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Fallout and Fertility: Chernobyl's Legacy and the Role of Compliance with Public Protection Measures

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Fallout and Fertility: Chernobyl's Legacy and the Role of Compliance with Public Protection Measures

Abstract

This paper examines the impact of early-life radiation exposure on adult fertility using a dynamic difference-in-differences approach. Analyzing 18 cohorts of women born between 1976 and 1993 in Italian municipalities, we utilize a radiation exposure indicator and administrative datasets on hospitalizations (2004-2016) and birth certificates (2002-2019). Findings show increased rates of thyroid complications and cancer among women exposed in utero or up to five years old, along with higher incidences of spontaneous abortions and stillbirths. Finally, municipalities with high agricultural employment experienced more severe fallout effects, while political beliefs did not significantly influence adherence to protective measures.

Keywords: fertility, radiation exposure, public health, health behaviors.

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1 Introduction

In the aftermath of the Chernobyl nuclear disaster in 1986, the scientific community was confronted with an unprecedented ecological and human health challenge. Beyond the immediate response and containment efforts, a growing body of research has since delved into the consequences of exposure to ionizing radiation. Recent events, such as the nuclear danger posed by the conflict in Ukraine and its impact on nuclear facilities and infrastructure, underscore the ongoing relevance of understanding the consequences of radiation exposure, not only from a historical perspective but also in light of contemporary challenges.

The Chernobyl disaster, much like the recent COVID-19 pandemic, highlights the challenges faced by states with limited capabilities and resources in managing large-scale crises. The success of a response to such emergencies hinges not only on the government's actions but also on the public's reaction to information and guidance. Societies do not merely receive policies passively; they actively contribute to the implementation of government measures [Ostrom \(1996\)](#). Consequently, the effectiveness of these responses is the result of a collaborative effort between the government and its citizens [Ji et al. \(2024\)](#). Official estimates of fallout effects assume full adherence to protective measures like food consumption bans ([Risica, 1987](#)), but actual compliance may be incomplete. Economic incentives, beliefs, trust in authorities, and social norms are likely to influence compliance ([Allcott et al., 2020](#), [Banerjee et al., 2019](#), [Barrios et al., 2021](#), [Flückiger et al., 2019](#)) and the net impact of the disaster.

This paper investigates a specific facet of this complex issue: the relationship between early life exposure to radiation and its subsequent impact on adult fertility. It also examines how economic incentives, along with education levels and government mistrust in regions with low support for the ruling authorities, affected adherence to protective measures and, in turn, influenced the disaster's impact on adult fertility and related health outcomes.

The Chernobyl disaster was an unanticipated accident that affected the population indiscriminately. The release of radioactive isotopes from the Chernobyl disaster started on April 26, 1986, and lasted until May 6. The majority of emissions occurred during the first few days, with peaks on May 4th and 5th. The nature of the contamination was non-homogeneous

across Europe, with diverse correlations between exposure levels and the distance from the plant driven by the complexity of weather patterns and the non-uniform timing of the emissions.

This paper focuses on Italy. The radioactive cloud passed over Italy between April 29th and 30th, and was detected in northern regions on the morning of April 30th. The population was exposed to various types of radioactive isotopes, including iodine-131, cesium-134 and cesium-137, tritium, strontium-90, and plutonium-239. The levels of radioactive contamination in Italy, compared to other affected countries, were moderate. In absolute terms, the national average dose estimates fall within the low-dose radiation range, albeit with significant variation observed across different municipalities in Italy ([Risica, 1987](#)).

The catastrophic event left an indelible mark on different ramifications of health threats. Following the deposition of fallout into the air and on the ground, individuals can absorb radiation through the penetration of rays emitted from the air and the ground, and through inhalation, skin absorption, or ingestion of contaminated food. Early medical literature on radiation, based on the effects of atomic bombs, demonstrated the impact of radiation on cancer development. Subsequently, studies have consistently associated exposure to ionizing radiation, specifically from Chernobyl, with an increased risk of cancer and thyroid disease [Jacob et al. \(1998\)](#), [Kazakov et al. \(1992\)](#), [Likhtarev et al. \(1995\)](#), [Pierce et al. \(1996\)](#), [Preston et al. \(1994\)](#), [Prisyazhiuk et al. \(1991\)](#), [Ron \(1998\)](#), [Stsjazhko et al. \(1995\)](#), [Thompson et al. \(1994\)](#).

There is however little research evidence on the long-term effects of low-dose radiation exposure early in life ([Elsner and Wozny, 2023](#)). Three decades post-catastrophe, the infants and children who were exposed have now reached reproductive age. Consequently, in light of the early risks they faced, it becomes crucial to scrutinize whether the fertility of these exposed cohorts has been impacted by the exposures during their early life.

The excess relative risk for most conditions tends to decrease with increasing age at exposure. This trend is influenced by several factors. First, iodine-131 and cesium-137 contaminated food supplies, particularly dairy products, exposing infants to higher levels of radioactivity, as milk is their primary food source for them. More importantly, given the same level of radioactivity, the rapid development of organs and tissues during early life (both fetal and infant)

increases the likelihood of radiation-induced mutations due to rapid cell division, which can lead to cancers and other health issues. Additionally, during this phase, bodies absorb nutrients and contaminants at higher rates, leading to increased metabolic activity and a higher rate of absorption of radioactive isotopes. Moreover, smaller body diameters inherently reduce shielding from surrounding tissues and decrease the distance between bodily organs (Haridasan, 2013). Specifically, infants have a smaller thyroid gland that is more sensitive to radioactive iodine-131, increasing the risk of thyroid cancer and other thyroid-related issues. For these reasons, the impact of radiation is expected to be more pronounced in newborns and during in utero development (Bakhmutsky et al., 2014, Petridou et al., 1996, Sadetzki and Mandelzweig, 2009). In-utero exposure effects may be further exacerbated by stress and worry, which are associated with adverse health outcomes in both the short and long term (Atella et al., 2023, Black et al., 2016). Lastly, from a mechanistic standpoint, fetuses and infants have a longer expected lifespan, which cumulatively extends their exposure duration. Given the lengthy latency period for certain radiation-induced conditions, this prolonged exposure increases the likelihood of developing radiation-related health issues over time.

For cohorts conceived after the fallout, recent literature using genome sequencing has not identified any transgenerational effects of ionizing radiation in offspring born to individuals exposed to acute high-dose emissions (Yeager et al., 2021). However, these offspring may still be affected by systematic compositional differences. Indeed, several studies have reported fewer live births in the year of the fallout and the year following the accident in various settings, attributable to a decrease in planned pregnancies and an increase in pregnancy interruptions (Bertollini et al., 1990, Källén, 1988, Körblein, 2021, Trichopoulos et al., 1987). The impact of the fallout is thus likely to manifest in all children born before the fallout due to radiation exposure, those in utero at the time of exposure due to radiation and stress, as well as those born one to two years after exposure due to birth selections. Cohorts conceived later on are therefore likely to be naturally shielded from the detrimental effects of the Chernobyl accident.

This paper focuses primarily on females in the context of thyroid-related cancers and the effects of Chernobyl radiation. Clinical studies consistently show that the impact of radiation on females is 2-3 times greater than on males Heidenreich et al. (2004), Jacob et al. (1999),

[Ron et al. \(1992\)](#). This disparity is likely due to females' heightened susceptibility to the carcinogenic effects of ionizing radiation possibly influenced by their distinct thyroid physiology and hormone regulation, including the role of estrogen. It might be also driven by enhanced detection of thyroid nodules and the diagnosis of thyroid cancer in females due to their more frequent healthcare utilization, especially for reproductive health visits [LeClair et al. \(2021\)](#). Still, to ensure comprehensive examination of health outcomes across genders, we conduct a number of comparative analysis of hospitalizations related to male fertility- and cancer-related hospitalizations.

We employ a dynamic difference-in-differences methodology to investigate the potential long-term impact of early-life exposure to radionuclides on adult female fertility. We unravel the radiation-fertility puzzle by examining 18 cohorts of women born between 1976 and 1993 and assessing their fertility-related outcomes, specifically spontaneous abortions, stillbirths, thyroid complications, and related cancer diagnoses. To gauge their early life exposure to the Chernobyl accident, we quantify the concentration of radionuclides in the municipalities of their birth, representing the finest territorial disaggregation of available data.

We use the radioactive environmental monitoring database maintained by the European Environmental Agency (EEA). We compute a radiation exposure index, which relies on the concentration of radioactive isotopes found in both the environment and food sources. Specifically, we construct a standardized measure of radioactive material using daily data at the Italian municipality level for 1986, the year of the Chernobyl accident. To gauge a statistically detectable effect of radiation, we construct a treatment variable indicating municipalities exposed to relatively high radiation levels.

We match the radiation data with two administrative datasets: the Hospital Discharge Data (SDO) encompassing the universe of hospitalization episodes in both public and private hospitals for the period 2004-2016, and the Standard Certificate of Live Birth Data (CEDAP) on the universe of delivery episodes, for the period 2002-2019, both sourced from the Italian Ministry of Health. By cross-referencing place and date of birth information, we are able to analyze the effect of early-life radiation exposure on fertility-related health records in the adult years of each cohort. In particular, given the clinical literature, we focus on thyroid complications,

cancer diagnosis, spontaneous abortions (distinct from voluntary termination of pregnancy), and stillbirths.

We leverage the documented heterogeneity in the impact of exposure across distinct age groups as observed in clinical literature, with individuals born several years after the accident being naturally shielded from the immediate radiation effects. We thus estimate reduced-form effects of early-life Chernobyl exposure using a difference-in-difference design that compares cohorts born at different times relative to the fallout (first difference) in municipalities that experienced a high dose of radiation (second difference).

Our model specifications support the validity of the design, demonstrating that adult outcomes track the patterns of early-life exposure to radioactivity very closely. Specifically, our findings reveal an elevated incidence of thyroid complications among women who were either in utero or between 0 to two years old at the onset of the fallout. Additionally, cohorts treated between the in-utero phase and 5 years of age exhibit an increased likelihood of hospitalization with a cancer diagnosis. We also observe a heightened occurrence of spontaneous abortions for those who were either in utero or born at the time of the fallout, as well as stillbirth episodes, among those who were in utero or up to three years of age at the time of the event.

Finally, the estimates of the effective dose exposure assume full adherence to protective measures enacted immediately after the fallout, such as restricting the consumption of certain food items (Risica, 1987), but according to the National Health Institute (Venuti et al., 1997), actual adherence may have been incomplete. Areas where information about the measures did not spread effectively due to mistrust and misinterpretation or where food was predominantly self-produced were likely to exhibit greater resistance to consumption restrictions.

To explore this issue, we exploit the 1983 election results to identify municipalities with a low share of votes received by the ruling party (Italian Socialist Party - PSI, led by Prime Minister Bettino Craxi). Additionally, we employ 1981 census data to distinguish municipalities with low education levels. Furthermore, based on the same census data, we identify municipalities with relatively high employment in agricultural activities (above the national median) to address the prevalence of self-produced food consumption.

Our estimates support the hypothesis that municipalities with more intensive agricultural

production saw significantly harsher consequences of the fallout in terms of both thyroid and cancer diagnoses. This suggests that when the ban on consuming fresh foodstuffs imposed economic costs, individuals' reduced compliance with protective measures was an economically rational and efficient short-term decision. Additionally, we show that the adverse effect of the fallout is grater in municipalities with lower education attainment.

Finally, our analysis found no support for the hypothesis that political beliefs influenced compliance with protective measures during the fallout era. This contrasts with recent literature on political polarization affecting health behaviors, especially during COVID-19 (see among others [Allcott et al., 2020](#), [Bargain and Aminjonov, 2020](#), [Beccari et al., 2023](#), [Gollwitzer et al., 2020](#)). While historically, lower social polarization and specific, non-overlapping debates limited the impact of political views on health behaviors, today's landscape shows a stronger intertwining of political opinions and policy-related issues ([Baumann et al., 2021](#)).

Our contribution is novel and significant, as clinical studies often lack the statistical power to detect the effects of low-dose radiation exposure due to the rarity of such events and the sufficient time frame between exposure and the relevant outcomes. Most clinical literature on radiation fallout focuses on events with far more severe consequences than those experienced by the majority of countries affected by Chernobyl.

Health consequences of minor radiation events assessed by nuclear and health institutes are typically obtained by extrapolating the stochastic effects observed in extreme radiation exposures to lower levels of additional radiation. This approach hinges on the assumption that even minimal doses of radiation constitute an excess dose, thereby increasing the baseline probability of developing radiation-related conditions.

