Early Exposure to Hazardous Waste and Academic Achievement: Evidence from a Case of Environmental Negligence

Tomás Rau, Sergio Urzúa, Loreto Reyes

Abstract: This paper estimates the effect of early exposure to toxic waste on academic achievement. We analyze longitudinal information from individuals attending primary and secondary schools in Arica (northern Chile). Between 1984 and 1989, the city received more than 20,000 tons of toxic chemicals containing high concentrations of lead, arsenic, and mercury. We implement difference-in-differences and reduced-form models to document robust relationships between residential and school proximity to the polluted area and academic performance. We find that attending a school 1 kilometer farther away from the polluted area significantly increases math and language scores by 0.09 and 0.07 standard deviations, respectively. Finally, we use georeferenced blood tests and administrative records on labor income to estimate that children living in the area could lose up to US$60,000 over the course of their lifetime as a result of their early life exposure to toxic waste.

JEL Codes: I12, I18, I21, O1, Q5

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THE NEGATIVE EFFECTS of exposure to hazardous waste, such as heavy metals and other toxic elements, on cognition and health-related outcomes have received increasing attention in the literature (Currie et al. 2014). It has been documented that exposure can irreversibly affect neurological and cognitive functions among hu-

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mans. While scientists have long been aware of these potential consequences, only in recent decades has chronic exposure to hazardous waste raised greater concerns worldwide. These concerns are reflected, for example, in the decisions to amend the international standards for lead concentration in gasoline, paints, and the soil and air of urban areas (Mielke and Reagan 1998; Mielke 2002). Governments, in turn, have reacted to the new standards by implementing prevention and information programs as well as public policies aimed at reducing emissions from major sources of pollution.

In this paper, we analyze the effects of mining waste exposure on academic performance among students in the city of Arica in northern Chile. The presence of toxic waste in the city is largely a result of the importation of 20,000 tons of mineral residues/waste from Sweden between 1984 and 1989. The waste was imported by the Chilean company PROMEL, initially to be reprocessed to extract gold and silver. However, PROMEL quickly determined that this would not be profitable and stopped processing it. As a result, the waste was left on the outskirts of the city at a location known as Site F.

In the late 1980s and early 1990s, Arica experienced rapid economic growth leading to an increasing demand for government housing projects. Unfortunately, and probably explained by the ignorance surrounding the situation, the local government decided to construct housing projects close to Site F. Between 1990 and 1995, two housing projects, Cerro Chuño and Los Industriales, were built only meters away from the site, and hundreds of families moved to the area.

We exploit these precipitating events to estimate the effects of exposure to toxic waste on academic achievement both in the short and long run. To do so, we first identify the main source of pollution in Arica. In particular, we correlate the results from georeferenced blood tests and household proximity to a set of potentially

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high-risk areas for environmental contamination. Our empirical analysis points definitively to Site F as the main source of contamination.

To identify the short-term impact, we follow a difference-in-differences (DID) approach and document a strong negative association between school proximity to the source of pollution and school-level test scores (math and language). To estimate the long-term effects, we use individual-level test scores from the 2008 Chilean college admission exam—more than two decades after the initial event—and exploit the empirical relationship between each student's residential proximity to Site F and their college admission test scores.

Despite growing evidence linking pollution exposure with a broad range of health outcomes (see Currie et al. [2014] and Graff Zivin and Neidell [2013] for recent reviews), empirical studies associating childhood exposure to any source of hazardous material with educational outcomes are still scarce in the literature.[1] This is precisely our main contribution. Specifically, we provide evidence of the impact of exposure to hazardous waste on cognitive development, as proxied by achievement test scores. Furthermore, although our empirical analysis cannot completely rule out the possibility that other elements present in the waste deposit at Site F also negatively affected cognition, we are able to identify lead as one important channel through which distance to contaminated areas affected student achievement.[2]

Our results suggest that if elementary school students had attended a school 1 kilometer (0.6 miles) farther away from the waste site, in the short run (2–5 years later), their average math test scores would have increased by 0.09 standard deviations. These effects become stronger in the long run. The point estimates in our preferred specifications indicate that if students had lived 1 kilometer farther away from Site F, their math college admission test scores 2 decades later would have been 0.22 standard deviations higher. The results for language test scores are of a similar magnitude. In addition, we empirically examine the potential threats to our identification strategy, confirming the robustness of our main findings.

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1. Almond, Edlund, and Palme (2009) and Black et al. (2013) are two exceptions. However, these papers document negative effects of exposure to radiation—not to mining waste—on academic achievement in Sweden and Norway, respectively. For empirical studies of the impact of pollution on health outcomes, see Chay and Greenstone (2003), Currie and Neidell (2005), Lleras-Muney (2010), Currie, Greenstone, and Moretti (2011), and Currie and Walker (2011), among others.

2. The effects of lead on the deterioration of cognitive and behavioral functions, especially in children, is the main focus of research in a number of developed countries (Koller et al. 2004). There is also evidence that other heavy metals may affect cognition. Axelrad et al. (2007) find that prenatal mercury exposure is associated with decrements in intelligence quotient (IQ). Also WHO (2012) discuss evidence about long-term arsenic exposure and its association with developmental effects.

We complement these results with a back-of-the-envelope calculation translating our estimated effects into expected monetary losses. We do this by exploiting the empirical relationship between pre–labor market test scores, levels of pollutants among residents of Arica, and annual earnings during adulthood. Focusing on lead as the principal contaminant, our estimates indicate that affected individuals can be expected to lose approximately $6,000 per microgram of lead per deciliter of blood. Thus, at an average of 10 micrograms of lead per deciliter of blood in our sample, we estimate a mean compensation of about $60,000. This ignores any nonpecuniary costs associated with blood lead levels and is therefore likely a lower bound of the true cost. To the best of our knowledge, this is the first estimate of this kind in the literature.

The paper is organized as follows. In section 1, we explain the origin of the lead pollution in the city of Arica. We describe our data in section 2, and section 3 presents our identification strategy and empirical findings. Robustness checks are presented in section 4, and monetary losses due to exposure are computed in section 5. Section 6 concludes.

