Teacher Ratio
I(86) ×		
R3	3.02 [31.0]	0.70 [2.21]
R2	5.90 [19.4]	0.96 [1.31]
R1	10.79 [21.3]	0.65 [1.43]
$R^2$	0.34	0.32
$N$	2,307	1,707

Standard errors in brackets.

I(86) is an indicator variable that is one for the years 1993-2002 and zero otherwise.

### B. Heterogeneity in Effects by Parental Education

Table X presents the results when we divide the sample according to father's education. The top panel presents the results for those whose father had two years or less of high school education, and the bottom panel the remainder of the sample.<sup>37</sup> First, we note that restricting the comparison to be within sibling pairs doubles the estimated effect size (see Table V). Second, these effects are concentrated among those with students with low-education fathers (see Table X). For the low education group, the effect size ordering is preserved for Mathematics and Swedish. The damage estimates for those with better educated fathers are smaller and not statistically significant. In the difference-in-differences analysis, damage is also concentrated among low-education families (results available on request).<sup>38</sup>

How do we interpret this finding that damage is concentrated among low-education families? One possibility is that the better educated were less affected in 1986. We do not believe this to be likely. The established view then (and now) was that the radiation doses in question were too small to have an effect.

Therefore, our starting point is that the children suffered a negative shock to their cognitive endowment that did not vary systematically with parental characteristics. Given this assumption, what can account for the observed pattern?

<sup>37</sup>The cutoff was chosen to create groups roughly equal in size.

<sup>38</sup>For average grades, qualification, and Swedish, tests of equality of effects across education groups are easily rejected.

Table X: Compulsory Schooling – Sibling Fixed Effects by Father’s Education

	(1)	(2)	(3)	(4)
	Grade Average	Qualify HS	Math	Swedish
Father 2-yr hs or less				
<i>inutero</i> × area:				
R3	-1.287** [0.516]	-0.113* [0.058]	-2.243*** [0.678]	-0.691 [0.792]
R2	-0.975** [0.387]	-0.056 [0.049]	-1.656*** [0.544]	-0.793 [0.539]
R1	-0.852** [0.405]	-0.031 [0.053]	-1.510*** [0.581]	-0.61 [0.574]
<i>N</i>	6290	6290	6290	6290
<i>R</i> <sup>2</sup>	0.78	0.66	0.7	0.75
Father 3 year HS or more				
<i>inutero</i> × area:				
R3	-0.253 [0.707]	0.027 [0.060]	-0.334 [0.772]	-0.426 [0.774]
R2	-0.394 [0.582]	0.017 [0.048]	-0.915 [0.738]	-0.733 [0.732]
R1	-0.129 [0.592]	0.03 [0.050]	-0.654 [0.745]	-0.6 [0.747]
<i>N</i>	4804	4804	4804	4804
<i>R</i> <sup>2</sup>	0.79	0.68	0.72	0.75

Standard errors clustered at the municipality level in brackets.

We consider three possibilities:

1. While the negative health shock might have been similar, initial endowment levels may have been different. For instance, the better educated likely had a higher initial cognitive endowment. If so, all we need for a smaller Chernobyl effect on the measured outcome is decreasing marginal productivity, be it in the production of “innate ability,” or in the transformation of this ability into, say, a Math grade. This first possibility assumes a purely mechanical effect, with no investment response (and does not explain the stronger results within families).
2. It is possible that parents responded to the observed cognitive endowment. These responses could either be compensating (offsetting endowment differences generated by Chernobyl) or reinforcing (varying positively with endowment differences) [Becker and Tomes, 1976]. Furthermore, better educated parents may have reacted differently to the endowment shock than less educated ones. The observed concentration of damage among children with low-education parents is consistent with a larger compensatory response by high education parents compared to low education parents. Alternatively, a smaller reinforcing response by high education parents is also possible.

Absent additional data on parental investments, it is difficult to discern which of these scenarios is more likely. The fact that sibling fixed effects estimates of Chernobyl damage are larger than the difference-in-differences estimates suggests that reinforcing investments may play a role.