Such estimates typically reveal slight increases in the relative probability of radiation-related health events compared to their baseline prevalence, making them statistically challenging to detect. Our study employs a precise identification strategy within a natural experimental design, utilizing comprehensive population-wide administrative data. This approach allows us to provide valuable insights into the effects of low-dose radiation over the long term, potentially contributing significantly to our understanding of its impact on health outcomes.

2 Data

The main objective of this paper is to investigate the impact of ionizing radiation exposure during fetal development and early childhood on adult fertility and the related clinical outcomes. To achieve this goal, we analyze historical data on radionuclide concentrations in environmental and food samples during the 1986 Chernobyl accident across Italian municipalities. Subsequently, 20-30 years later (between 2002 and 2019), we analyze hospital admissions and pregnancy-related outcomes of cohorts exposed to the fallout in their early life according to their municipality and year of birth. Our study focuses on four primary outcomes: (i) spontaneous abortions, (ii) stillbirth deliveries, (iii) thyroid complications, and (iv) cancers.

2.1 Radioactivity data of Chernobyl accident

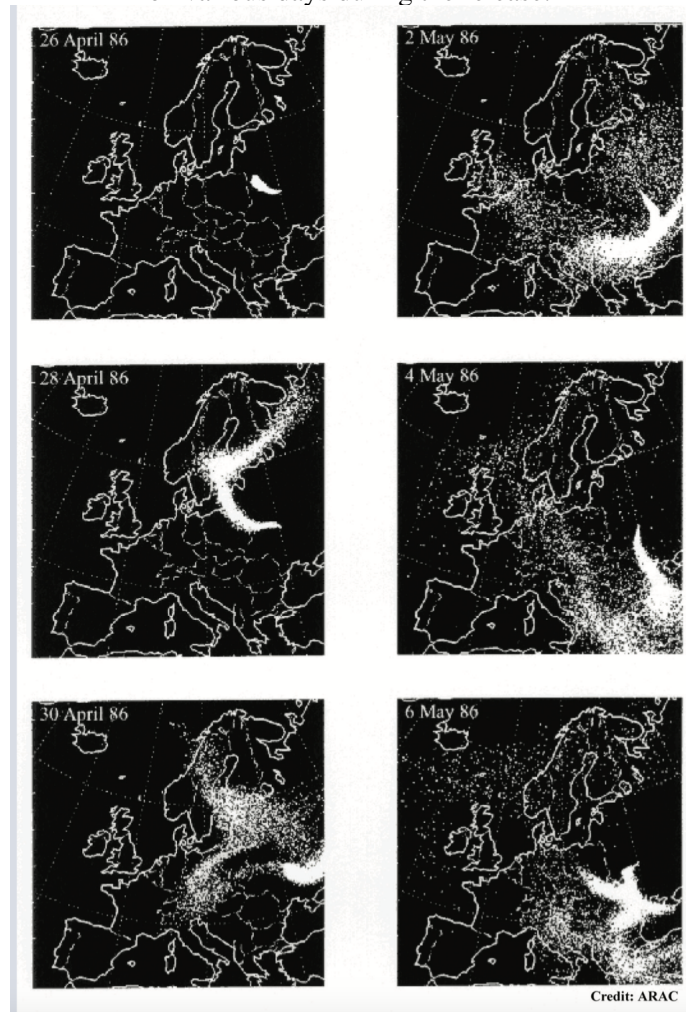
In the environment, there are two types of radioactivity sources: natural (which accounts for approximately 80% of radiation) and artificial.¹ Some examples of artificial radioactivity sources include detonations of nuclear weapons, nuclear waste handling and disposal, medical procedures, and nuclear accidents such as Chernobyl or Fukushima (see, e.g., [Gabrieli et al., 2011](#), [Imanaka et al., 2015](#)).

The release of radionuclides from the Chernobyl plant began on April 26, 1986, and continued until May 6, with the majority of the emissions occurring during the first few days and on May 4th and 5th. Due to the complex meteorological conditions and the non-uniformity of the emissions over time, the transboundary contamination was heterogeneous across different European regions.

As shown in [Figure 1](#), in Italy, the radioactive cloud arrived on April 29th. It was first detected only on the morning of April 30th in the northern regions, where the levels of radiation were the highest. As a response, the government swiftly imposed restrictions, prohibiting the consumption and sale of fresh milk and milk products until May 24th, as well as leafy vegetables until May 12th ([Risica, 1987](#)).

¹The main natural sources of radioactivity are cosmic radiation generated by the interaction of primary radiation with atoms in the atmosphere, terrestrial radiation produced as a result of the presence of radioactive materials in the Earth's crust such as ^{40}K , ^{238}U , ^{232}Th , and their daughter nuclides, as well as internal radiation, which is generated by the presence of ^{40}K , ^{14}C , and ^{210}Pb in the human body from birth.

Figure 1: Areas covered by the main body of the radioactive cloud on various days during the release.



Notes: The figure shows the progression of the Chernobyl cloud in 1986 from the 26th of April to the 6th of May. Source: The Lawrence Livermore National Laboratory Atmospheric Release Advisory Capability (ARAC) (OECD, 2002).

The Italian National Health Institute initially estimated that the Chernobyl disaster's additional radioactivity was relatively low. In 1987, the average effective dose for adults in the first year was 0.6 mSv (60 mRem) (Risica, 1987). This additional exposure constitutes approximately 25 and 35% of the yearly dose of natural background radiation, which typically amounts to around 2 mSv/year (200 mRem). A decade later, these estimates were revised, showing an increase to 0.7 mSv in the first year and a lifetime dose of 1 mSv (Rogani and Tabet, 1997).

In terms of exposure, Italy ranked eighth, following Bulgaria, Austria, Finland, Romania, Greece, and Yugoslavia, but surpassed Norway, Switzerland, Poland, Hungary, Sweden, and Germany (Rogani and Tabet, 1997). Notably, the exposure varied across Italy: northern regions

experienced 0.8 mSv (80 mRem), central regions 0.6 mSv (60 mRem), and southern regions 0.5 mSv (50 mRem) in the first year.

These estimates are computed as grand averages and rely on the assumption that the population adhered strictly to the safety measures implemented immediately after the disaster. However, as noted by the National Health Institute ([Rogani and Tabet, 1997](#)), this assumption might not hold uniformly across all demographic segments. Variations in exposure combined with differences in individual adherence to safety protocols likely led to heterogeneous effects of the disaster among different subgroups, which we leverage in this paper.

The populations were exposed to various radionuclides, among which iodine-131 (accumulating in the thyroid gland), cesium-134 and cesium-137, tritium (accumulating in the whole body), strontium-90 (accumulating in the bones), and plutonium-239 (accumulating in the bones and liver) ([Bennett et al., 2006](#)).

We utilize the Radioactivity Environmental Monitoring database (REM) maintained by the European Commission, which contains a historical record of radionuclide concentrations in both environmental samples and foodstuffs from 1984 to 2011, along with information on sampling circumstances (sampling type, begin-end time), measurement conditions (value, nuclide, apparatus, etc.), location, and date of sampling.² The REM database collects radionuclide concentrations for a number of representative locations at a daily level.

We employ the main categories of sample types available in the REM database, including environmental samples, uncultivated products, crops, vegetables and fruits, manufactured agricultural products, animal products, dairy products, technical samples, and mixed diets ([De Cort et al., 2009](#)), to construct a measure of “radiation exposure.” Radiation exposure can be categorized into two types: external and internal exposure. External exposure occurs when a person is exposed to radiation from radioactive materials present on the ground, suspended in the air, or attached to clothing or the surface of the body. In contrast, internal exposure can occur through (i) ingestion of radioactive materials in food or drink when consuming a meal, (ii) inhalation of radioactive materials in the air, (iii) percutaneous absorption of radioactive mate-

²Records stored in the REMDdb are publicly accessible until 2011 through two unrestricted repositories: “REM data bank - Years 1984-2006” and “REM data bank - Years 2006-2011” ([De Cort et al., 2012, 2007](#)). A detailed description of the REM database is provided by [Sangiorgi et al. \(2019\)](#).

rials through the skin, (iv) wound contamination, or (v) administration of radiopharmaceuticals containing radioactive materials for medical treatment purposes. Once radioactive materials enter the body, the body continues to be exposed to radiation until the materials are excreted or the radioactivity weakens over time.

Table 1: Descriptive statistics of radioactivity concentrations

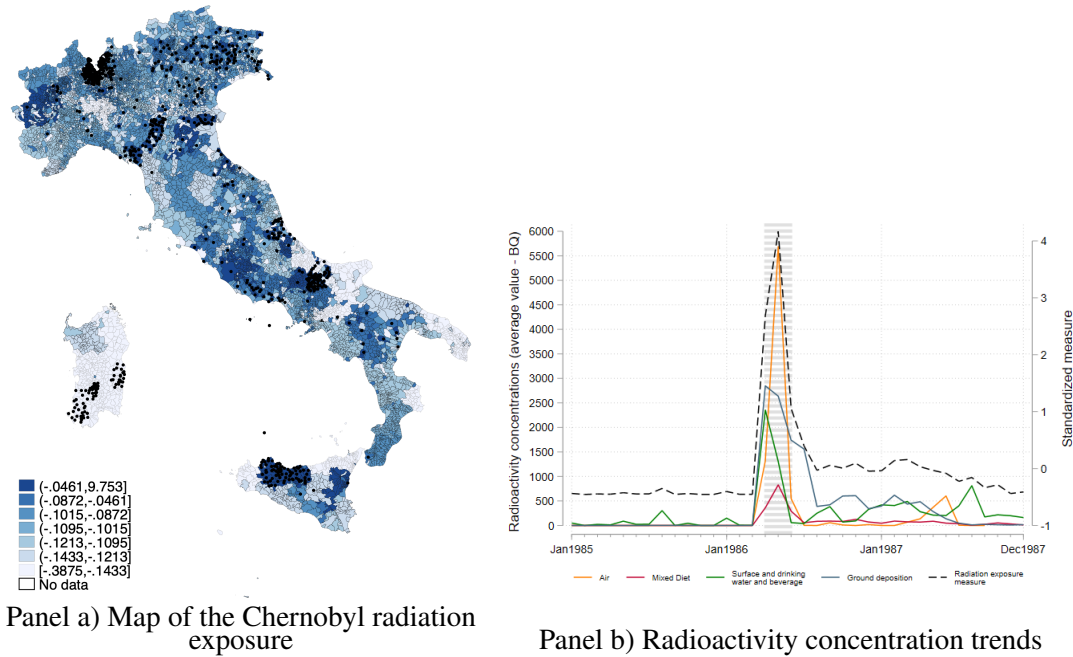
	N	Mean	Std. Dev.	Min	Max
<i>Panel a: radioactivity concentrations</i>					
Air (bq/m^3)	2,210	3,253.4	6,881.5	0.001	47,845.5
Mixed diet (bq/kg)	8,063	448.6	4,427.2	0	247,435.8
Surface and drinking water and beverage (bq/l)	7,784	123.7	338.3	0	6,891.3
Ground deposition (bq/m^2)	6,733	4,215.4	7828.0	0.008	231,920.0
<i>Panel b: standardized measure and treatment indicator</i>					
Standardized measure	8,090	-0.01	0.181	-0.387	9,753
Treatment indicator	8,090	0.090	0.287	0	1

Notes: The statistics refer to the year 1986 and are obtained for the sample of 8090 mui.

We create a *radiation exposure index* using daily municipality-level radioactivity concentration data from 1986. We calculate the daily average exposure based on the levels of ^{137}Cs , ^{134}Cs , ^{131}I , ^3H , ^{90}Sr , and ^{239}Pu identified in: *i*) air (measured in Bq/m^3), *ii*) surface and drinking water and beverages (i.e., milk, measured in Bq/l), *iii*) mixed diet (measured in Bq/kg), and *iv*) ground deposition (measured in Bq/m^2). For municipalities with missing information, we impute the data with the province-level averages to ensure a homogeneous measure of radionuclide concentrations over space and time for all 8,090 Italian municipalities. To determine the 1986 standardized measure of radiation exposure, we compute the standardized picks of radioactive elements (refer to Table 1 for the main statistics). Figure 2 depicts the distribution of the aforementioned standardized measure across municipalities.

To concentrate on high exposure, we define a treatment indicator, represented by T_m , as follows: for each municipality m , T_m takes a value of 1 if its standardized measure of radiation exposure (SE_m) exceeds the 90th percentile of the distribution ($T_m = 1$ if $SE_m > SE_{0.90}$). Among the 8,090 municipalities in our sample, 730 municipalities that exceed the 90th percentile of the radiation exposure index are indicated by black points in Figure 2, Panel A. Figure 2, Panel B, on the other hand, illustrates the average trends in radioactivity concentration and the standardized measure on a monthly basis for the period 1985-1987, indicating no significant peaks after the disaster.