1. EXPOSURE TO TOXIC WASTE IN ARICA: A BRIEF HISTORY

1.1. The Arrival and Abandonment of Waste Material

PROMEL was a Chilean company founded in the 1970s. The company operated in the north of Chile and offered secure transportation and processing services for mineral and chemical waste. On March 21, 1984, PROMEL requested authorization from the Chilean National Border Agency to import mineral waste from Sweden. The request was based on the company's intention to reprocess these minerals to extract gold.[3] The chemical description of the minerals included in the official request indicated the presence of lead, arsenic, mercury, and other substances. With respect to the level of toxicity, on its customs declaration form, PROMEL described the waste as being nontoxic metallic mud unless eaten or handled without proper protection.

After a few months of deliberation, the Chilean government granted permission to import the minerals. As a result, between August 29, 1984, and July 17, 1985, Arica received three shipments of 8,096, 6,997, and 4,041 tons of minerals, respectively. The importation of these products continued until January 21, 1989. By that time, approximately 21,091 tons of toxic waste had entered Chile. The collection point of the waste became known as Site F (*sitio F*). The area was located northeast of downtown Arica and, at that point, was outside of the city limits. PROMEL rented this site from the Bureau of Land Management (Ministerio de

3. The complete process would have involved ridding the mineral waste of arsenic, then converting the resulting material into trioxide, and, finally, extracting gold.

Bienes Nacionales). The area was initially secured by a concrete perimeter and was marked with warning signs indicating the presence of hazardous waste.

In December 1993, PROMEL requested permission to abandon the mineral waste.[4] The company argued that the high costs of inputs, the constant fluctuation of metal prices in international markets (particularly of copper and silver), and the exchange rate policy made the originally profitable project nonviable.

1.2. The Housing Projects

During the 1980s the city of Arica faced an increasing demand for government subsidized housing. In 1985, the central government launched the construction of the first social housing project, which later became the neighborhood of Los Industriales I. It was located only meters away from Site F, and its completion date was March 1989. It is unknown why Chilean authorities decided to build at that location, but there was likely a lack of information about the characteristics of the materials contaminating the area.[5] Moreover, even if the local authority (Municipalidad de Arica) had wanted to stop or prevent the construction, this would have not been possible since the land was originally outside the city limits (in a nonresidential area), and consequently it was not under Arica's jurisdiction.

The neighborhood's location outside of Arica's jurisdiction had another consequence for future residents. According to the Chilean legislation, house titles can only be granted by local governments. Therefore, since the housing projects were originally outside the city limits, the new homeowners did not receive official titles for several years. Only after 1996, once the city limits were extended, were housing titles granted. As we discuss below, this prevented houses from being sold, mitigating some of the threats to our identification strategy.

The construction of Los Industriales I (1989) was followed by that of Los Industriales II and III (1991), Los Industriales IV (1992), and Cerro Chuño I–VII (after 1993). Table 1 presents the exact date of completion for each project. Figures 1 and 2 present satellite photographs of the area before and after the construction of the housing projects. They illustrate the proximity of the new neighborhoods to Site F.

1.3. Government Responses, Evaluation of Consequences, and Compensations

In December 1996, after multiple complaints from the local residents, the Health Service of Arica began a series of actions aimed at removing the toxic waste from

4. The request was directed to the National Border Agency. This agency owned the waste after PROMEL decided not to pay taxes on the importation.

5. It is worth noting that the original decision was made by the central government, specifically by the Chilean Department of Housing (Ministerio de Vivienda y Urbanismo).

Table 1. Construction, Completion, and Reception Dates of Housing Projects in Arica

Housing Project (1)	Construction Date (2)	Number of Houses Built (3)	Completion Date (4)	Building Authorization Date (5)	Registration Date (6)	Number of Houses Registered (7)
Los Industriales I	1985	536	March, 1989	NA	NA	NA
Los Industriales II	NA	316	April 29, 1991	November 21, 1994	NA	NA
Los Industriales III	1990	279	April 29, 1991	June 11, 1997	September 16, 1997	279
Los Industriales IV	1991	405	December 17, 1992	November 21, 1994	NA	NA
Cerro Chuño I	1993	149	NA	January 4, 2001	September 9, 2001	118
Cerro Chuño II	1994	60	NA	January 4, 2001	September 9, 2001	NA
Cerro Chuño III-a	1994	203	NA	January 4, 2001	September 24, 2001	105
Cerro Chuño III-b	1995	38	NA	January 4, 2001	September 11, 2001	19
Cerro Chuño IV	1994	185	NA	January 4, 2001	October 9, 2001	44
Cerro Chuño V	1995	110	NA	January 4, 2001	October 4, 2001	47
Cerro Chuño VII	1996	134	NA	January 4, 2001	October 9, 2001	36

Note.—The information provided in this table was obtained from documents of Chilean Congress and from a report elaborated by Peace and Justice Service (SERPAJ 1996). Columns 2, 3, and 4 show the construction dates, number of houses built, and house completion dates. Since the neighborhoods were built in areas destined for industrial activities, the Housing Ministry (Ministerio de Vivienda y Urbanismo) did not request the building authorization of the neighborhoods to the municipality. In turn, the municipality of Arica could not authorize the construction of housing projects due to the fact that areas were out of its jurisdiction. As soon as the areas were incorporated into the regulatory plane of the city, the Housing Ministry requested the building authorizations to the municipality in the dates in column 5, and the property titles were delivered to the residents. The final reception dates and the number of houses registered by the municipality are presented in columns 6 and 7, respectively.

Figure 1. Site F before the construction of housing projects

Figure 2. Site F after the construction of housing projects

Site F. In 1997, the department of chemistry at the University of Tarapaca (a local university) carried out the first scientific study of the levels of pollution in Arica. The results documented the presence of high concentrations of toxic minerals in the city.[6] These were confirmed by a second study conducted in the same year by the National Service of Geology and Mining (Servicio Nacional de Minería y Geología, SERNAGEOMIN). This study included a detailed analysis of the concentration of material in Site F's stockpiles. The analysis concluded that the material contained approximately 10% of arsenic, 4.4% lead, 2.1% zinc, 1.5% copper, and also other heavy metals such as mercury, antimony, bismuth, and tin. Of these chemicals, lead, arsenic, and mercury have been identified as potentially harmful to cognition.