The production technology may also have shaped the parental response to Chernobyl damage. Economic models implicitly assume that: “production of skills at different stages of childhood are perfect substitutes” [Cunha and Heckman, 2007]. Here, we consider the substitutability between prenatal damage and postnatal investments in producing cognitive ability. If postnatal investments in cognitive ability are perfect substitutes for prenatal ones, then the timing of investments across stages of childhood is not very important (discounting aside). If instead postnatal investments are a poor substitute for prenatal ones, then altering the cognitive trajectory set *in utero* is more costly (e.g. in terms of foregone consumption required for investing). In the extreme case of perfect production com-

plements, compensatory investments would be completely ineffective. In fact, the optimal response would be to reinforce prenatal cognitive damage. In this Leontief case, “early disadvantages should be perpetuated” on efficiency grounds [Cunha and Heckman, 2007]. A reinforcing response is thus consistent with a low elasticity of substitution in production among different stages of childhood.<sup>39</sup>

3. A third possibility is that parents have a target level for school performance, for instance that the child achieves at the parental level. Furthermore, assume that absent Chernobyl, the target is binding for children with high education parents, but not for children of low education parents. Following an equivalent-sized Chernobyl shock, children of high education parents would be further away from their target than children of low education parents. High education parents would have much more remediation to do following the Chernobyl shock than low education parents. Here as well, greater damage would be observed among children of less educated parents. However, unless these targets varied within family across siblings, we would not expect larger damage estimates from the siblings comparison.

Finally, a parallel literature in health economics [Currie and Hyson, 1999, Currie and Moretti, 2007, Lin et al., 2007] considered whether the negative impact of poor childhood health on subsequent human capital accumulation is greater in low education or low income families. In general, these papers find larger effects of poor health among low-SES families, consistent with our findings for cognitive damage. However, there is evidence that the “arrival rate” of subsequent health conditions is also higher among low-SES families [Case et al., 2002, Currie and Stabile, 2003, Condliffe and Link, 2008]. In contrast, we do not expect subsequent cognitive shocks to be correlated with prenatal exposure to Chernobyl fallout.

## VI. EXTERNAL VALIDITY

The external validity of our findings does not rest on the likelihood of “another Chernobyl.” Among the various sources of ionizing radiation, the applicability of our results

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<sup>39</sup>Heterogeneity in the magnitude of a reinforcing response across families is possible for high complementarity that is short of a Leontief production function.

can be roughly ordered. We start with the most closely related:

1. **Power plant accidents** Major nuclear accidents are expected in the next 50 years. It is not the case that technological advances in reactor design since Chernobyl have effectively eliminated the risk of future accidents. For example, an interdisciplinary study by MIT (strongly supportive of additional nuclear power plant construction) concluded:

With regard to implementation of the global growth scenario during the period 2005-2055, both the historical and the PRA [probability risk assessment] data show an unacceptable accident frequency. The expected number of core damage accidents during the scenario [of increased reactor construction] with current technology would be 4.

As “Reactor core damage has the potential to release radioactivity to air and groundwater,” [Sharp, 2003, p. 48] our findings are potentially relevant for the pregnant population downwind (and not exclusively nearby) future accidents. Moreover, the recent upsurge of interest in nuclear power generation, driven both by increased energy prices and concerns of global warming, has made the “global growth scenario” advocated by Sharp [2003] more relevant.

As of October 2008, 38 new nuclear power plants were under construction, most in China, India, or Russia.<sup>40</sup> In the US, the 2005 Energy Policy Act offers Federal incentives and loan guarantees for nuclear power (Wall Street Journal, Nuclear Energy’s Second Act? September 5, 2007). Upon signing the bill in 2005, President Bush announced: “We will start building nuclear power plants again by the end of this decade.”<sup>41</sup>

Part of an efficient response to a future accident might include the rapid dissemination of information on where the plume is headed and the likelihood of rain: “A second key global lesson of Chernobyl is that atmospheric transport disasters lead

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<sup>40</sup>The breakdown is as follows: Argentina 1, Bulgaria 2, China 6, Taiwan 2, Finland 1, India 6, Iran 1, France 1, Japan 2, Pakistan 1, Russia 8, S. Korea 4, Ukraine 2, US 1.

<http://www.iaea.org/programmes/a2/index.html>

<sup>41</sup><http://www.whitehouse.gov/news/releases/2005/08/20050808-6.html>

to highly variable impacts, strongly dependent on local rainfall...and dispersion patterns” [Hohenemser, 1988].<sup>42</sup> Sheltering indoors is highly effective in reducing radiation exposure [Finck, 1991]. In terms of foregone labor earnings, it would have been cost effective for women in Sweden who were pregnant during the accident to remain indoors for 2 weeks: with conservative assumptions, the internal rate of return to sheltering was 6% (see Appendix B for details). Thus, were a nuclear accident to occur, our findings suggest that pregnant women between weeks 8 and 25 weeks in the zone of wet deposition might be advised to shelter indoors. The strength of the IV estimates’ first-stage (and magnitude of our 2SLS estimates) underscores the importance of wet deposition immediately following an accident.