Figure 2: Chernobyl radiation exposure



Notes: Panel A displays the map of the standardized measure of radiation exposure and the radiation exposure index (depicted by black points). Panel B presents the average trends in radioactivity concentration on a monthly basis for the period 1985-1987 for *i*) air, *ii*) mixed diet, *iii*) surface water, drinking water, and beverages, *iv*) ground deposition, and *v*) our standardized measure (y-axis 2). The dashed gray vertical line indicates the period related to the Chernobyl accident.

2.2 Health data

Spontaneous abortions, thyroid complications, cancer diagnoses and male infertility. Our data source is the Hospital Discharge Data (SDO) provided by the Italian Ministry of Health. This comprehensive dataset captures information on hospitalization episodes across both public and private hospitals. Italy's universal healthcare system ensures that hospitalization is largely free of charge for all residents, downplaying selection issues. The records include important demographic information such as age, gender, nationality, place of birth, and residence, as well as clinical information such as diagnoses, procedures performed, hospital transfers, and many discharge details. Additionally, the records contain information on the hospital type and specialty where the patient received treatment.

Between 2004 and 2016, there were approximately 11 million hospital admissions per year across the 8,090 municipalities in Italy. In our core analysis, we focus on women with Italian citizenship and episodes related to complications of pregnancy with abortive outcomes, exclud-

ing legal and illegal abortions (hereafter referred to as spontaneous abortion diagnoses)³ Moreover, we also consider hospitalization episodes related to thyroid complications⁴ Additionally, we consider other cancer-related hospitalizations, net of the ones that refer to the thyroid.⁵

From 2004 to 2016, hospitalizations for women born between 1964 and 1996 involving spontaneous abortion diagnoses comprised 0.67% of the total admissions (942,850 cases), while thyroid disorders accounted for 0.24% of hospitalizations (350,961 cases) and cancers constituted 0.70% of the hospitalizations (927,217 admissions). For reasons explained in [section 3](#), we specifically focus on 18 cohorts of women born between 1976 and 1993 aged 20-40 at the moment of hospitalization. We aggregate the hospitalizations data by age at the Chernobyl accident, year of admission, and municipality of residence, obtaining yearly counts of hospitalizations for the entire relevant female population. Our final outcomes are represented by yearly municipality-level admission counts for each cohort, expressed as a rate per 10,000 female residents.

Finally, we also investigate the potential impact on the effects of Chernobyl exposure on males. We analyze hospitalizations based on infertility diagnoses (26,464 cases corresponding to 0.018% of total admissions) well as cancers and other specific conditions that contribute to male infertility (249,514 cases corresponding to 0.17% of total admissions), creating variables similar to those described previously for females.⁶

The relevant descriptive statistics are presented in [Table 2](#). Since all results are derived from aggregation procedures that consolidate relevant variables into rates, we apply the relevant population size-based weights to observations, aligning with the standard approach adopted in several related studies. ([Giaccherini et al., 2021](#), [Janke, 2014](#), [Janke et al., 2009](#), [Knittel et al.,](#)

³The corresponding ICD-9 codes for complications of pregnancy are: retained (in utero) abortion (632), Ectopic pregnancy (633), Spontaneous abortion (634) and Unspecified abortion (637).

⁴The corresponding ICD-9 codes for thyroid complications are: Thyroiditis (245[0 – 9]), Other disorders of thyroid (246[0 – 9]), Congenital hypothyroidism (243), Acquired hypothyroidism (244), Malignant neoplasm of thyroid gland (193), Malignant neoplasm of other endocrine glands and related structures (194), Benign neoplasm of thyroid glands (226), Benign neoplasm of other endocrine glands and related structures (227), Thyroid dysfunction complicating pregnancy childbirth or the puerperium (648.1).

⁵The corresponding ICD-9 codes refer to all Malignant neoplasms 140[0-9]-165[0-9], 170[0-9]-200[0-9], Carcinomas 230[0-9]-234[0-9], other neoplasms 235[0-9]-239[0-9], Leukemias 203[0-9]-208[0-9], Lymphomas 202[0-8] and Melanomas 203[0-8].

⁶The corresponding ICD-9 codes refer to Male infertility 606[0-9], Testis direct irradiation 186[0,9], 187[1-9], Acute lymphoblastic leukemia (testicular relapse) 20[4-9][0-9][0-2], Soft tissue sarcoma (deep and high-grade) 171[0-9], Prostate cancer 185[0-9], Rectal cancer 197[5-6], Anal canal carcinoma 150[0-9]-159[0-9], Bladder cancer 18[8-9][0-9], Hodgkin lymphoma 201[0-2][0-9], Hypothalamic–pituitary axis dysfunction 253, 194[0-9].

2016, Schlenker and Walker, 2016, among others).

Table 2: Descriptive statistics of hospitalizations for spontaneous abortion, thyroid complication, and cancer diagnoses for cohorts born between 1973 and 1996 and aged 20-40 at hospitalization.

	Mean	Std. Dev.	Min	Max
<i>Panel a: female fertility</i>				
Spontaneous abortion	67.05	135.77	0.00	10,000.00
Thyroid complications	20.96	92.76	0.00	10,000.00
Cancer diagnoses	33.73	133.84	0.00	10,000.00
<i>Panel b: male fertility</i>				
Infertility	1.81	29.92	0.00	10,000.00
Causes of infertility	10.90	112.85	0.00	10,000.00

Notes: The statistics refer to 8,090 municipalities for the time period between 2004-2016, pertaining to the cohort 1976-1993 and aged 20-40 at the moment of hospitalization, referring to 1,529,010 observations. As depicted in panel *a* for females and panel *b* for males, the number of hospitalizations is expressed for 10,000 female and male residents and is weighted by the female and male municipality population size of the relevant cohort, respectively.

The average hospitalization rates for the diagnosis of spontaneous abortions, thyroid complications, and cancer are 67, 21, and 33 per 10,000 women residents, respectively. Regarding male infertility and conditions that can lead to infertility, the average hospitalization rates are approximately 2 and 11 per 10,000 male residents, respectively. The overall counts exhibit significant variability, with standard deviations exceeding the means.

Stillbirths and birth outcomes We rely on the Standard Certificates of Live Births (CEDAP) provided by the Italian Ministry of Health to capture information on stillbirth events. These certificates compile all birth data from private and public Italian hospitals, spanning the years 2002 to 2019 (due to data validity issues year 2009 is absent in the collection). The CEDAP dataset provides a thorough depiction of both mothers and newborns. The key clinical and demographic characteristic we focus on are occurrences of stillbirths at any week of the pregnancy, as well as dates and places of birth of both the mothers and the offspring.

We focus exclusively on singleton births. Between 2002 and 2019, and for women born between 1962 and 1999, we collected 39,568 stillbirth episodes, accounting for 0.56% of all

singleton deliveries (7,100,806). Also in this case, we focus on cohorts of women born between 1976 and 1993, aged 20 to 40. Our dependent variable is defined as the annual stillbirth count at the municipality level for each cohort, expressed as a rate per 10,000 female residents. We compile a balanced panel consisting of 7,480 Italian municipalities.⁷

As an additional set of indicators of newborns' health status, we focus on the Apgar score⁸, and gestational age. To operationalize these indicators, we generate binary variables at the individual level for each marker. A value of 1 is assigned to deliveries resulting in an Apgar score below 7 or a gestational age under 37 weeks, which is the threshold for diagnosing preterm births. Subsequently, the dependent variable is defined as the annual proportion of births with low Apgar scores or classified as preterm, calculated at the municipality level for each cohort. For clarity in interpretation, these variables are scaled to a range from 0 to 100.

The descriptive statistics presented in Table 3 indicate an average hospitalization rate of 3.24 per 10,000 for stillbirth diagnoses. Additionally, the data show that 0.51% of births have a low Apgar score, and 2.76% are classified as preterm.

Table 3: Descriptive statistics of hospitalizations for stillbirth diagnoses for cohorts born between 1973 and 1996 and aged 20-40 at hospitalization.

	Mean	Std. Dev.	Min	Max
Stillbirth diagnoses	3.24	28.94	0	10000.00
Share of Apgar score <7	0.51	3.37	0	100
Share of gestational age <37	2.76	6.91	0	100

Notes: The statistics refer to 7,480 municipalities for the time period between 2002-2019, pertaining to the cohort 1976-1993 and aged 20-40 at the moment of hospitalization, referring to 1,761,412 observations. The number of hospitalizations is expressed for 10,000 women residents and is weighted by the female municipality population size of the relevant cohort.

⁷ The difference in data between the SDO and CEDAP municipalities can be attributed to a lack of information in the second database.

⁸The Apgar score is a standardized assessment conducted immediately after birth, evaluating the newborn based on five criteria: 1) color, 2) heart rate, 3) reflexes, 4) muscle tone, and 5) breathing, with each criterion scored as 0, 1, or 2. Scores below 7 may indicate newborn depression, characterized by symptoms such as cyanosis or pallor, bradycardia, reduced reflex response, hypotonia, and apneic gasping respiration. Initial scores are recorded at 1 and 5 minutes after birth; infants with scores below 7 have their scores reassessed at 5-minute intervals up to 20 minutes.

3 Empirical strategy

To examine the long-run effects of the Chernobyl fallout on fertility-related health outcomes among female cohorts born during the accident era, we match the radiation data with the adult outcomes based on municipality and year of birth.

Due to climatic conditions, the Chernobyl accident led to a sharp surge in radiation levels in certain Italian municipalities. The research design exploits these circumstances using a difference-in-difference strategy that compares cohorts born closer to or farther away from the fallout (first difference) in municipalities with higher or lower radiation (second difference).

3.1 Sample selection

As explained in the introduction, the medical literature associates exposure to ionizing radiation, Chernobyl in particular, with a greater risk of cancer and thyroid disease (Jacob et al., 1998, Kazakov et al., 1992, Likhtarev et al., 1995, Pierce et al., 1996, Preston et al., 1994, Prisyazhiuk et al., 1991, Ron, 1998, Stsjazhko et al., 1995, Thompson et al., 1994). The risk of most of these conditions diminishes with advancing age at exposure, attributable to an elevated rate of cell division during early life and smaller body diameters that result in reduced shielding from surrounding tissues and decreased inter-organ distances (Haridasan, 2013). For similar reasons, the influence of radiation is anticipated to be more significant in newborns and during in-utero development (Bakhtmutsky et al., 2014, Petridou et al., 1996, Sadetzki and Mandelzweig, 2009). The effects of in-utero exposure may be additionally exacerbated by stress and anxiety, which are found to adversely affect health outcomes in both the short and long term (Atella et al., 2023, Black et al., 2016).

Recent studies employing genome sequencing have not identified any transgenerational effects of ionizing radiation in offspring conceived after the fallout by individuals exposed to acute high-dose emissions (Yeager et al., 2021). The authors acknowledge, however, that their results do not conclusively rule out the possibility of effects for births conceived in immediate proximity to the fallout radiation. Furthermore, cohorts conceived immediately after the fallout are likely to be influenced by distinct selection mechanisms. Multiple studies across different

settings have documented a decline in live births in the year of the fallout and the subsequent year. This reduction is ascribed to a decrease in planned pregnancies and an increase in pregnancy interruptions (Bertollini et al., 1990, Källén, 1988, Körblein, 2021, Trichopoulos et al., 1987).

3.2 Selective fertility

To assess the potential presence of selective fertility and its relevance for our identification strategy, we examine the municipal cohort sizes within a ten-year period surrounding the fallout (1981-1990). As highlighted by Bertollini et al. (1990), the Italian media extensively covered the consequences of the accident on the environment and health in Italy, suggesting possible risks of cancer and fetal abnormalities in locations seemingly more exposed to radiation due to climatic conditions (see also Figure 3).