Given this evidence, the Chilean government declared the situation to be an "environmental health emergency." The relocation of the waste began in January 1998, under the supervision of the Arica Department of Environmental Protection and with the approval of the local government.[7]

Between July 14 and September 8, 2000, the Chilean Ministry of Health carried out a third study, "Lead in *Cerro Chuño* and *Los Industriales*" (CONAMA 2009). In this study, blood samples were taken from about 5,000 residents. The tests showed high concentrations of lead for 579 of the residents. As a result of these studies, residents of Cerro Chuño and Los Industriales initiated legal actions against PROMEL and the Arica Health Service, demanding financial compensation. In 2007, the Supreme Court upheld the claims and decided on a compensation of 8 million pesos (approximately US$16,000) per claim (Corte Suprema 2007).

Between August 2008 and October 2009, the National Environmental Commission (Comisión Nacional de Medio Ambiente, CONAMA) carried out a new environmental study specifically designed to identify sources of pollution in the city.[8] The results demonstrated the presence of three different sources of pollution: Site F, the Arica–La Paz Line Railroad, and a set of 26 points whose lead levels exceeded the international standard of 400 milligrams of lead per kilogram of soil

6. The study was motivated by the increasing complaints of the residents of Cerro Chuño and Los Industriales, and it had the support of the Peace and Justice Service of Chile (Servicio de Paz y Justicia de Chile, SERPAJ).

7. Some of the items outlined in the plan were implemented through the relocation of toxic waste to Quebrada Encantada, an area located northeast of Site F. Figures 1 and 2 show the locations of Site F, Cerro Chuño, Los Industriales, and Quebrada Encantada. Notice that the distance between the houses located at the eastern edge of Cerro Chuño and the new point of collection of toxic waste is approximately 600 meters (or 0.375 miles).

8. In order to establish the chemical composition of soil and subsoil of the city of Arica, the study followed a sampling scheme that considered the division of the city in 40 quadrants. For each quadrant, an average of 11 random samples were taken in three levels (surface, 15 cm, and 30 cm below the surface).

analysis (400 mg/Kg).[9] Site F was identified as the oldest source of lead contamination in Arica. The study also showed that both the rail line and the 26 points were associated with contemporary sources of contamination (AGQ 2009). Below we examine the relative importance of each of these sources of pollution in our sample.

Using the report by CONAMA, the Department of Health established a multidisciplinary committee to investigate the effects of metal residue contamination in Arica and to develop policies leading to the relocation of the affected families. This committee focused on three highly contaminated areas: the harbor area (one of the 26 locations originally identified by CONAMA), Maestranza (site associated with the Arica–La Paz railroad system), and Site F. They also considered how two airstreams might contribute to the dispersion of pollutants: south-southwest (predominant) and northeast. Among the main policy initiatives resulting from this analysis was the relocation of approximately 1,880 housing sites adjacent to Site F and the development of special educational programs for the students attending schools in the affected areas.[10]

Finally, according to the analyzed evidence, the primary channel of exposure was through soil contamination and wind-borne lead (most likely spread via the northeast airstream). To our knowledge, there is no strong evidence on the contamination of drinking water. CONAMA (2009) only reports that a few water distribution points are "above the norm," but it also does not specify any distribution points nor does it provide a measure of contamination.

2. THE DATA

We gather multiple sources of information to quantify the short- and long-run effects of toxic waste exposure on academic achievement.

2.1. Test Scores

We analyze data from two national standardized test scores: the SIMCE (Sistema de Medición de la Calidad de la Educación) and the Chilean college admission tests or PSU (Prueba de Selección Universitaria).

The SIMCE test scores are aimed at measuring the quality of teaching and the degree of student learning at various educational levels in Chile. The tests are taken

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9. The Environmental Protection Agency (EPA) has established a risk value of 400 mg/Kg lead for sites where children are active (Soil Hazard Standard for Children Play's Area, SHSCPA).

10. For details, see "The Intervention in Areas with Presence of Polymetallic in Arica: A Master Plan" (CONAMA 2009). During 2010 and 2011, the Ministry of Housing granted 898 housing subsidies and approved the construction of two housing projects to relocate 230 families of Cerro Chuño and Los Industriales (GORE 2011).

annually by students enrolled in fourth, eighth, and tenth grades.[11] The system started in 1988, so we are able to identify schools near Site F at the time the chemical waste was brought to the city and, consequently, we can analyze academic achievement before and after students were exposed to lead pollution from Site F.

Only school-level SIMCE data are available for 1988–96. The information includes school-level averages in mathematics and language test scores for fourth graders (1988, 1990, 1992, and 1996), time-invariant covariates such as type of school (public, voucher, or private), and school-level socioeconomic variables.

Since fourth graders in 1988 initially enrolled in school in 1983 or 1984, we define 1990 as the first year of treatment (the completion date of the first government housing projects was 1989). Below we show that our results are robust to this decision.[12] To estimate the short-term impact of exposure to hazardous waste we use the distance between the school and Site F (measured in kilometers) as our measure of treatment. Section 3 describes our empirical strategy.

Our second source of information on academic achievement, the PSU scores, comes from the Chilean college admission system. We use the individual-level 2008 PSU data, which contains information on age, gender, math and language test scores, family background variables (mother's and father's education, family income, mother or father absence), high school–level information (private, voucher, or public), and residential address. Moreover, for those in this sample who have just graduated from high school we recover additional individual-level information from the 2004 SIMCE (eighth grade). This allows us to observe multiple measures of academic achievement and also to identify each individual's place of residence (municipality) in 2004 and 2008.[13] We restrict our main analysis to the sample of individuals who reported living in Arica in both years. We use data from those not living in Arica in either 2004 or 2008 to perform robustness checks.[14] Descriptive statistics for this sample are presented in table 2.

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11. Since 2006, SIMCE tests fourth graders and alternates between eighth and tenth graders every other year.

12. Fourth graders in 1988 were born in 1978 and started school in 1983 or 1984 (at that time, 83% of schools in Arica offered kindergarten). It is worth mentioning that only in 1997 did residents of Arica learn about the toxic content of Site F, reducing the likelihood of endogenous migration before that date.

13. From the 2004 SIMCE data we extract the exact location of each individual's high school. We use this information to analyze the impact of pollution on test scores as a function of the distance from Site F to high schools. Unfortunately, information on home addresses is only available in the 2008 PSU.