2. **Nuclear attacks** It is obviously difficult to assess the likelihood of future attack. What is more certain is that whether propelled by a nuclear explosion or by a terrorist’s radiological dispersion device (i.e., “dirty bomb”), an attack would “probably be targeted at a public area, possibly in an urban environment” [Valentin, 2006] and thus more damaging, other things equal, than a nuclear accident. In addition, because “Nuclear explosions produce air movements, which disperse the radioactive substances” [Vogel, 2007], these may create substantial health damage both to the targeted area and afar. This cognitive damage can be expected to occur at doses an order of magnitude lower than those evaluated for Nagasaki and Hiroshima.

3. **Radon** In addition to comprising the bulk of natural radiation exposure, the population distribution of radon exposure has a high variance. For example, Price and Gelman [2004] found that the average radon concentration in U.S. residences has mean of  $\log(.67)$  pCi/L and standard deviation of  $\log(3.1)$ .<sup>43</sup>

In light of the above, radon doses can be high relative to doses from Chernobyl fallout. In 1986, Hůlka and Malátová [2006] took *in vivo* radiation measurements in Czechoslovakia (direct “whole body” measurements).<sup>44</sup> Radiation doses from

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<sup>42</sup>Additionally, with power plant accidents, “the share of radionuclides with a long half-life time is larger than in nuclear explosions” [Vogel, 2007], though both release the short-lived radionuclides.

<sup>43</sup>1 pCi/L corresponds to 37 Bq/m<sup>3</sup>.

<sup>44</sup>Which can identify radiation sources by distinguishing among specific radionuclides.

“indoor natural exposure were often higher than outdoor exposure to Chernobyl impact,” *even over the summer of 1986*. As sheltering would tend to increase radon exposure, our findings suggest that remediation efforts (e.g., ventilation of basements) might be increased.

4. **Medical Radiation** Current medical doses can be substantial, particularly for Computer Tomography (CT) scans: mean whole-body doses are between 10 and 40 mGy (or roughly an order of magnitude greater than the estimated Swedish dose from Chernobyl). Because the exposure window is shorter for medical x-rays and CT scans relative to Chernobyl related irradiation, a given medical dose should be expected to cause more damage.<sup>45</sup> The largest radiation doses to the fetus come from pelvic and abdomen CT scans of the mother (10 to 25 mGy), procedures of nuclear medicine, and Barium enema (70 mGy) [DeSantis et al., 2005].

An advantage of studying medical radiation itself is that radiation exposures are directly-measurable at the individual level. A shortcoming is basic weakness in the research designs utilized to date.<sup>46</sup> Insofar as mental retardation is concerned (the manifestation of cognitive damage typically considered), current practice in radiology considers the relationship with mental retardation to be “deterministic,” where the probability of damage is zero at small radiation doses, “but above some level of dose, called the *threshold dose*, the probability increases rapidly with dose to 100%” [Hall and Giaccia, 2005]. This threshold is considered to exist at “about .1 to .2 Gy,” [Hall and Giaccia, 2005] i.e., 100-200 mGy. In contrast, radiation is believed to have a “stochastic” effect on cancer (a dose-response relationship with

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<sup>45</sup>“In general, protracted exposures to x- or  $\gamma$ -radiation are associated with lower risks than those of an acute exposure to the same total dose, both for cancer and other endpoints” [Brenner et al., 2003].

<sup>46</sup>Epidemiological research on prenatal exposure to medical radiation has focussed on birth outcomes. For example, the study by Hujuel et al. [2004], published in *JAMA*, linked antepartum dental x-rays and low birth weight. However, various observable characteristics of mothers receiving dental x-rays were *worse* (e.g., they more likely to smoke or have inadequate prenatal care). Similar problems plague earlier work linking medical x-rays to reduced birth weight (e.g., Hamilton et al. [1984]). Perhaps as a result of these weaknesses, there is no consensus that prenatal medical radiation (as currently practiced) is generally hazardous.

no threshold). Quantifying the dose-response relationship for cognitive damage at low doses is beyond the scope of our research design, but is suggested by our findings.<sup>47</sup>

More generally, our findings suggest that radiation damages cognitive ability and thereby human capital at doses currently viewed as safe.<sup>48</sup> As noted above, the maximum dose to the Swedish population was estimated at 4 mSv in the first year [Edvarson, 1991a]. If this estimate is accurate, it falls well below the doses studied in Hiroshima and Nagasaki (around 40 mSv)<sup>49</sup> and is comparable to annual doses from background radiation (around 6 mSv). Our findings contrast with those of the International Atomic Energy Agency, which concluded: “the mental health impact of Chernobyl is the largest public health problem unleashed by the accident to date” [IAEA, 2006]:36. As Sweden received just 5% of Chernobyl fallout, future research might evaluate whether those born in other European countries were similarly affected.