Figure 3: Example of news coverage of the fallout in Italy

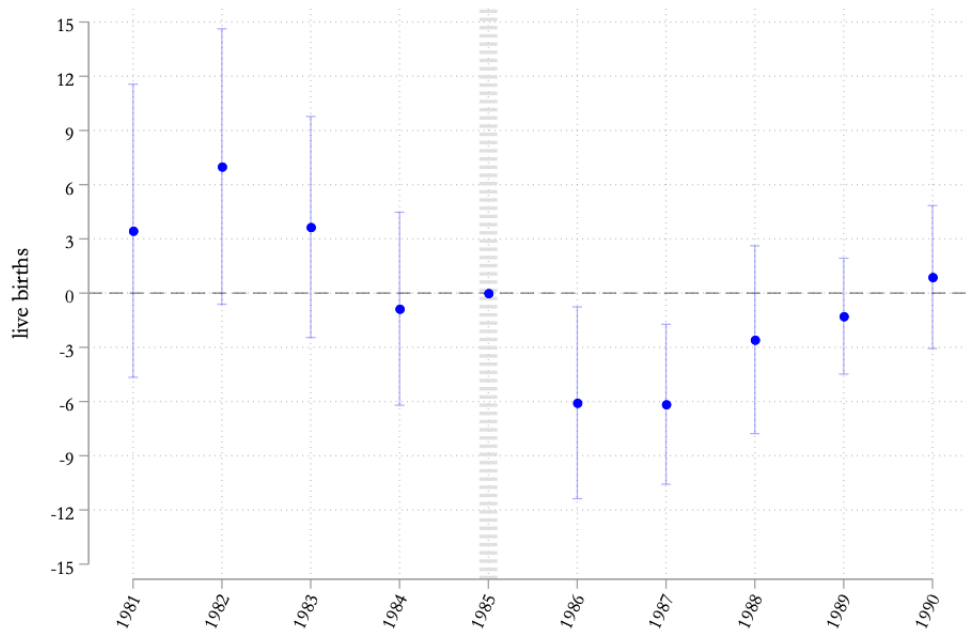


"It is already above our heads. (...) The state of alert in Veneto, Friuli and Alto Adige" *"The cloud arrives in Veneto. Extraordinary measures adopted in Austria. All children are kept at home"*

Notes: Two examples of newspaper titles, May 1st 1986, *Mattino di Padova*

We thus analyze the temporal evolution of births in Italian municipalities that experienced radiation doses above the 90th percentile, comparing them to municipalities that did not face such exposure. Figure 4 shows that total live births registered in 1986 and 1987 in municipalities with higher radiation doses were lower than in 1985, suggesting a trend consistent with several studies that identify a voluntary decrease in planned pregnancies and their termination up to two years following the accident. This decrease is attributed to post-disaster stress, resulting in a lower conception rate and/or an increase in abortions, both voluntary and non-voluntary, as in Källén (1988), Körblein (2021), Trichopoulos et al. (1987).

Figure 4: Live births in treated versus control municipalities before and after the fallout year.



Notes: The figure presents coefficient estimates of the interaction term between the treatment variable and birth cohorts, where the dependent variable is the number of live births registered in any given year. The spikes represent 95 percent confidence intervals based on standard errors clustered at the municipality level.

The repercussions of the fallout are thus expected to be evident in all children born before the fallout due to radiation exposure, those in utero at the time of exposure facing both radiation and stress, as well as those born one to two years after exposure due to birth selections. Cohorts conceived two years after the accident are consequently anticipated to be naturally protected from the adverse effects of the Chernobyl incident.

Further evidence of local awareness regarding exposure is provided by the analysis of the 1987 referendum results on nuclear plants. In the wake of the Chernobyl disaster, Italian citizens were given the opportunity to vote on halting the civilian nuclear program.⁹ As a result of the fallout, approximately 80% of the votes favored shutting down the nuclear program. We find that localities directly exposed to high radiation effect supported this measure to a greater extent, contributing to a significant 5 percentage point increase in affirmative votes at the province level.¹⁰

⁹The nuclear power referendum held on November 8–9, 1987, allowed citizens to directly vote on nuclear energy policy, bypassing the regular election process.

¹⁰Data for the 1987 referendum is provided by the Italian Ministry of the Interior. The OLS estimate is weighted

3.3 Cohorts as time variation

Our research design capitalizes on the age-specific sensitivity to radiation, serving as the temporal dimension in our framework. Since each exposed cohort is treated only at age a , the ensuing long-term effects effectively represent distinct experiments. The fallout's impact unfolds across ages $a = -7$ to $a = 10$ as follows: individuals aged -7 to -3 in 1986 correspond to cohorts born between 1989 and 1993, who were yet to be born and conceived at a sufficient distance from the fallout, defining the pre-treatment period. Age -2 pertains to the 1988 cohorts conceived after the fallout in 1987, potentially influenced by birth selectivity. Age -1 corresponds to the 1987 cohort, either in utero or conceived in the year of the fallout, likely affected by selectivity, in-utero radiation, and in-utero stress. Age 0 represents individuals born in 1986, typically exposed in utero or during their first year of life. Similarly, ages 1 through 10 encompass individuals born between 1985 and 1976, representing children in various stages of development, all impacted by radiation exposure, with an anticipated progressively diminishing effect.

We conduct an analysis on these cohorts through the examination of hospital records spanning 2004 to 2016 and certificates of live births data from 2002 to 2019. These cohorts include a range of age groups, systematically linked to differing likelihoods of adverse reproductive outcomes, thyroid disorders, or cancers. Our identification strategy aims to gauge the disparate impact of the Chernobyl accident in municipalities exposed to high versus low doses of radiation. We specifically focus on cohorts either conceived or already born in the accident era (born between 1976-1988) compared to individuals from the same municipalities but born after the radiation's effects subsided (born in 1989-1993).

As depicted in [Figure 5](#), in 2016 (2004), the cohorts exposed to radiation after birth and conceived during the accident era, born between 1976 and 1988 and shaded in dark grey, range in age from 28 to 40 (16 to 28). In contrast, those conceived at a greater time interval after the accident, born between 1989 and 1993 and colored in light grey, are aged 23 to 27 (11 to 15).

by province voters size and our outcome represents the province-level percentage of favorable votes in support of stopping the civilian nuclear program (count of positive votes over the corresponding voters denominators and expressed as percentage per 100). The treatment indicator at the province level takes a value of 1 for provinces where the treated share of population exceeds the national median (see [Figure A1](#) in [A](#)).

To meaningfully assess the impact of radioactivity exposure on fertility-related outcomes, our primary analysis in the main body of the paper focuses on individuals aged at least 20 and at most 40 at the time of hospitalization and born between 1976 and 1993. The common set refers to the intersection between the grey cells and the bold section of the table. The consequences of this sample trimming imply that the coefficients on ages at treatment are computed based on an increasingly broader composition of hospitalization waves (e.g., age at treatment -7 relies solely on hospitalizations recorded in 2013-2016, age at treatment -6 is based on 2012-2016, and so forth).

Figure 5: Selection of data and composition of cohorts at the time of the 1986 Chernobyl accident and during hospitalization years.

Age in 2004	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40
Age at treatment	-7	-6	-5	-4	-3	-2	-1	0	1	2	3	4	5	6	7	8	9	10															
2004	1996	1995	1994	1993	1992	1991	1990	1989	1988	1987	1986	1985	1984	1983	1982	1981	1980	1979	1978	1977	1976	1975	1974	1973	1972	1971	1970	1969	1968	1967	1966	1965	1964
2005	1996	1995	1994	1993	1992	1991	1990	1989	1988	1987	1986	1985	1984	1983	1982	1981	1980	1979	1978	1977	1976	1975	1974	1973	1972	1971	1970	1969	1968	1967	1966	1965	1964
2006	1996	1995	1994	1993	1992	1991	1990	1989	1988	1987	1986	1985	1984	1983	1982	1981	1980	1979	1978	1977	1976	1975	1974	1973	1972	1971	1970	1969	1968	1967	1966	1965	1964
2007	1996	1995	1994	1993	1992	1991	1990	1989	1988	1987	1986	1985	1984	1983	1982	1981	1980	1979	1978	1977	1976	1975	1974	1973	1972	1971	1970	1969	1968	1967	1966	1965	1964
2008	1996	1995	1994	1993	1992	1991	1990	1989	1988	1987	1986	1985	1984	1983	1982	1981	1980	1979	1978	1977	1976	1975	1974	1973	1972	1971	1970	1969	1968	1967	1966	1965	1964
2009	1996	1995	1994	1993	1992	1991	1990	1989	1988	1987	1986	1985	1984	1983	1982	1981	1980	1979	1978	1977	1976	1975	1974	1973	1972	1971	1970	1969	1968	1967	1966	1965	1964
2010	1996	1995	1994	1993	1992	1991	1990	1989	1988	1987	1986	1985	1984	1983	1982	1981	1980	1979	1978	1977	1976	1975	1974	1973	1972	1971	1970	1969	1968	1967	1966	1965	1964
2011	1996	1995	1994	1993	1992	1991	1990	1989	1988	1987	1986	1985	1984	1983	1982	1981	1980	1979	1978	1977	1976	1975	1974	1973	1972	1971	1970	1969	1968	1967	1966	1965	1964
2012	1996	1995	1994	1993	1992	1991	1990	1989	1988	1987	1986	1985	1984	1983	1982	1981	1980	1979	1978	1977	1976	1975	1974	1973	1972	1971	1970	1969	1968	1967	1966	1965	1964
2013	1996	1995	1994	1993	1992	1991	1990	1989	1988	1987	1986	1985	1984	1983	1982	1981	1980	1979	1978	1977	1976	1975	1974	1973	1972	1971	1970	1969	1968	1967	1966	1965	1964
2014	1996	1995	1994	1993	1992	1991	1990	1989	1988	1987	1986	1985	1984	1983	1982	1981	1980	1979	1978	1977	1976	1975	1974	1973	1972	1971	1970	1969	1968	1967	1966	1965	1964
2015	1996	1995	1994	1993	1992	1991	1990	1989	1988	1987	1986	1985	1984	1983	1982	1981	1980	1979	1978	1977	1976	1975	1974	1973	1972	1971	1970	1969	1968	1967	1966	1965	1964
2016	1996	1995	1994	1993	1992	1991	1990	1989	1988	1987	1986	1985	1984	1983	1982	1981	1980	1979	1978	1977	1976	1975	1974	1973	1972	1971	1970	1969	1968	1967	1966	1965	1964
Age in 2016	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52

Notes: Cells shaded in light grey represent cohorts born at a considerable distance from the accident, while the dark shaded cells denote the cohorts exposed to the radiation. Ages at hospitalizations within the 20-40 range are delineated by bold borders.

We further perform two robustness exercises where we refrain from imposing the joint restrictions. In the first exercise, we maintain balance in age at outcome by considering all cohorts aged between 20 and 40 from 2004 to 2016. In this scenario, we bin all cohorts born after 1993 in age at treatment -7 and all cohorts born before 1976 in age at treatment 10 (highlighted by bold borders in all cells). While achieving balance in age at hospitalization, this approach introduces an imbalance in age at treatment.

We also adopt the converse approach, concentrating solely on achieving balance in age at treatment, independent of the age at outcome measurement. Balancing age at treatment results in the inclusion of cohorts in the early waves of hospitalizations that are too young to exhibit measurable fertility-related adverse health outcomes.¹¹ The results obtained with the alternative sample selection are included in A.

3.4 Identification strategy

We define exposure to the radiation in municipality m for a cohort c in year 1986 as a cumulative exposure of the moment when the fallout occurred as well as any further residual radiation. We thus estimate reduced-form event-study models (or dynamic difference-in-differences specifications) that trace out the relationship between adult outcomes and the fallout for cohorts born in different years relative to the accident. The outcomes are represented by the count of admissions calculated for specific cells based on the municipality of birth, year of birth, and year of hospitalization, divided by the corresponding population denominators and expressed as rates per 10,000 residents.

The estimating equation for a hospitalization outcome $H_{cm,y}$ is:

$$H_{cm,y} = \alpha_y + \lambda_m + \gamma_c + \sum_{a=-7|a \neq -3}^{10} \beta_a \times \mathbf{1}T_m \times \mathbf{1}(1986 - Birth = a) + \varepsilon_{cm,y} \quad (1)$$

where the dependent variable $H_{cm,y}$ is one of the four main outcomes, i.e. spontaneous abortions, thyroid complications, cancer diagnoses and stillbirths per 10,000 female residents for the 18 cohorts considered, $c = [1976, 1993]$ aged between 20 and 40 at hospitalization, in each municipality m , detected in year y .¹² The treatment indicator T_m takes value one for municipalities where the radiation exposure standardized measure in 1986 exceeds the 90th percentile. $a \in [-7, 10]$ indicates the age of women at the Chernobyl disaster. β_a are the

¹¹Similar considerations hold for the CEDAP data, which we observe for a longer time period (2002-2019), expect year 2009 when the data was not collected.