14. The sample of students in both the 2004 SIMCE and the 2008 PSU data sets are not exactly the same. We do not observe PSU scores for those who took the SIMCE in

Table 2. Summary Statistics. 2008 PSU Sample

Variable	Mean	SD	Min.	Max.
Distance from Site F to home	2.321	.938	.222	4.049
Home located to the east of Site F	.153	.360	0	1
Age	18.591	.535	18	21
Male	.446	.497	0	1
Mother absence	.059	.236	0	1
Father absence	.275	.446	0	1
Mother with less than 8 years of education	.165	.371	0	1
Mother with 8–11 years of education	.150	.357	0	1
Mother with 12 years of education	.237	.426	0	1
Mother with more than 12 years of education	.386	.487	0	1
Father with less than 8 years of education	.121	.327	0	1
Father with 8–11 years of education	.108	.311	0	1
Father with 12 years of education	.182	.386	0	1
Father with more than 12 years of education	.312	.463	0	1
Private school	.0481	.214	0	1
Voucher school	.459	.498	0	1
Public school	.492	.500	0	1
Math PSU 2008 score	502.805	92.341	203	800
Language PSU 2008 score	483.632	93.900	204	747
Observations	1,076			

Note.—Source: 2008 PSU. Distances are expressed in kilometers. In order to consider the wind currents and the dispersion of pollutants around the city, we include the variable "home located to the east of Site F," which is equal to one if a student lives to the east of Site F (main contaminated area) and zero otherwise. Parent's absence is equal to one if the biological parent or stepfather/stepmother does not live with the student. Parental education was tabulated only if parents were present.

Ideally, we would like to analyze individual-level longitudinal information from individuals exposed to pollution since childhood. Unfortunately, to the best of our knowledge, such information does not exist. Therefore, we combine information from the 2008 PSU and the 2004 SIMCE to identify individuals exposed to the toxic waste during their teenage years. However, as it was illegal to sell government housing for at least 5 years, many of the teenagers in our sample were most likely exposed to the pollution beginning at early ages. This unfortunate situation is

2004 and did not take the PSU in 2008. Therefore, we do not observe PSU scores or place of residence in 2008 for those who retained a course during high school, dropped out of high school, or for those high school graduates who opted to not take the PSU in 2008. The 2004 SIMCE data contain 272,198 observations, whereas the 2008 PSU contains information for 240,682 high school graduates.

exacerbated by the limited regional migration for this period as documented by Soto and Torche (2004). Although we cannot rule out endogenous moves within the city limits, these facts help to mitigate the potential impact of the phenomena on our results.

2.2. Blood Tests

We use geocoded blood tests measuring lead concentration both to identify the main sources of pollution in the city of Arica and to document the association between waste deposit proximity and blood lead levels as a proof of concept. In particular, we use data from the study "Lead in *Cerro Chuño* and Los *Industriales*" (LCCI), carried out by the Chilean Ministry of Health in 2000. This study included the collection of 4,990 intravenous blood tests from local residents: 3,240 children (aged 0–15 years) and 1,750 adults (aged 16 or older). The results show that 4,411 people had concentrations of lead of 10 micrograms per deciliter of blood or less, the maximum level of lead allowed by the US Centers for Disease Control and Prevention (CDC).[15] For the remaining 579 cases, the study found levels exceeding the maximum standards according to the CDC. Of these 579 cases, 538 were reexamined by the Institute of Public Health through the *leadcare* system, and we have access to only this subsample. The new examination found that a total of 407 samples had concentrations of lead below the CDC standard, while 131 had levels at or above the standard (120 were children between ages 0 and 15 years). Importantly, the data contain information on each individual's street address. This allows us to link lead levels to distance to Site F. Figure 3 presents the distributions of lead levels in blood for the two examinations.[16]

3. EMPIRICAL ANALYSIS

3.1. Identifying Sources of Pollution

To confirm that Site F was the main source of pollution in Arica during the study period, we first evaluate the importance of all of the sites originally identified by CONAMA: Site F, the Arica–La Paz Line Railroad, and the set of 26 points whose lead levels exceeded the international standard of 400 milligrams of lead per kilogram of soil (400 mg/Kg) (see CONAMA, Comisión Nacional de Medio Ambiente, for further details). We do this by analyzing the correlation between the lead levels in blood collected from residents of Cerro Chuño and Los Industriales and their proximity to each of the exposed locations. As previously explained, the original sample of blood tests was collected in 2000 from 4,990 residents of those

15. In the absence of substantial changes in lead exposure, blood lead levels in adults are stable and for their environmental monitoring a single blood lead concentration is an excellent biological indicator (Delves, Sherlock, and Quinn 1984).