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<sup>47</sup>To this end, we are collaborating with Johanna Adami and Magnus Kaijser (Clinical Epidemiology Unit, Karolinska Institute) to evaluate the natality and subsequent schooling outcomes of some 1,700 children born in the 1980s whose mothers had pelvic x-ray exams during pregnancy (such exams were routinely used in that period to determine the need for c-section). In addition to mapping individual prenatal radiation doses to schooling outcomes, this project will use breech presentations as a control group for radiation exposure.

<sup>48</sup>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.

<sup>49</sup>In a linear extrapolation of Otake and Schull [1998], a reduction of 30 IQ points per Gy (assuming a 1:1 conversion to Sv), implies a negligible effect ( $4 \times 30 / 1000 = 0.12$  points maximum). However 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]

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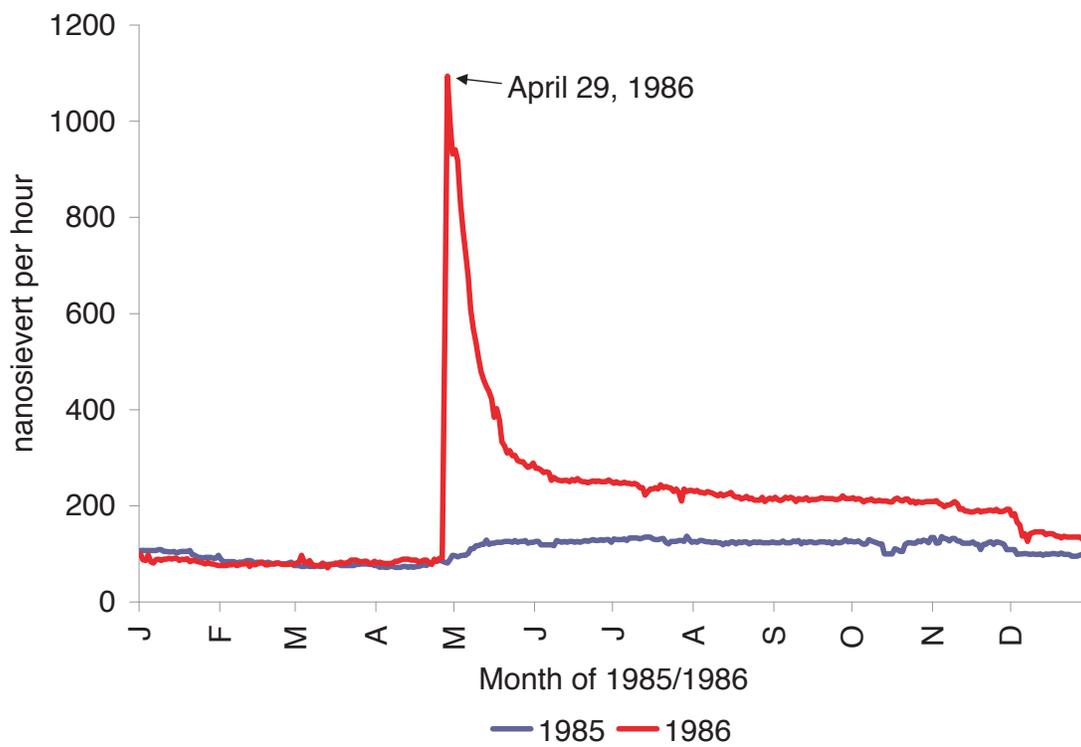


Figure I: Daily Gamma Radiation in Njurunda, Sweden

Source: Kjelle [1987].