¹²As denoted in the data section, abortions, thyroid complications and cancer diagnoses are registered between 2004 and 2016 and are paired with radiation exposure based on the municipality of residence, whereas stillbirth diagnoses are retrieved over the period 2002 to 2019, with a gap in 2009, are matched based on the municipality of birth.

parameters of interest that measure the marginal difference in the health outcomes between treated and control municipalities after the exposure to the treatment, relative to the same difference in $a = -3$. α_y , λ_m and γ_c are year, municipality and cohort fixed effects and $\varepsilon_{cm,y}$ is an idiosyncratic error term. The combination of year and cohort fixed effects captures the decline in female fertility that occurs as women age. Standard errors are clustered at municipality level. All estimates are weighted by the municipality-cohort specific population size.

4 Results

The following section presents the results starting from health complications that the literature has typically associated with exposure to radiation. We discuss the effects on thyroid disease, cancers, and death of the fetus, distinguished into miscarriages (spontaneous abortions occurring before the 180th day of gestation) and stillbirths, referring to losses that occur at later times during pregnancy (after the 180th day of gestation).¹³

4.1 Thyroid complications

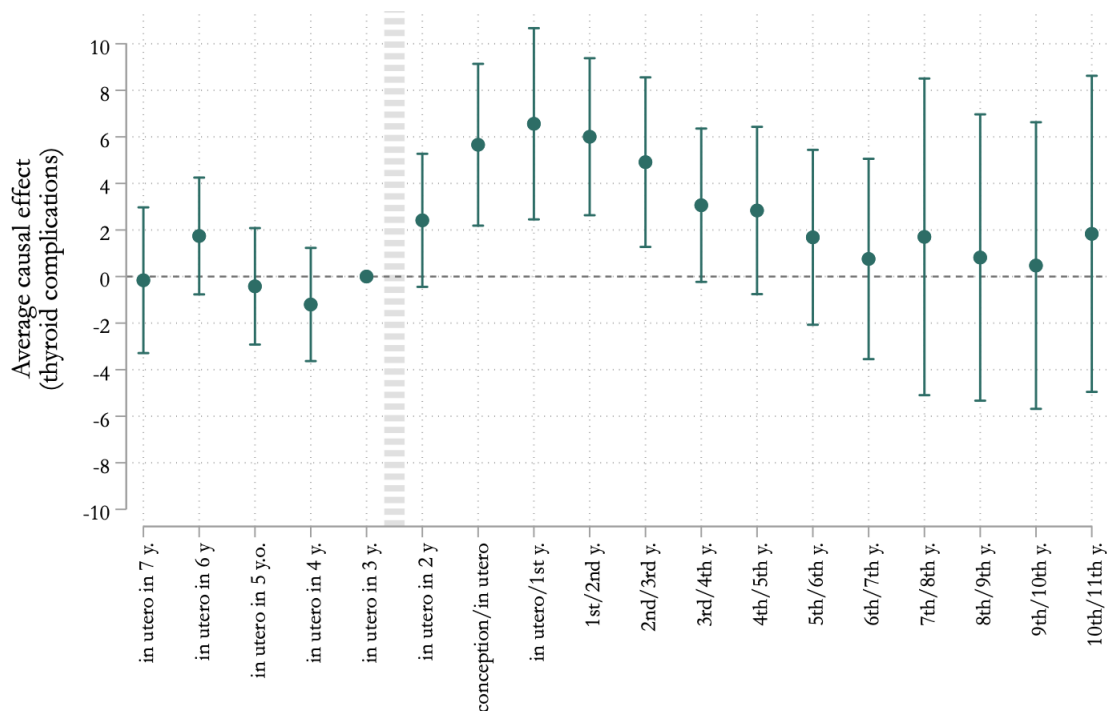
Radiation exposure is associated with an increased risk of thyroid complications. This may include the development of thyroid nodules, thyroid cancer (particularly papillary thyroid cancer), and other thyroid disorders. The onset of thyroid complications may not be immediate and can manifest years after exposure, especially in cases of radioactive iodine exposure.

As shown in [Figure 6](#), our analysis suggests that adult women exposed to high levels of radiation in utero or in the first through the third year of life are more likely to be hospitalized for thyroid complications (including thyroid cancers) as adults. As our results confirm, the risk associated with most of these conditions tends to decrease as the age at exposure advances. A higher rate of cell division, faster metabolic processes, as well as smaller body size that reduce shielding are likely to drive these results ([Haridasan, 2013](#)). The evidence suggests that exposure in utero is also likely to produce significant excess risk thyroid disease in the adulthood.

¹³Due to the presence of zeros in some municipality-cohort-age cells, we further validate our estimates using Poisson pseudo-maximum likelihood regressions across all model specifications. These results confirm the qualitative patterns observed in all models and align quantitatively with most of our baseline findings. Detailed results are available upon request.

This particular exposure period in our setting is however conflated with other effects, possibly also related to stress. Stress-related maternal, placental and fetal neurobiological alterations may affect the developing fetus, in a process also named “fetal programming” (Barker, 1990). Research has suggested that maternal stress during pregnancy may contribute to an increased risk of certain health issues in offspring, including thyroid-related conditions. Stress can potentially affect the functioning of the maternal thyroid gland, and disruptions in the maternal thyroid function during pregnancy may influence fetal thyroid and neurological development (Miranda and Sousa, 2018).

Figure 6: The effect of the radiation exposure on thyroid complications related hospitalizations (cohorts born 1976-1993 aged 20-40).



Notes: The figure presents coefficients estimates of the interaction term between the treatment variable and the a indicators from Eq. (1). Estimates are weighted by municipality population size. The spikes represent 95 percent confidence intervals based on standard errors clustered at the municipality level. The findings are based on 1,529,010 observations distributed across 8,090 municipalities. $P - value$ pretrend 0.295.

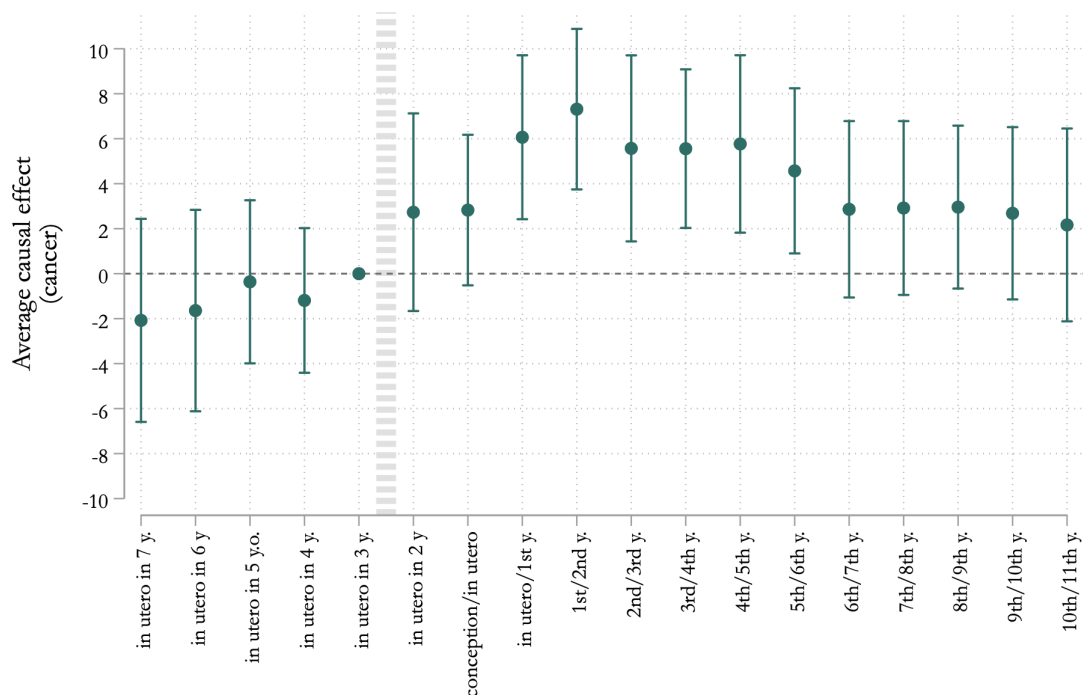
4.2 Cancers

High levels of radiation exposure are also known to increase the risk of various cancers, including but not limited to thyroid cancer, extending also to leukemia, breast cancer, lung cancer

and others. Similar to thyroid complications, the development of cancer due to radiation exposure often has a latency period, and cancer cases may become apparent many years after the exposure occurred.

Additionally, the impact of radiation is expected to be more pronounced in early childhood and during in-utero development due to these physiological factors (Bakhtmutsky et al., 2014, Petridou et al., 1996, Sadetzki and Mandelzweig, 2009).

Figure 7: The effect of the radiation exposure on cancer related hospitalizations (cohorts born 1976-1993 aged 20-40).



Notes: The figure presents coefficients estimates of the interaction term between the treatment variable and the a indicators from Eq. (1). Estimates are weighted by municipality population size. The spikes represent 95 percent confidence intervals based on standard errors clustered at the municipality level. The findings are based on 1,529,010 observations distributed across 8,090 municipalities. P – value pretrend 0.859.

The findings presented in Figure 7 indicate that exposure to elevated levels of radioactivity in specific Italian municipalities resulted in an excess occurrence of cancers among cohorts who were in their first through sixth year of life at the time of the accidents. The coefficient estimates peak for individuals who were in their second year of life during the year of the accident, with a gradual decline in the observed effect for cohorts from the third year onward at the time of the radioactive incident.

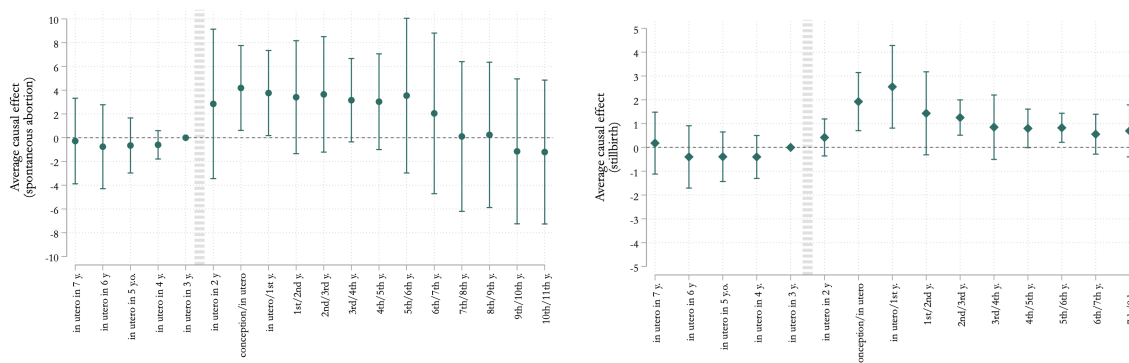
Figure A3 exhibits similar trends to the foundational findings. Specifically, Panel *a* maintains the constraint that ages at hospitalization fall within the range of 20-40. Cohorts born after 1993 are categorized at age -7, while those born before 1976 are categorized at age +10. The results, albeit slightly less statistically significant, are observed in Panel *b*, which encompasses all cohorts born between 1976 and 1993, evaluating cancer rates regardless of their age at hospitalization.

4.3 Reproductive health outcomes

Applying the same methodology, we scrutinize outcomes relative to reproductive health. As seen before, radiation exposure during early life stages can contribute to reproductive cancers, and thyroid complications later in life, which on their own are likely to interfere with reproductive health. Additionally, as discussed earlier, excess radiation in in fetuses and infants is likely to disrupt normal metabolic development and alter hormonal balance.

Based on the available data, we retrieve hospitalizations for spontaneous abortions from the SDO dataset and occurrences of stillbirths from the CEDAP dataset. In both cases, the dependent variables are standardized per 10,000 female residents. These phenomena can be seen as different stages of pregnancy loss: after 180 days of pregnancy, fetal death is classified as a stillbirth rather than a miscarriage. It is important to note that our data do not capture the most common form of spontaneous abortion, the so called that occurs without the need for hospital intervention or the expulsion of the fetus, referred to as a "missed abortion" or "silent miscarriage", that occurs without the need for hospital intervention or the expulsion of the fetus or pregnancy tissues. Therefore, the overall combined effect of radiation on spontaneous abortions in our setting is very likely to be underestimated.

Figure 8: The effect of the radiation exposure on reproductive health (cohorts born 1976-1993 aged 20-40)



Panel a) Hospitalizations for spontaneous abortions

Panel b) Stillbirth occurrences

Notes: The figure presents coefficients estimates of the interaction term between the treatment variable and the a indicators from Eq. (1). Estimates are weighted by municipality population size. The spikes represent 95 percent confidence intervals based on standard errors clustered at the municipality level. Panel a) findings are based on 1,529,010 observations distributed across 8,090 municipalities. P – value pretrend 0.841. Panel b) results are based on 1,761,412 observations distributed across 7,480 municipalities. P – value pretrend 0.7265.