16. Table A1 in the appendix presents the descriptive statistics of this sample.

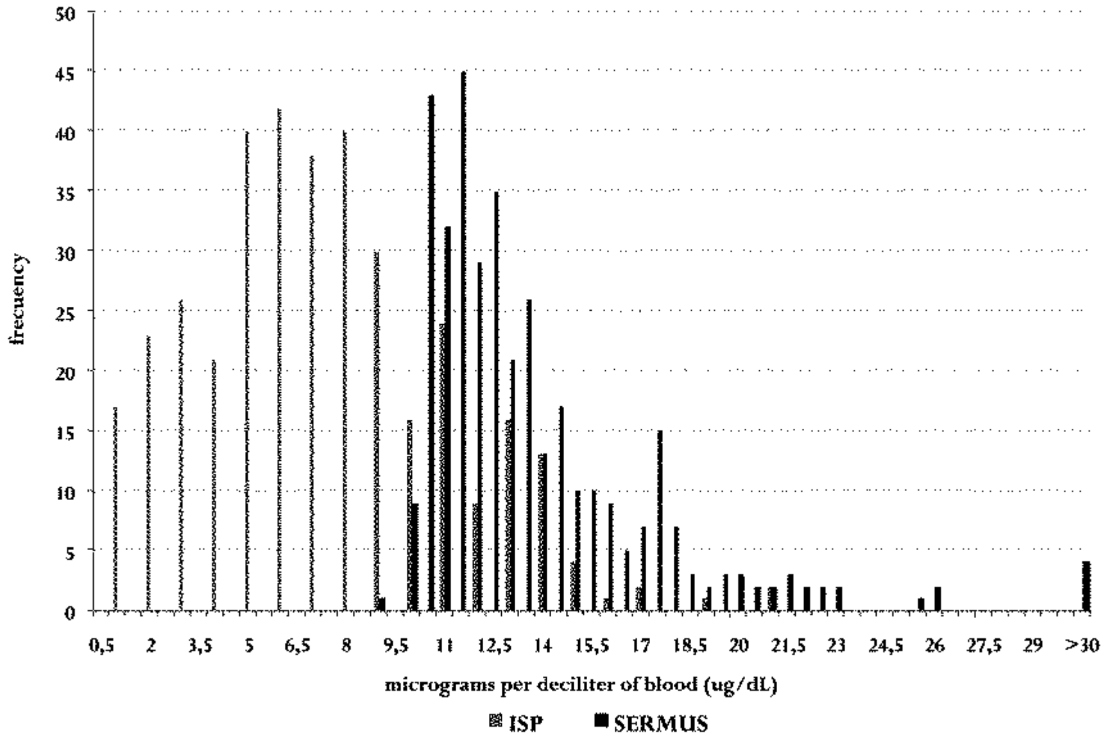

Figure 3. Histogram of blood lead levels: ISP and SERMUS samples. This figure presents histograms of blood lead level samples collected from the residents of Cerro Chuño and Los Industriales during 2000. For each individual, we have two measures: SERMUS and ISP.

two household projects (Tchernitchin et al. 2006). Due to data restrictions, we focus our analysis on the 579 individuals whose blood lead levels exceeded the risk threshold defined by the CDC (10 μg/dL) and for which we have information on two different and independent blood lead tests (ISP and SERMUS).

We estimate linear regression models of individual blood lead levels on (ln) distance from residence to each source of pollution.[17] Formally, for each source of pollution we estimate:

$$Pb_i = \alpha_0 + \alpha_1 \ln D_{home,i} + \alpha_2 Gender_i + \alpha_3 Age_i + \eta_i, \quad (1)$$

where Pb_i is the blood lead level associated with individual i (measured in micrograms per deciliter of blood, μg/dL), $D_{home,i}$ is the distance between individual's i place of residence and the location of the respective contaminated area in Arica, and Age_i denotes age at time of testing. Finally, in order to reduce the measurement error we use the average blood lead level of the two measures.[18]

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17. We follow (Sinnott 1984) and generate the distance between two locations, A and B, as follows. Let A and B be two different locations, with associated latitudes and longitudes (lat(A),lon(A)) and (lat(B),lon(B)), respectively. We compute the distance between A and B ($d(A,B)$) from:

$$\tau(A, B) = \left(\frac{\sin(\text{lat}(B) - \text{lat}(A))}{2}\right)^2 + \cos(\text{lat}(A)) \times \cos(\text{lat}(B)) \times \left(\sin\frac{(\text{lon}(B) - \text{lon}(A))}{2}\right)^{2-},$$

$$d(A, B) = 6,367 \times (2 \times \arctan(\tau(A, B), 1 - \tau(A, B))),$$

where $d(A, B)$ is expressed in kilometers, $\arctan(x, y)$ is the arctangent of x/y, and 6,367 is the radius of the earth expressed in kilometers.

Distances were obtained as follows. We first define 33 centroids of pollution covering the full extent of the railway. Similarly, we define 26 points of contamination in soil. The distance from each household to the railway is defined as the minimum distance to any of the 33 centroids. Likewise, distance from each household to leaded soil is calculated as the minimum distance of each household to any of the 26 centroids. In the case of Site F, we consider Chapiquiña 3066 as the reference address. This corresponds to the place rented by PROMEL. Due to their remoteness, we are unable to locate some of the addresses reported in the data. We restrict our analysis to the set of 390 tests with valid address information.

18. Our results are robust to the use of either sample (ISP or SERMUS). Results are available from the authors upon request. The logarithmic distance gradient is posited after estimating nonparametric models (penalized splines) that suggest a logarithmic like relationship between blood lead levels and distance. The nonparametric estimates are provided in the appendix. Section 5 explains how our preferred parametric model (eq. [1]) allows us to scale up the estimates from a reduced-form model relating academic performance and distance to indirectly estimate the effect of lead levels on test scores.

Table 3. The Effect of Distances to Sources of Pollution on Blood Lead Levels (BLLs)

Variable	(1)	(2)	(3)
(ln) distance from Site F to home	−.636**		
	(.318)		
(ln) distance from railway to home		.114	
		(.337)	
(ln) distance from leaded soil to home			.159
			(.148)
Constant	9.973***	10.242***	10.501***
	(.324)	(.287)	(.341)
Age and male	Yes	Yes	Yes
Observations	377	377	378
R^2	.0428	.0369	.0377

Note.—All distances are expressed in kilometers. BLLs are measured in micrograms per deciliter of blood (μg/dL). As we described in the text, we use the average of two independent blood tests taken from residents of Cerro Chuño and Los Industriales during 2000. One of these samples was taken by the Municipal Health Service (SERMUS) and another, which is the confirmation of these findings, was collected by the Public Health Institute (ISP). We present the estimated coefficients of regressions of home distance to the nearest centroid of pollution of each of the three sources of lead contamination using the average of these two measures of blood lead levels. In this case we control for influential observations using Cook's distance (Cook 1979). All the numbers in the table are robust to this procedure. Standard errors in parentheses.

* $p < .10$.
** $p < .05$.
*** $p < .01$.

Table 3 presents the estimated coefficients. The results presented in column 1 indicate a significant correlation between concentration of lead in blood and distance to Site F. Specifically, we estimate that increasing the distance by 1 kilometer (0.6 miles), from 0.16 to 1.16 kilometers to Site F, would imply a reduction of 1.26 micrograms of lead per deciliter of blood (or 0.413 standard deviations).[19] Columns 2 and 3 show that the coefficients associated with distances to the railway and *leaded soil* sites have the opposite sign as expected, and they are not significant. Thus, these results point toward Site F as the main source of pollution in the city of Arica. Consequently, we focus our analysis on this source.

19. The nonlinear association between Pb_i and $D_{home,i}$ implies that the magnitudes of the effects depend on the original distance to Site F. For example, increasing the distance from 0.66 to 1.66 kilometers to Site F would imply a reduction of 0.587 micrograms of lead per deciliter of blood (or 0.193 standard deviations). Likewise, increasing the distance from 1.3 to 2.3 kilometers would imply a reduction of 0.363 micrograms of lead per deciliter of blood (or 0.119 standard deviations).