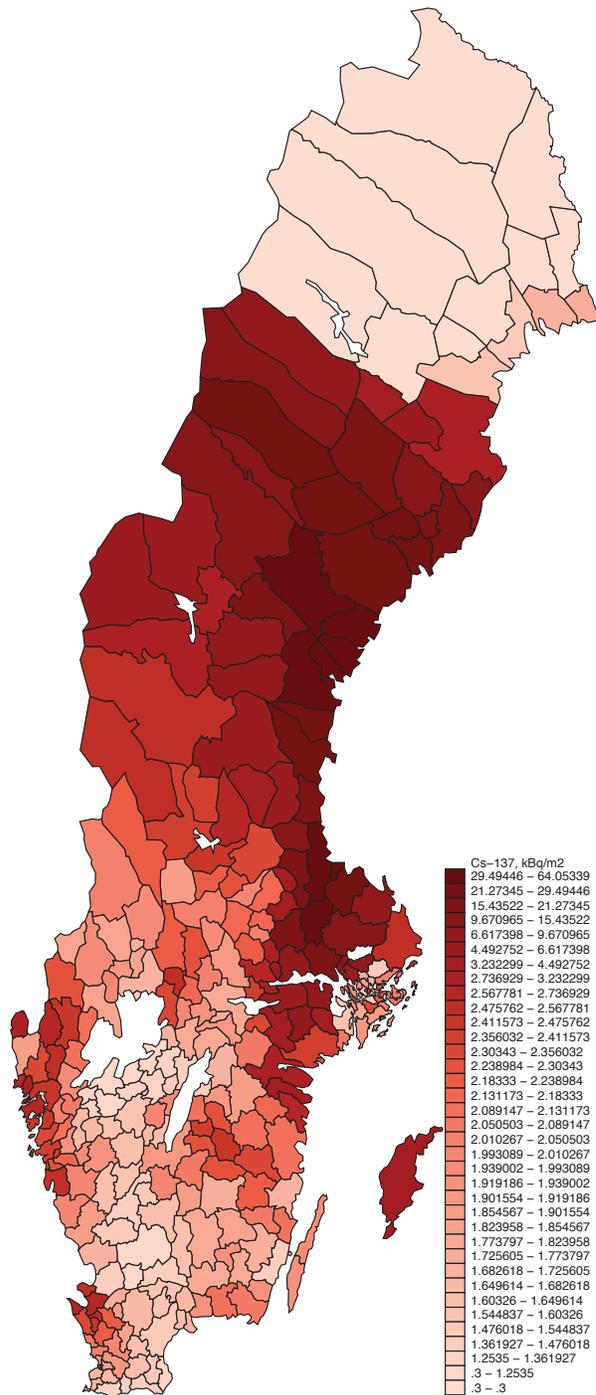


Figure II: Caesium-137 ground deposition in kBq/m<sup>2</sup> by Municipality.