Given the additional information and focusing on the specific reproductive outcomes, we observe a visible increase in the rates of spontaneous abortions (panel a Figure 8) and stillbirths (panel b Figure 8) for cohorts of women who were conceived or aged up to one year at the time of the accident. The impact on miscarriage rates, just like with stillbirths, tends to decrease for groups that were more advanced in age at the time of the fallout.

Finally, given the effects on pregnancy loss, we additionally investigate the relevance of radiation exposure on a number of birth outcomes. In particular we focus on preterm birth, and low Apgar score. The results however do not point to any effect of the fallout exposure in utero or in early childhood on the probability of adverse outcomes when giving birth in the adulthood (the results are reported in A subsection A.6).

4.4 Male infertility

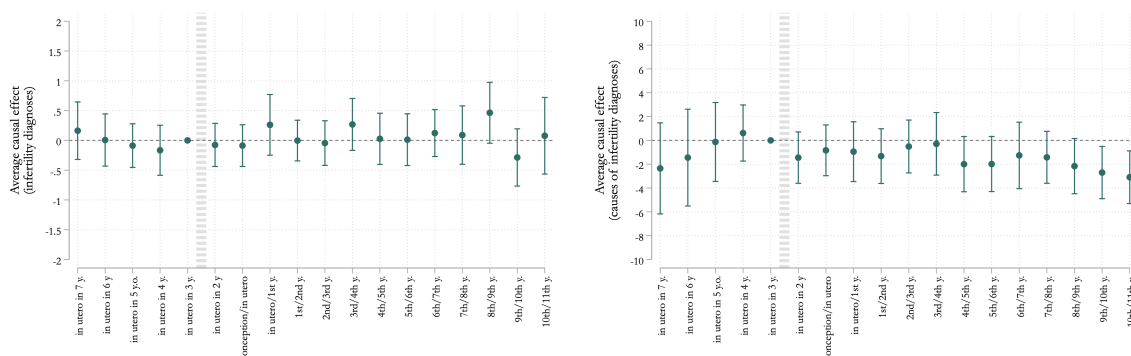
The main analysis of the paper is concentrated on the effects of Chernobyl radiation on females, following the clinical literature consistently demonstrating that radiation impact is 2-3 times greater on females compared to males Heidenreich et al. (2004), Jacob et al. (1999), Ron et al. (1992). The motivation behind this systematic difference is argued to originate in a particular female thyroid physiology and hormone regulation, including estrogen, resulting in an

increased susceptibility to the carcinogenic effects of ionizing radiation on the thyroid gland.

Additionally, this systematic difference might be exacerbated by different diagnostic patterns. Females tend to access healthcare services more frequently, particularly for reproductive health visits, which enhances the detection of thyroid nodules and diagnosis of thyroid cancer [LeClair et al. \(2021\)](#). Hospitalizations related to fertility issues are also significantly more common among females, providing insights into health patterns within this gender group.

To ensure a comprehensive examination of health outcomes across genders, this section includes a comparative analysis of hospitalizations related to male fertility and cancer. Panels a and b of [Figure 9](#) reveal no significant impact of radiation exposure at any age compared to the baseline. It is possible that the effects have yet to manifest, both clinically and statistically, suggesting that a longer time interval from the fallout might yield different results for males in future observations.

Figure 9: The effect of radiation exposure on infertility and cancer related hospitalizations (male cohorts born 1976-1993 aged 20-40).



Panel a) Male infertility

Panel b) Causes of infertility

Notes: The figure presents coefficients estimates of the interaction term between the treatment variable and the a indicators from Eq. (1). Estimates are weighted by municipality population size. The spikes represent 95 percent confidence intervals based on standard errors clustered at the municipality level. Findings are based on 1,529,010 observations. Panel a) P – value pretrend 0.727. Panel b) results a P – value pretrend 0.688.

5 Compliance with protective measures and heterogeneous health effects

The Italian National Health Institute estimates of the effective dose exposure to the Chernobyl fallout, as conventionally done, are net estimates that account for the protective measures enacted in Italy immediately after the fallout, such as restricting the consumption of certain food items (Risica, 1987). Yet, reasonable doubts might exist about whether the actual adherence to these measures has been complete.

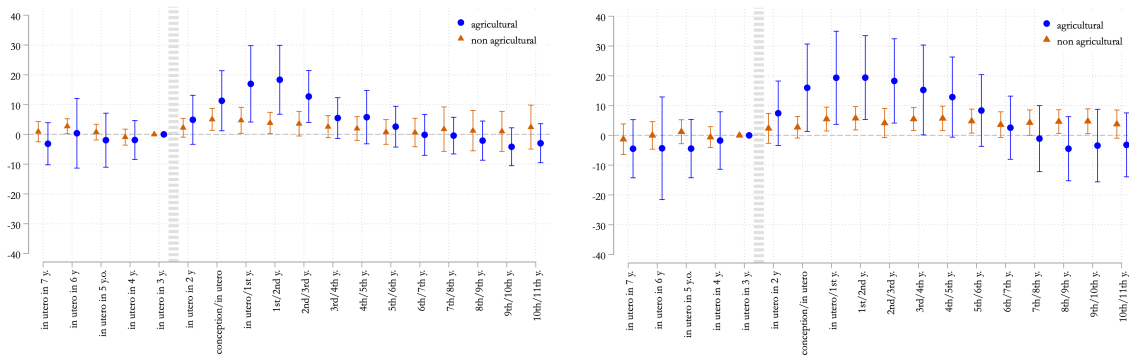
Optimizing behavior by heterogeneous agents leads to different responses across various population groups. Responses regarding compliance with public health recommendations, such as those implemented by the Italian government during the Chernobyl fallout, can be influenced by multiple factors. One key factor is economic incentives, where different evaluations of the costs and benefits of adherence come into play. Some groups may comply less with protective measures because their relative cost of doing so is higher, making their non-compliance an economically rational decision. One main protective measure in that era was the ban on consuming fresh foodstuffs. According to the estimates of Italian National Health Institute, compliance with this ban helped halve the adverse effects of radiation in the immediate aftermath of the fallout, especially for infants and children whose diet heavily relied on milk contaminated by the fallout (Risica, 1987). However, these estimates of radiation doses, particularly iodine-131, assume full compliance with food consumption bans, which likely did not hold. Individuals working in agriculture might incur significant income losses if they discard their crops instead of consuming them. Consequently, during the Chernobyl era, residents in Italian municipalities with intensive agricultural production found it less convenient to refrain from consuming self-grown foodstuffs, highlighting economic constraints in adhering to public health measures.

Additionally, inefficient differences in compliance may arise from variations in beliefs, influenced by trust in authorities or political views (Allcott et al., 2020) as well as by social norms leading individuals to emulate the compliance behavior of their peers and community members (Banerjee et al., 2019).

We investigate the potential gap in economic incentives for protective measures driven by the issue of self-produced food consumption by analyzing data from the 1981 census. In particular, we focus on municipalities where the share of employment in agricultural activities exceeds the national median and analyze if the adverse effect of radiation is higher in such areas.

Due to power constraints and the relatively rare nature of the clinical events studied, we limit the study of the mechanisms to thyroid complications and radiation-related cancers. Our estimates support the hypothesis that municipalities with more intensive agricultural production registered significantly harsher consequences of the fallout. Panel a and b of [Figure 10](#) present coefficient estimates of the previously studied interaction term between the treatment variable and birth cohorts, augmenting the baseline specification with another difference, namely the high vs. low share of agricultural production (the share of employment in the agricultural sector above the national median). Our results of this difference-in-differences-in-differences exercise show a consistently greater effect for both thyroid and cancer diagnoses in agriculture-intensive municipalities (blue plot), over and above the underlying time- and municipality-systematic differences, as well as the baseline radiation effect (red plot). The differences struggle to be statistically significant, but the distance between point estimates is sensible and systematic and follows the underlying age pattern.

Figure 10: The effect of the radiation exposure by share of employment in agriculture.



Panel a) Thyroid complications

Panel b) Cancers

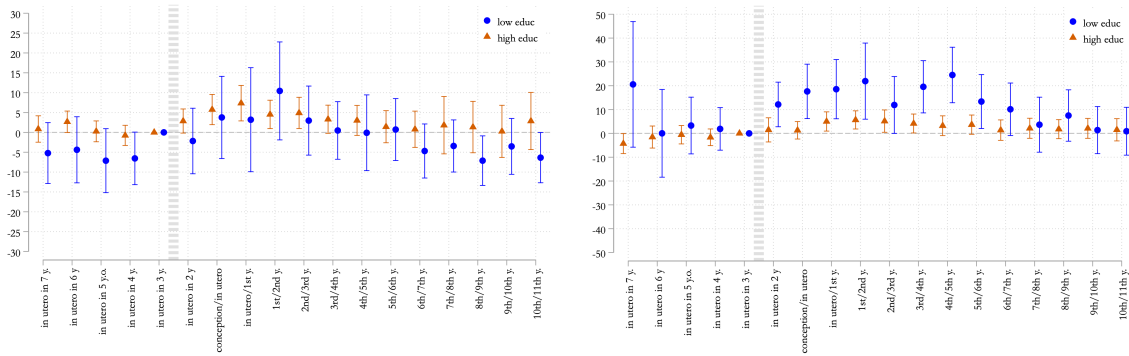
Notes: The figures present coefficient estimates of the interaction term between the treatment variable and birth cohorts, additionally interacted with an indicator variable taking value one for municipalities with the share of employment in the agricultural sector above the national median. The dependent variable is the number of live births registered in any given year. The spikes represent 95 percent confidence intervals based on standard errors clustered at the municipality level.

We also investigate the role of heterogeneous beliefs by examining two key factors: education level, which may influence the interpretation and comprehension of guidelines, and rational mistrust in the government, particularly in municipalities with low support for the ruling government at that time.

For the education aspect, we analyze 1981 census data, conducting a similar exercise as before, but focusing on municipalities with a share of the population holding a secondary school degree below the national median.

In Figure 11, we show that the adverse effect of the fallout on radiation-related cancers is greater in municipalities with lower levels of education. The estimates obtained in this setting point to a significant role of education, which is likely to mitigate the most harsh effects of radiation.

Figure 11: The effect of the radiation exposure by share of secondary education attainment.



Panel a) Thyroid complications

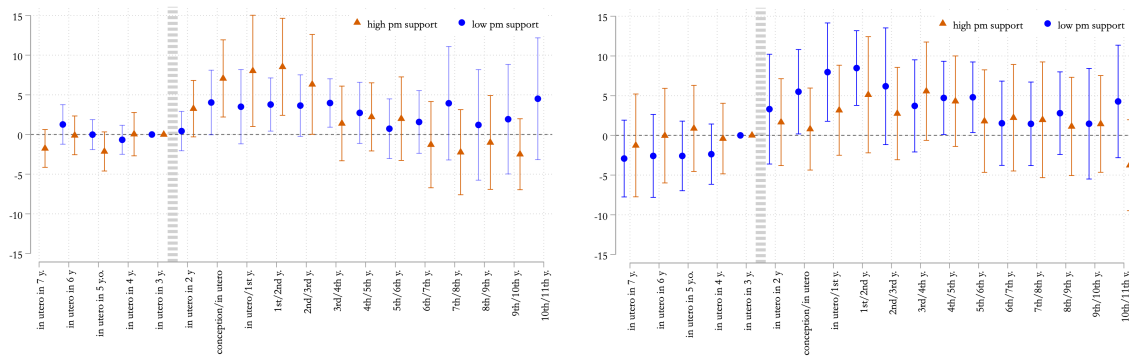
Panel b) Cancers

Notes: The figures present coefficient estimates of the interaction term between the treatment variable and birth cohorts, additionally interacted with an indicator variable taking value one for municipalities with the share of secondary educational attainment below the national median. The dependent variable is the number of live births registered in any given year. The spikes represent 95 percent confidence intervals based on standard errors clustered at the municipality level.

Finally, we investigate the role of political heterogeneity across Italian municipalities during the era of the Chernobyl fallout. In 1986, the Italian government was led by Prime Minister Bettino Craxi, whose administration was elected in the 1983 national elections. Bettino Craxi, a member of the Italian Socialist Party (PSI), served as Prime Minister from 1983 to 1987. His handling of the fallout elicited mixed reactions. The government’s response to the potential health risks posed by radioactive fallout, particularly its management of food safety measures, was criticized for its adequacy and timeliness, prompting debates and scrutiny over the crisis management.