3.2. Short-Run Effects: DID Analysis

We first analyze school-level data for different years from the SIMCEs. Figure 4 presents (standardized) school-level average test scores for fourth graders enrolled in schools located less than 1.5 kilometers from Site F, in schools located between 1.5 and 3 kilometers from Site F, and in schools located 3 or more kilometers away from Site F. We present the evolution of the test scores from 1988 to 1996.

The results show a clear pattern. At the time the chemical waste arrived in the area (1988), schools near Site F performed better than those located between 1.5 and 3 kilometers from the site. Just 4 years after the arrival of the material, average test scores for those schools start reducing dramatically, potentially because of the prolonged exposure to the toxic materials.

Table 4 displays the results of the difference-in-differences (DID) analysis for (standardized) math and language test scores using data for fourth graders in 1988, 1990, 1992, and 1996. The coefficient associated with the interaction between the post dummy variable (one if 1990 or later and zero otherwise) and the school distance to Site F is our parameter of interest. In all specifications we control for school fixed effects and family background, and standard errors are clustered at the school

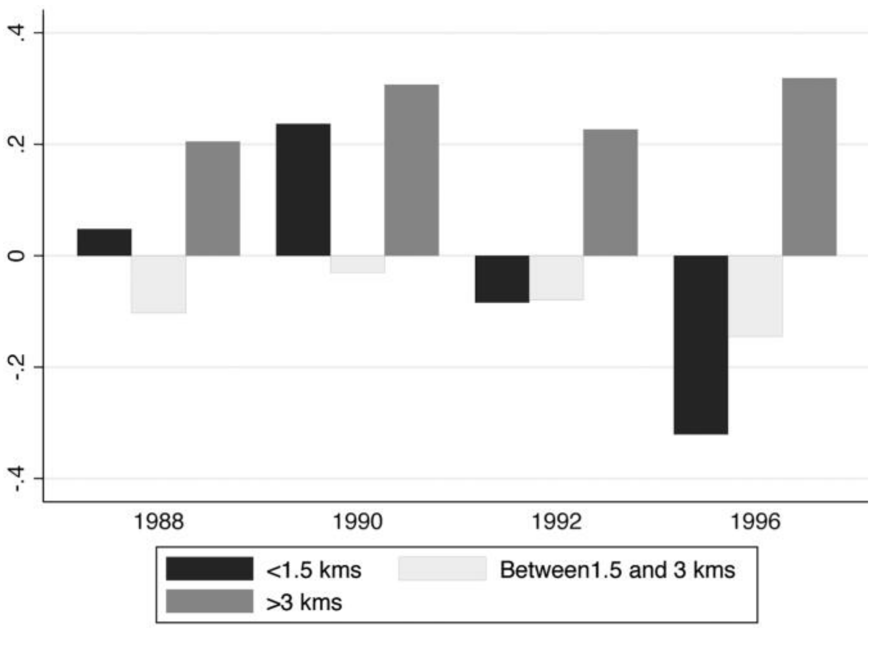

Figure 4. Evolution of school-level academic achievement (average fourth-grade test scores) by distance to Site F. This figure shows average standardized test scores of schools located less than 1.5 kilometers from Site F, schools located between 1.5 and 3 kilometers from Site F, and schools located 3 or more kilometers from Site F. The results consider fourth-grade test score results.

Table 4. Difference-in-Differences Results: The Effect of Distance on Math and Language SIMCE Scores

	Math			Language		
	(1)	(2)	(3)	(4)	(5)	(6)
Post	.863***	.862***	.416**	.627***	.627***	.175
	(.153)	(.154)	(.181)	(.142)	(.142)	(.155)
Post × Distance_Site F	.081***	.094***	.094***	.064***	.068***	.069***
	(.016)	(.015)	(.015)	(.016)	(.017)	(.017)
SES Index = 2	.645***	.742***	.539***	.636***	.671***	.477***
	(.053)	(.074)	(.091)	(.058)	(.072)	(.098)
SES Index = 3	.687***	.779***	.527**	.771***	.805***	.562**
	(.205)	(.200)	(.232)	(.195)	(.195)	(.223)
SES Index = 4	.859**	.944**	.742*	.974***	1.006***	.812**
	(.371)	(.366)	(.380)	(.307)	(.310)	(.329)
Constant	−1.428***	−1.517***	−1.308***	−1.195***	−1.228***	−1.027***
	(.077)	(.108)	(.112)	(.080)	(.112)	(.117)
Fixed effects	Yes	Yes	Yes	Yes	Yes	Yes
East × Post	No	Yes	Yes	No	Yes	Yes
Linear trend	No	No	Yes	No	No	Yes
R^2	.754	.756	.795	.757	.757	.799
$N \times T$	150	150	150	150	150	150

Note.—"Post" takes a value of one if year is 1990 or later, and zero otherwise. "Distance_Site F" is the distance from school to Site F. "SES Index" (socioeconomic index) takes four values. It is generated by the Ministry of Education, and it is based on parental education and family income. It ranges from 1 (lowest SES) to 4 (highest SES). Number of schools is 42 and number of periods four (1988, 1990, 1992, and 1996). Distances are presented in kilometers. SIMCE test scores for fourth graders only, standardized with zero mean and variance equal to one. Clustered standard errors (at the school level) in parentheses.

* $p < .10$.
** $p < .05$.
*** $p < .01$.

level.[20] For math, our first specification (col. 1) shows that each additional kilometer in distance between schools and Site F increased test scores after 1988 by 0.08 standard deviations. This result is statically significant at the 1% level. Column 2 includes the interactions between the post dummy and a dummy variable indicating whether the school is located to the east of Site F to control for airstreams. The previous result slightly increases from 0.08 to 0.09 standard deviations. Column 3 adds a linear trend, and the results are robust to this specification as well. Columns 4–6 show the same results for language. The effects are slightly smaller, about 0.07 standard deviations, but are also statistically significant at the 1% level.

In thinking about potential mechanisms, one interesting question is whether toxic waste exposure has an immediate effect on test scores or whether there is some lag before the effects surface. To test this hypothesis we include two post dummies at 1990 and 1992 and their interactions with the school distance to the contaminated area. In table 5 we can see the results for math and language in the complete specification (with fixed effects, trend, and interaction between east and post dummies). The effects are larger after 1992, especially for language, suggesting that the effects manifest with some lag after the arrival of toxic waste.