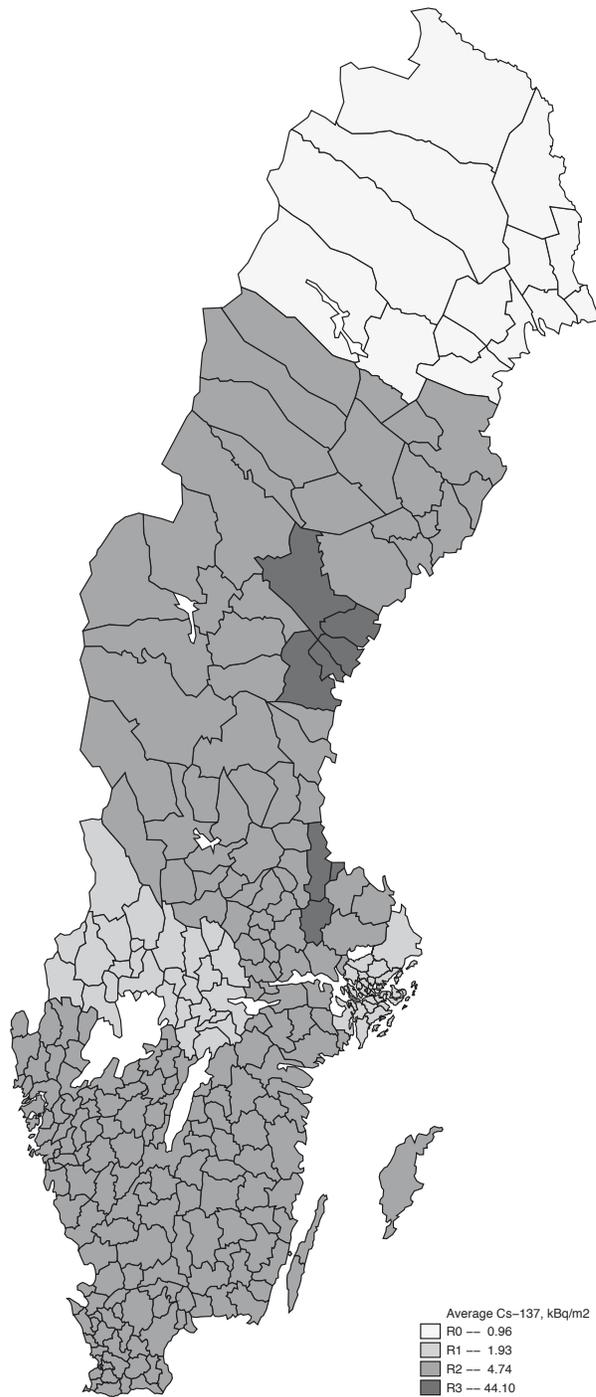


Figure III: Caesium-137 ground deposition in kBq/m<sup>2</sup> by Regions.

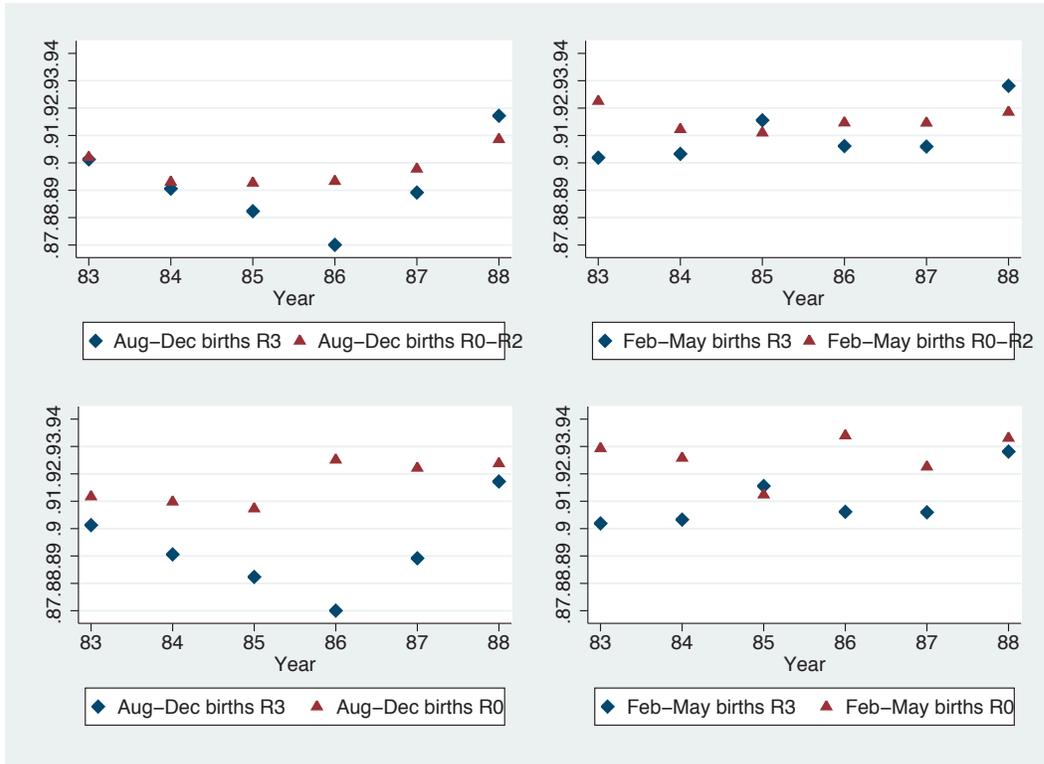


Figure IV: Fraction qualified to high school by year and season of birth. Treatment group: R3 (“Gävle-Sundsvall”) – Control group: Rest of Sweden (top panels); R0 (bottom panels)

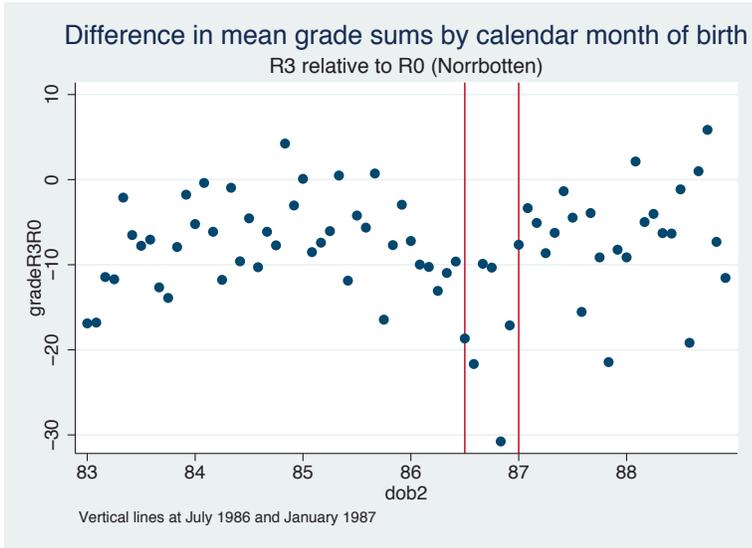


Figure V:

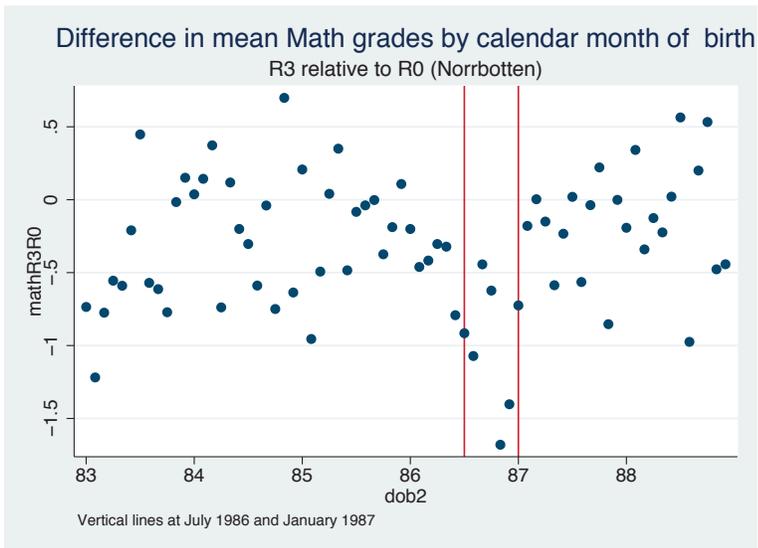


Figure VI:

## APPENDIX A

The becquerel (symbol Bq) is the SI derived unit of radioactivity, defined as the activity of a quantity of radioactive material in which one nucleus decays per second. Radioactivity thus expressed also need to specify the relevant radionuclide and the unit (say  $\text{m}^2$ ,  $\text{m}^3$  or event) to be meaningful. The becquerel replaces the old unit curie (Ci), which corresponds to roughly the activity of 1 gramme of the radium isotope Ra-226, and 37 kBq corresponds to 1  $\mu\text{Ci}$ . Areas that measured more than 37 kBq Cs-137/ $\text{m}^2$  (or 1 Ci/ $\text{km}^m$ ) have been called “contaminated” [UNSCEAR, 2000].

The material below draws heavily on Hall and Giaccia [2005].

Absorbed dose is measured in gray (Gy) and is the absorption of one joule of radiation energy by one kilogram of matter. One gray is equivalent to 100 rad.

The sievert (Sv) measures equivalent dose, which is the product of absorbed dose and the radiation weighing factor, which for x and gamma rays is one, thus rendering Sv numerically equivalent to the Gy for these types of radiation.

The relative biological effectiveness (RBE) is the inverse of the dose of a particular radiation required to produce the same biological effect as a dose of 250-kV x-rays. RBE depends on the dose, the type of radiation, the tissue involved and how the dose is delivered (number of installments and time).

Table XI: Descriptive Statistics Compulsory School

Variable	Mean	Std. Dev.	Min	Max
Qualify to HS	.91	.284	0	1
Grade Average	12.78	3.97	0	20
Math	11.96	4.66	0	20
Swedish	12.72	4.70	0	20
<b>inutero</b>	.06	.246	0	1
R0	.03	.176	0	1
R1	.25	.435	0	1
R2	.68	.466	0	1
R3	.03	.178	0	1
I-131 (municipality)	44.96	114.186	3.26	627.2
Cs-134 (municipality)	4.61	11.003	.12	53.66
Cs-137 (municipality)	4.86	8.999	.3	64.05
Cs-137 (county)	4.93	7.546	1.00	32.26
Male	.51	.499	0	1
Mother's Education:				
6-year Compulsory	.02	.169	0	1
9-year Compulsory	.17	.378	0	1
2-year HS	.43	.495	0	1
3-year HS	.09	.287	0	1
Some College	.16	.368	0	1
3-year College	.10	.312	0	1
Graduate Degree	.00	.042	0	1
Father's Education:				
6-year Compulsory	.06	.241	0	1
9-year Compulsory	.18	.388	0	1
2-year HS	.36	.482	0	1
3-year HS	.11	.324	0	1
Some College	.11	.323	0	1
3-year College	.13	.342	0	1
Graduate Degree	.01	.09	0	1
Labor Market (County):				
Unemployment Rate	.02	.008	.002	.05
Employment Rate	.80	.030	.72	.87