Therefore, we examine the 1983 election results and explore the underlying heterogeneity across municipalities based on the share of votes received by PSI. This investigation aims to understand the potential influence of political views and trust in health authorities and the government, as higher levels of trust are associated with greater adherence to guidelines.

Figure 12: The effect of the radiation exposure by share of votes in the 1983 parliament elections for the ruling party.



Panel a) Thyroid complications

Panel b) Cancers

Notes: The figures present coefficient estimates of the interaction term between the treatment variable and birth cohorts, additionally interacted with an indicator variable taking value one for municipalities with the share of votes in parliament elections for the ruling party below the national median. The dependent variable is the number of live births registered in any given year. The spikes represent 95 percent confidence intervals based on standard errors clustered at the municipality level.

Our analysis of the political stance does not provide any support for the hypothesis that political beliefs might have inefficiently shaped different responses to protective measures in the fallout era. This set of results is not in line with the most recent literature on the effect of political polarization on health-related behaviors, especially in the COVID era (see among others [Allcott et al., 2020](#), [Bargain and Aminjonov, 2020](#), [Beccari et al., 2023](#), [Gollwitzer et al., 2020](#)). Yet, it is however reasonable to believe that in the past, political views had less impact on health behaviors due to lower levels of social polarization and ideological alignment. [Baumann et al. \(2021\)](#) argue that historically, debates were often confined to specific, non-overlapping topics, limiting the broader emergence of ideological states. However, the landscape has shifted dramatically today. The COVID-19 pandemic has catalyzed a widespread ideological state encompassing various topics such as vaccines, face masks, and mobility restrictions, deeply intertwined with political opinions. The politicization of COVID-related issues, documented by [Giaccherini et al. \(2022\)](#) and [Gollwitzer et al. \(2020\)](#), demonstrates how political affiliations now significantly influence attitudes towards public health measures and vaccine hesitancy.

6 Conclusions

The Chernobyl disaster of 1986 remains a landmark event in understanding the long-term effects of radiation exposure on human health. This study focuses on the impact of early-life radiation exposure from the Chernobyl fallout on adult female fertility, a crucial yet underexplored facet of post-radiation health research. By employing a dynamic difference-in-differences approach, we have examined 18 cohorts of women born between 1976 and 1993 in Italy, linking radiation exposure data with administrative health records to assess outcomes such as thyroid complications, cancer diagnoses, spontaneous abortions, and stillbirths.

Our findings reveal a notable correlation between early-life radiation exposure and adverse health outcomes in adulthood. Women who were in utero or very young at the time of the Chernobyl fallout and lived in municipalities affected by a relatively higher dose of radiation exhibit a higher incidence of thyroid complications and cancer diagnoses. Additionally, these women show an increased likelihood of experiencing spontaneous abortions and stillbirths. These results underscore the lasting impact of early-life radiation exposure, highlighting that even relatively low doses can have significant long-term health consequences.

A common challenge in assessing the effects of low to moderate radiation is the difficulty in statistically detecting these impacts, as the resulting increase in cases is often marginal and dispersed, making them hard to identify in a broader population. By focusing on municipalities with higher radiation exposure, our study not only illuminates the health effects of such exposure but also reveals the variability of these effects among individuals exposed at different ages. This approach enhances the understanding of how radiation exposure at various stages of early life can lead to diverse health outcomes, thereby providing a clearer picture of the broader implications of low-dose radiation.

The observed increase in thyroid-related issues and cancers among those exposed at a young age aligns with clinical findings that highlight the heightened vulnerability of infants and young children to radiation-induced health problems. This increased sensitivity is attributed to factors such as rapid cell division, greater absorption rates of radioactive isotopes, and smaller body sizes, which contribute to a higher likelihood of radiation-induced mutations.

Additionally, the analysis sheds light on the variability of the disaster's impact based on local conditions. We find that municipalities with high agricultural employment—where food self-production was prevalent—experienced more severe health consequences, likely due to reduced compliance with protective measures. The significance of economic incentives in shaping health behaviors highlights the need for tailored emergency response strategies that account for local contexts. To enhance compliance with protective measures, policymakers must consider how economic incentives can be structured to make adherence more financially viable for individuals. Understanding these local economic factors is crucial for designing effective interventions that align with the financial realities faced by different communities.

Conversely, beyond the influence of economic incentives, some suboptimal compliance may stem from inefficient decision-making. The observed impact of educational attainment on adherence to protective measures underscores the critical role of information dissemination and public awareness. Effective communication and education are essential for improving compliance and reducing health risks during emergencies.

Finally, political beliefs did not significantly affect adherence to these measures, contrasting with recent studies that have highlighted the role of political polarization in health behavior during crises like the COVID-19 pandemic.

The study also reveals the limitations of relying solely on assumptions about compliance and protective measures. In real-world scenarios, adherence to such measures can be incomplete, influenced by a range of socio-economic and psychological factors. Our results suggest that future research should continue to explore these dimensions to better predict and mitigate the long-term health impacts of radiation exposure.

Our study underscores the necessity for continued research into the long-term effects of lower-dose radiation exposures, especially among vulnerable populations. While our findings offer valuable insights into a specific age group, they represent only a partial view of the broader picture. Given the latent nature of certain health conditions, additional research is needed to fully understand the delayed impacts of radiation exposure. Future studies that focus on radiation-related health outcomes across different demographics, including males, are essential for providing a more comprehensive understanding of the full spectrum of radiation effects.

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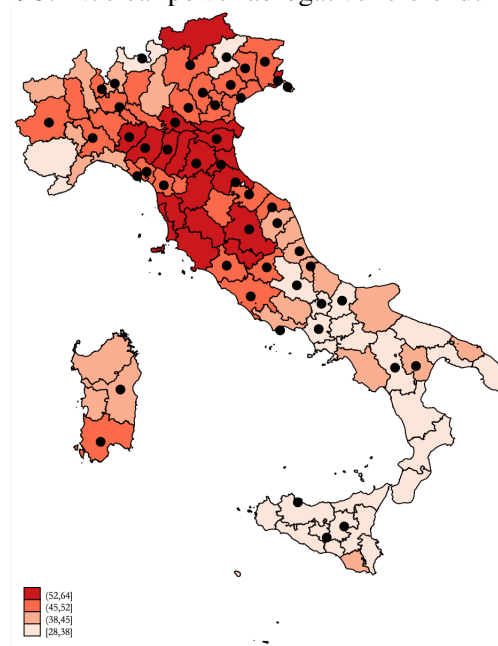
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Appendix A

A.1 Additional Figures

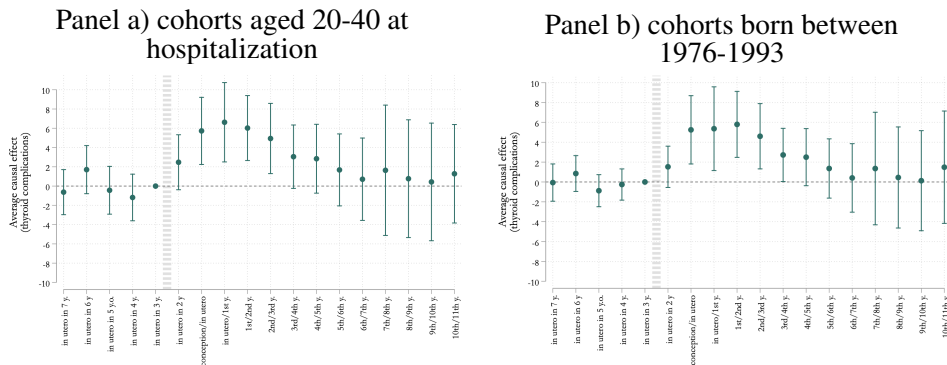
Figure A1: Percentage of favorable votes at the province level - 1987 Nuclear power abrogative referendum



Notes: The figure presents the percentage of favorable votes at the province level related to the 1987 Nuclear power abrogative referendum. The black points depict the treated provinces. The treatment indicator at the provincial level takes a value of 1 for provinces where the number of treated municipalities exceeds the median value.

A.2 Alternative sample selection: Thyroid complications

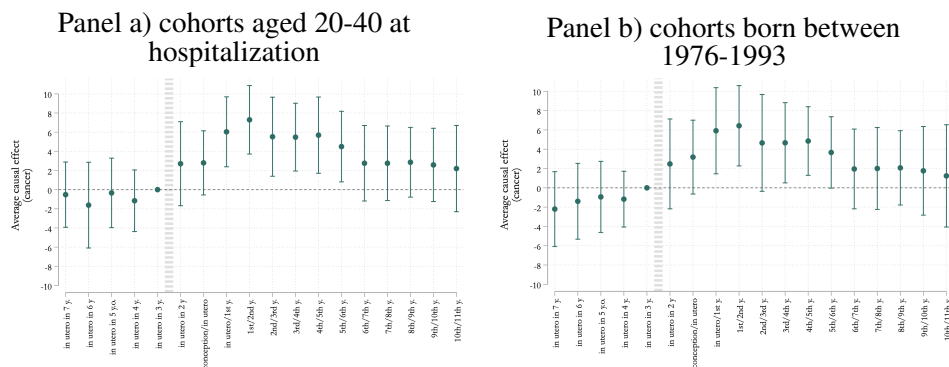
Figure A2: The effect of the radiation exposure index



Notes: The figure presents coefficients estimates of the interaction term between the treatment variable and the a indicators from Eq. (1). Estimates are weighted by municipality population size. The spikes represent 95 percent confidence intervals based on standard errors clustered at the municipality level. *Panel a* findings in are based on 2,208,569 observations distributed across 8,090 municipalities (as defined in 2010). P – value pretrend 0.331. *Panel b* findings are based on 1,893,060 observations distributed across 8,090 municipalities (as defined in 2010). P – value pretrend 0.378. Cohorts born after 1993 are binned at -7, while cohorts born before 1976 are binned at +10.

A.3 Alternative sample selection: Cancer diagnoses

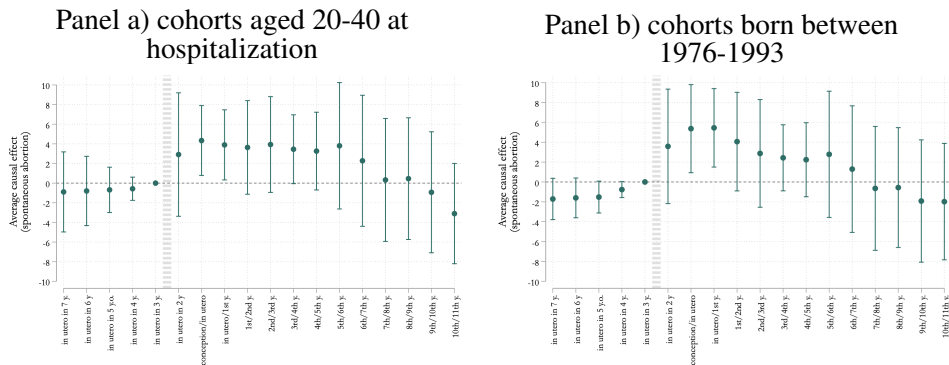
Figure A3: The effect of the radiation exposure index



Notes: The figure presents coefficients estimates of the interaction term between the treatment variable and the a indicators from Eq. (1). Estimates are weighted by municipality population size. The spikes represent 95 percent confidence intervals based on standard errors clustered at the municipality level. *Panel a* findings in are based on 2,208,569 observations distributed across 8,090 municipalities (as defined in 2010). P – value pretrend 0.930. *Panel b* findings are based on 1,893,060 observations distributed across 8,090 municipalities (as defined in 2010). P – value pretrend 0.844. Cohorts born after 1993 are binned at -7, while cohorts born before 1976 are binned at +10.