Overall, the results show a significant impact of exposure to hazardous waste on school-level test scores. It is worth mentioning that the environmental emergency was declared in late 1997, so it is not obvious that residents of Arica were aware of the situation and could take action to avoid it. Also, even though the location of the toxic waste cannot be considered randomly assigned, if the relationship between school unobserved factors and test scores is time invariant the results should not be affected by sorting (i.e., if parallel trends assumption holds). However, this could have been violated if there was sorting. In this case, our results would confound the effect of exposure itself and the attributes of new families. Nevertheless, our estimation of the long-term effects accounts for these potential threats to validity.

3.3. Long-Run Effects

In this section we present the long-run estimates of the effect of toxic waste on academic achievement. We do this by analyzing individual-level academic test scores, the PSU, measured decades after the initial exposure.

Let PSU_i denote individual i's PSU test score and $D_{home,i}$ the distance between the student's place of residence and Site F. We estimate the following model:

$$PSU_i = \gamma_0 + \gamma_1 \ln D_{home,i} + \gamma_2 Age + \gamma_3 Gender + \gamma_4 X_i + \gamma_5 Z_{school,i} + \eta_i, \qquad (2)$$

where X_i represents a set of individual-specific exogenous controls (family background and variables controlling for wind direction), $Z_{school,i}$ is a vector of variables

20. There are four categories of family background constructed by the Ministry of Education based on parental schooling and family income ranging from 1 (the lowest) to 4 (the highest).

Table 5. Difference-in-Differences Results: The Effect of Distance on Math and Language SIMCE Scores

	Math (1)	Language (2)
Post (1990)	.649***	.399***
	(.166)	(.131)
Post (1990) × Distance_Site F	.043**	.020
	(.021)	(.018)
Post (1992)	.452**	.327*
	(.221)	(.186)
Post (1992) × Distance_Site F	.084***	.081***
	(.021)	(.018)
SES Index = 2	.054	.090
	(.121)	(.106)
SES Index = 3	−.050	.101
	(.207)	(.200)
SES Index = 4	−.166	.085
	(.370)	(.330)
Constant	−.755***	−.600***
	(.129)	(.125)
Fixed effects	Yes	Yes
East × Post (1990)	Yes	Yes
Linear trend	Yes	Yes
R^2	.844	.835
$N \times T$	150	150

Note.—We consider two post dummies: "Post (1990)" equals one if year is 1990 or later, and zero otherwise; "Post (1992)" equals one if year is 1992 or later, and zero otherwise. "Distance_Site F" is the distance from school to Site F. "SES Index" (socioeconomic index) takes four values. It is generated by the Ministry of Education, and it is based on parental education and family income. It ranges from 1 (lowest SES) to 4 (highest SES). Number of schools is 42 and number of periods four (1988, 1990, 1992, and 1996). Distances are presented in kilometers. SIMCE test scores for fourth graders only, standardized with zero mean and variance equal to one. Clustered standard errors (at the school level) in parentheses.

* $p < .10$.
** $p < .05$.
*** $p < .01$.

describing the characteristics of the high school from which the individual graduated from, and η_i is an idiosyncratic component.[21]

21. Our nonlinear specification is motivated by the estimation of non- and semi-parametric models of the relationship between PSU test scores and distance from place of residence to

Table 6. Estimates from Reduced Form Model: The Effect of Distance on Math and Language PSU Scores

	Math			Language		
Variable	(1)	(2)	(3)	(4)	(5)	(6)
ln(dist. from Site F to home)	13.901**	10.005*	8.783**	17.430***	13.234***	12.325***
	(6.204)	(5.097)	(3.951)	(4.922)	(3.801)	(4.074)
Home to the east of Site F	−7.028	−3.731	−4.665	−5.306	.848	.153
	(13.168)	(12.304)	(10.764)	(12.077)	(10.627)	(9.983)
Age and gender	Yes	Yes	Yes	Yes	Yes	Yes
Mother and father absence	No	Yes	Yes	No	Yes	Yes
Parental education	No	Yes	Yes	No	Yes	Yes
Type of school	No	No	Yes	No	No	Yes
R^2	.0396	.0789	.0939	.0269	.0789	.0871
Observations				1,076		

Note.—Distances are measured in kilometers. In order to consider the wind currents and the dispersion of pollutants around the city, we include the variable home located to the east of Site F, which is equal to one if a student lives to the east of Site F (main contaminated area), zero otherwise. Parental absence is equal to one if the biological parent or stepfather/stepmother does not live with the student. Parental education was tabulated only if parents were present. Clustered standard errors (at the school level) in parentheses.

* $p < .10$.

** $p < .05$.

*** $p < .01$.

Table 6 presents the results of estimating equation (2) for math and reading PSU test scores under different specifications.[22] They document a strong relationship between PSU test scores and distance from a student's place of residence to Site F. This finding remains even after controlling for family background, high

Site F. Figures A1 and A2 in the appendix present the results for math and language scores, respectively. The results suggest that the natural logarithm of the distance variable provides a good fit for the data. Fortunately, this specification also allows us to directly implement the data combination strategy discussed in section 5. Currie and Walker (2011) use a similar reduced-form specification to study the link between health outcomes and distance to a source of pollution.

22. In order to restrict our analysis to individuals living in Arica, the analysis only includes those reporting a home street address at most 4 kilometers away from Site F. This is consistent with the maximum distance from Site F to the edge of the city.

school characteristics, and geographic factors. Our preferred specifications (cols. 3 and 6), imply that increasing the distance 1 kilometer (starting at 100 meters from the site) would increase math and language test scores in approximately 21.06 (0.22 standard deviations) and 29.55 (0.31 standard deviations) points, respectively. The nonlinear model implies decreasing effects as we move away from the pollution site. These magnitudes are robust to different specifications.

3.4. Caveats: Sorting and Migration

A natural threat to our identification strategy is the possibility of endogenous migration. Once alerted to the presence of the chemical waste, families could have decided to move away from the vicinity of Site F and even to leave the city. A related threat is endogenous enrollment of students in schools near Site F. Specifically, better-educated parents might elect to send their children to schools farther away from Site F (sorting).[23]

To assess the plausibility of sorting, we investigate the relationship between the proportion of parents with a college education (from the sample of parents with children enrolled in schools in Arica) and proximity to the contaminated area. Table 7 presents the proportion of parents with a college education in Arica by school distance to Site F for 1989, 1999, and 2008. The numbers come from the school-level SIMCE records. The proportion of parents with a college education for children enrolled in schools located 1.5 kilometer or less from Site F is stable over the 20-year period. On the other hand, we observe an increase in the fraction of college-educated parents with children enrolled in schools located between 1.5 and 3 kilometers from the site. However, most of the increase can be explained by a single school.[24] For schools located more than 3 kilometers away from Site F there is a less pronounced increase which follows the national trend over the period.