$N = 551,630.$

Table XII: Descriptive Statistics High School

Variable	Mean	Std. Dev.	Min	Max
Graduate HS	.73	.44	0	1
Grade Average	14.19	2.97	0	20
Math	13.27	4.53	0	20
Swedish	13.93	3.88	0	20
inutero	.080	.272	0	1
R0	.030	.173	0	1
R1	.246	.431	0	1
R2	.689	.462	0	1
R3	.032	.177	0	1
male	.495	.4999	0	1
Mother's Education:				
6-year Compulsory	.027	.1622	0	1
9-year Compulsory	.146	.3539	0	1
2-year HS	.111	.314	0	1
3-year HS	.392	.488	0	1
Some College	.171	.376	0	1
3-year College	.133	.340	0	1
Graduate Degree	.016	.126	0	1
Father's Education:				
6-year Compulsory	.064	.245	0	1
9-year Compulsory	.169	.375	0	1
2-year HS	.012	.111	0	1
3-year HS	.444	.496	0	1
Some College	.131	.337	0	1
3-year College	.146	.353	0	1
Graduate Degree	.031	.174	0	1
Labor Market (County):				
Unemployment Rate	.021	.008	.00	.05
Employment Rate	.805	.029	.72	.87

$N = 325,255$  (except for Graduate HS, where  $N = 444,583$ ).

Table XIII: Means of Control Variables by Region

Variable	Region:			
	R0	R1	R2	R3
<b>Mother's Education:</b>				
6-year Compulsory	0.015	0.032	0.029	0.019
9-year Compulsory	0.127	0.156	0.18	0.191
2-year HS	0.517	0.386	0.445	0.455
3-year HS	0.088	0.105	0.085	0.082
Some College	0.155	0.178	0.156	0.158
3-year College	0.094	0.137	0.1	0.092
Graduate Degree	0	0.002	0.001	0
<b>Father's Education:</b>				
6-year Compulsory	0.034	0.048	0.069	0.046
9-year Compulsory	0.117	0.168	0.194	0.198
2-year HS	0.482	0.33	0.375	0.417
3-year HS	0.128	0.136	0.113	0.107
Some College	0.112	0.132	0.114	0.116
3-year College	0.12	0.172	0.124	0.11
Graduate Degree	0.004	0.01	0.009	0.002
<b>Labor Market (County):</b>				
Unemployment Rate	0.04	0.014	0.02	0.024
Employment Rate	0.748	0.836	0.803	0.788

*Compulsory School Sample*

## APPENDIX B

Considering the geographic extent of the ground contamination and the fact that most of the radiation exposure were in the first two weeks, well before any maps detailing fallout were available, it is not obvious that evacuations beyond what was done (from the aforementioned exclusion zone) were warranted. People need somewhere to go. Moreover, road travel in likely heavy traffic comes with its own risks.

A perhaps more practical proposition would have been for the population at risk to stay indoors to the extent possible, which was not recommended at the time nor indicated ex post [Moberg, 1991]. Residential buildings were estimated to provide up to 99 percent shielding, depending on the materials used and the structure [Finck, 1991].<sup>50</sup> Assuming that the cost of seclusion is captured by lost labor income of a full time worker, this amounts to 4 percent in productivity (2/50). Furthermore, assume that this action results in a 1 percent gain in adult productivity and that the child will work between ages 25-65 and have the same baseline productivity as its mother (conservative, since half the children male and no productivity growth is assumed). In this case, the internal rate of return is 6 percent.<sup>51</sup> If we think of 6 percent as being a reasonable discount rate, another way of estimating the monetary cost of prenatal damage due to Chernobyl is to cost two weeks of seclusion for the roughly 1.7 million women who were 8-25 weeks pregnant at the time. Assuming that the opportunity cost is given by full time earnings, and an annual income of 30,000 USD, we arrive at a figure of 2 billion USD ( $30,000 \times 0.04 \times 1.7M$ ).

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<sup>50</sup> Assuming not a radon house.

<sup>51</sup> Assuming a lower opportunity costs, say 2 percent of earnings (for instance from pregnant women working only 50 percent), raises the internal rate of return to 8 percent.