A.4 Alternative sample selection: Spontaneous abortion

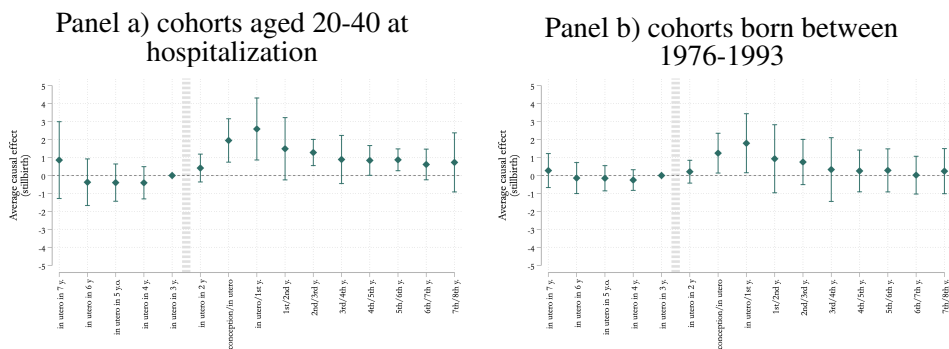
Figure A4: The effect of the radiation exposure index



Notes: The figure presents coefficients estimates of the interaction term between the treatment variable and the a indicators from Eq. (1). Estimates are weighted by municipality population size. The spikes represent 95 percent confidence intervals based on standard errors clustered at the municipality level. *Panel a* findings are based on 2,208,569 observations distributed across 8,090 municipalities (as defined in 2010). P – value pretrend 0.913. *Panel b* findings are based on 1,893,060 observations distributed across 8,090 municipalities (as defined in 2010). P – value pretrend 0.345. Cohorts born after 1993 are binned at -7, while cohorts born before 1976 are binned at +10.

A.5 Alternative sample selection: Stillbirths

Figure A5: The effect of the radiation exposure index

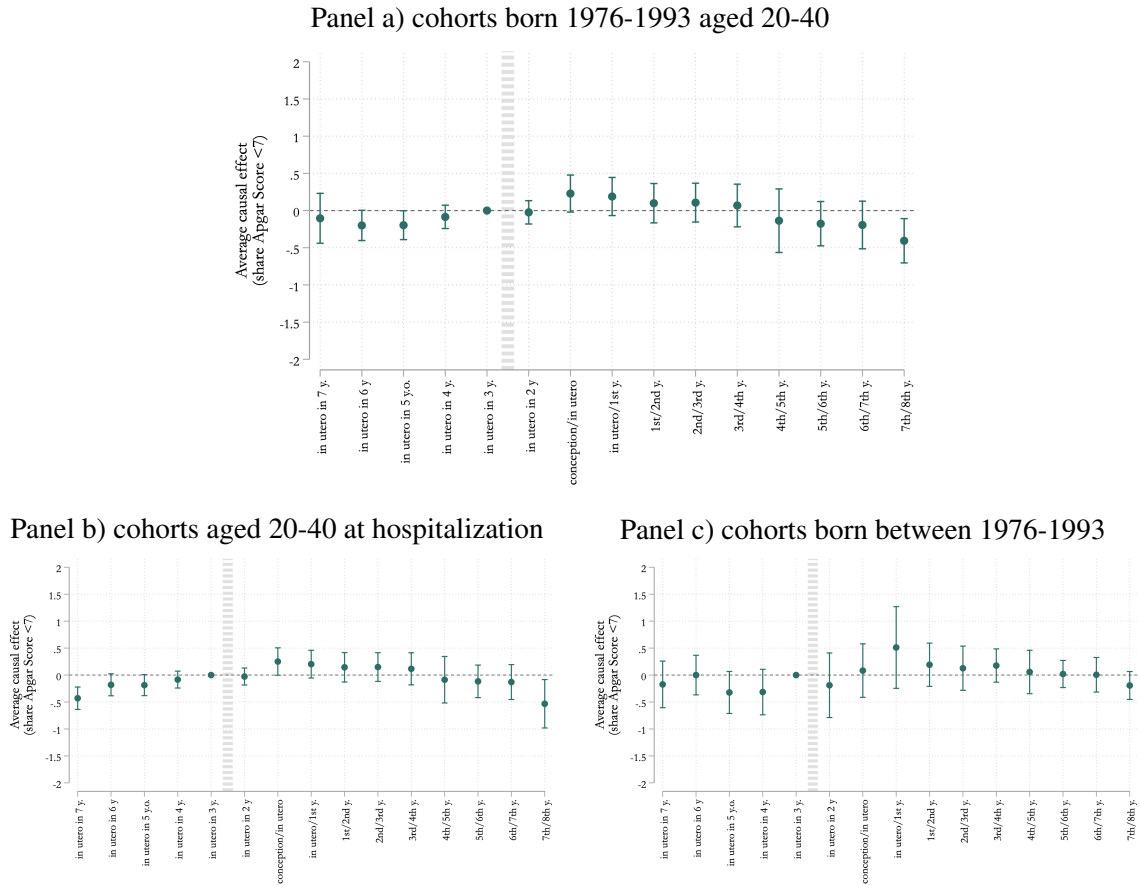


Notes: The figure presents coefficients estimates of the interaction term between the treatment variable and the a indicators from Eq. (1). Estimates are weighted by municipality population size. The spikes represent 95 percent confidence intervals based on standard errors clustered at the municipality level. *Panel a* findings are based on 2,628,762 observations distributed across 7,480 municipalities (as defined in 2010). P – value pretrend 0.5685. *Panel b* findings are based on 2,249,308 observations distributed across 7,480 municipalities (as defined in 2010). P – value pretrend 0.416. Cohorts born after 1993 are binned at -7, while cohorts born before 1976 are binned at +10.

A.6 Birth outcomes

A.6.1 Apgar score

Figure A6: The effect of the radiation exposure index on Apgar score

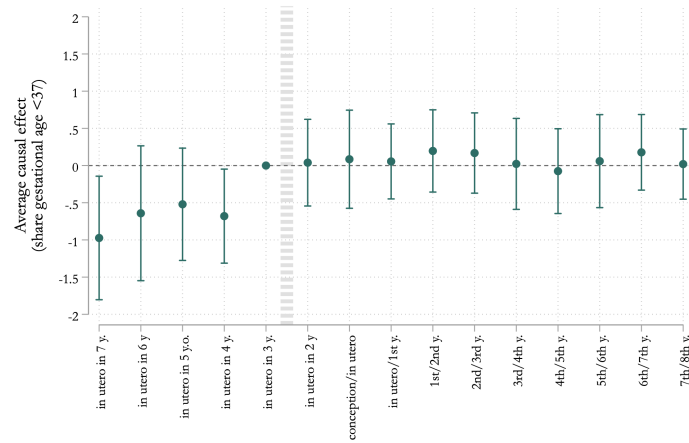


Notes: The figure presents coefficients estimates of the interaction term between the treatment variable and the a indicators from Eq. (1). Estimates are weighted by municipality population size. The spikes represent 95 percent confidence intervals based on standard errors clustered at the municipality level. *Panel a* findings are based on 197,018 observations distributed across 3,868 municipalities (as defined in 2010). P -value pretrend 0.247. *Panel b* findings are based on 661,402 observations distributed across 7,413 municipalities (as defined in 2010). P -value pretrend 0.002. *Panel c* findings are based on 213,382 observations distributed across 3,913 municipalities (as defined in 2010). P -value pretrend 0.513. Cohorts born after 1993 are binned at -7, while cohorts born before 1976 are binned at +10.

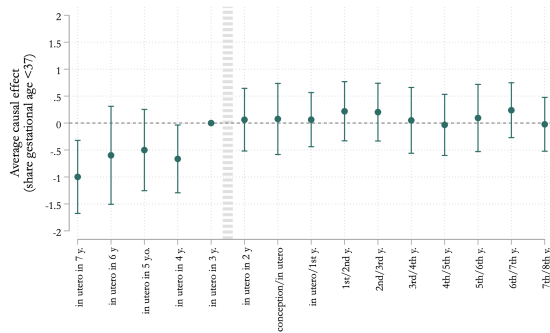
A.6.2 Gestational age

Figure A7: The effect of the radiation exposure index on gestational age

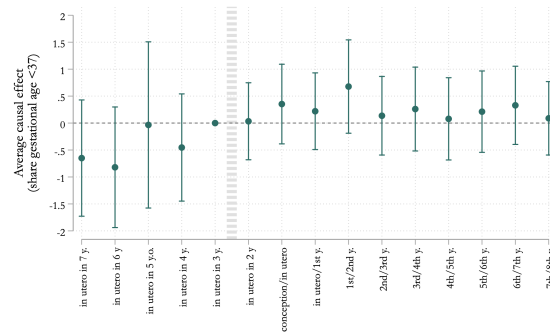
Panel a) cohorts born 1976-1993 aged 20-40



Panel a) cohorts aged 20-40 at hospitalization



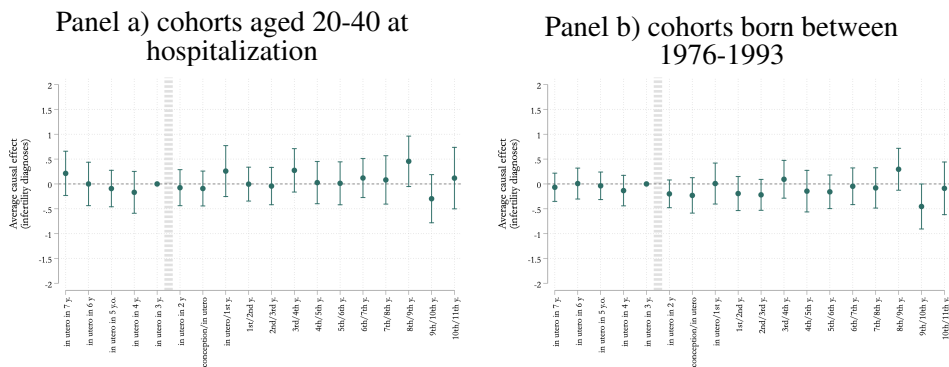
Panel b) cohorts born between 1976-1993



Notes: The figure presents coefficients estimates of the interaction term between the treatment variable and the a indicators from Eq. (1). Estimates are weighted by municipality population size. The spikes represent 95 percent confidence intervals based on standard errors clustered at the municipality level. *Panel a* findings are based on 197,018 observations distributed across 3,868 municipalities (as defined in 2010). P -value pretrend 0.111. *Panel b* findings are based on 661,402 observations distributed across 7,413 municipalities (as defined in 2010). P -value pretrend 0.0579. *Panel c* findings are based on 213,382 observations distributed across 3,913 municipalities (as defined in 2010). P -value pretrend 0.5691. Cohorts born after 1993 are binned at -7, while cohorts born before 1976 are binned at +10.

A.7 Alternative sample selection: Male infertility

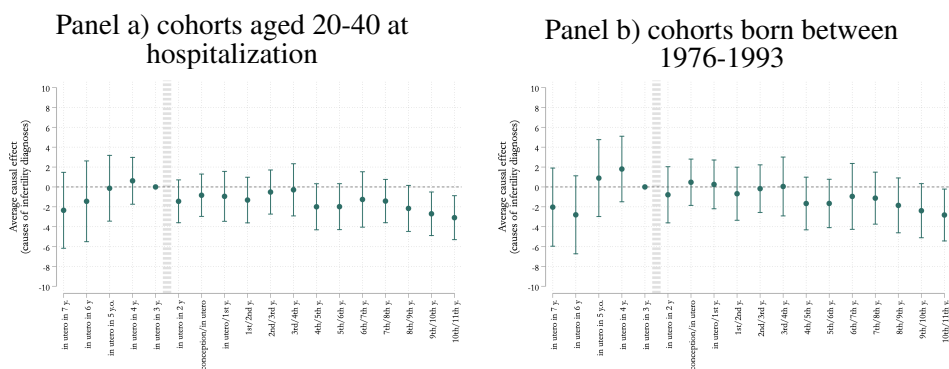
Figure A8: The effect of the radiation exposure index



Notes: The figure presents coefficients estimates of the interaction term between the treatment variable and the a indicators from Eq. (1). Estimates are weighted by municipality population size. The spikes represent 95 percent confidence intervals based on standard errors clustered at the municipality level. *Panel a* findings in are based on 2,208,569 observations distributed across 8,090 municipalities (as defined in 2010). P – value pretrend 0.4778. *Panel b* findings are based on 1,893,060 observations distributed across 8,090 municipalities (as defined in 2010). P – value pretrend 0.682. Cohorts born after 1993 are binned at -7, while cohorts born before 1976 are binned at +10.

A.8 Alternative sample selection: Causes of male infertility

Figure A9: The effect of the radiation exposure index



Notes: The figure presents coefficients estimates of the interaction term between the treatment variable and the a indicators from Eq. (1). Estimates are weighted by municipality population size. The spikes represent 95 percent confidence intervals based on standard errors clustered at the municipality level. *Panel a* findings in are based on 2,208,569 observations distributed across 8,090 municipalities (as defined in 2010). P – value pretrend 0.819. *Panel b* findings are based on 1,893,060 observations distributed across 8,090 municipalities (as defined in 2010). P – value pretrend 0.555. Cohorts born after 1993 are binned at -7, while cohorts born before 1976 are binned at +10.