Figure 5 presents further evidence on these matters. It shows the trends in enrollment by school distance to Site F for fourth graders between 1988 and 2008 in Arica. The proportions are relatively stable over time, with a slight decline in the proportion of children enrolled at schools 1.5 kilometer or less from Site F.

To complement these findings, we analyze the individual-level data (the 2008 PSU) to investigate if family background is correlated with distance to Site F.

23. There is a large literature analyzing schooling choices in Chile. The evidence suggests that proximity is an, if not the most, important factor explaining enrollment decisions (see Carnoy and McEwan 2000; and Gallego and Hernando 2008). This result supports our empirical strategy.

24. Colegio Arica College explains most of the increase in parental education between 1999 and 2008. If we exclude this school from this calculation, the distribution of parents with a college education with children enrolled in schools between 1.5 and 3 kilometers from Site F increases by 1.3 percentage point (instead of 10) during the period.

Table 7. Proportion of Parents with College Education with Children Enrolled in Primary Schools in Arica, by Distance from School to Site F (%)

Distance from School to Site F	1989	1999	2008
Less than 1.5 kilometers	10.2	9.7	11.4
Between 1.5 and 3 kilometers	1.7	2.1	12.0
More than 3 kilometers	23.9	30.3	31.3

Note.—Source: SIMCE 1989–2008. We present the proportions of parents with college education by distance from home to Site F.

Table 8 shows that parental education is positively correlated with distance from home to Site F (parents with 12 or more years of schooling). This suggests that more educated parents may have avoided living close to the contaminated area. In the estimation of equation (2) we account for this by including parental education and a rich set of controls.[25] However, we acknowledge that our results might be affected by biological and behavioral responses. In section 4, we perform robustness checks to assess the potential endogeneity of distance to the source of contamination.

Another threat to our identification strategy is internal migration. There is little evidence of regional migration in Chile. Soto and Torche (2004) show that on average, the regional migration rate for the 1965–2000 period was 0.6% per year, which is especially low considering the relatively homogeneous population across regions and high rates of urbanization, factors that would be expected to promote greater regional movement. Also, data from the CASEN 2006 survey show that 86.17% of respondents aged 17 or younger who lived in Arica reported that they were born in Arica.[26] Likewise, among the same individuals, 96% reported that they were living in Arica in 2002.

Finally, institutional features of the government housing system also support the idea that there is little internal migration. Specifically, the eighteenth article of the Supreme Decree on “The Regulation on Social Housing” (MINVU 1990) establishes that houses in Cerro Chuño and Los Industriales could not be sold before 5 years after the inscription date of the house in the registry of deeds (Conservador de Bienes Raíces). As mentioned in section 1, since the housing projects were originally outside the city limits, the new homeowners did not receive official titles for several years. In fact, only after 1996, once the city limits were extended, were house

25. Although we do control for a set of family characteristics, it is not clear that we have controlled for all of them, nor is it clear that we should control for them as they could be catalogued as “bad controls” (Angrist and Pischke 2009).

26. CASEN (Socioeconomic Characterization Survey) 2006 corresponds to a cross-sectional household survey representative of the population in 2006.

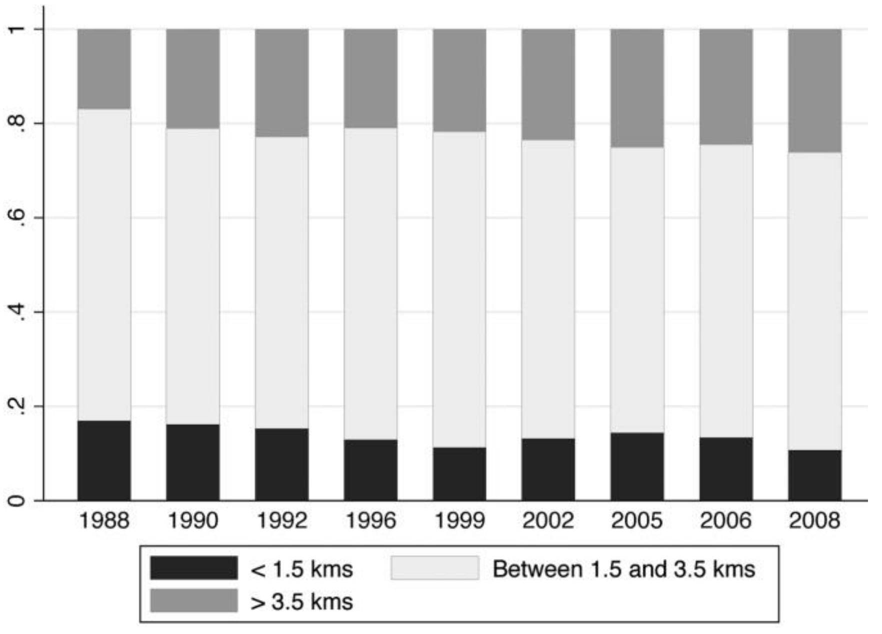

Figure 5. The distribution of enrollment (fourth grade) by school distance to Site F between 1988 and 2008. Source: Authors' calculations based on administrative records (SIMCEs).

titles granted.[27] Therefore, we have reason to assume that the families and their children were exposed to lead for a long period of time, although the possibility remains that they could have moved to other places in order to avoid lead contamination.

4. ROBUSTNESS CHECKS

4.1. Falsification Tests: Randomizing Site F Location

A potential concern regarding our long-run measured effects is that they might arise from the proximity of households to a different source of pollution, not necessarily Site F.

To investigate this possibility, we implement two falsification tests. They involve the random allocation of false "sources of pollution" throughout the city of Arica:

1. We randomly sample 1,000 sites from the city of Arica, assigning each of them the role of pollution source. This is done by defining a rectangle

27. The law establishes that if the owners want to sell the property before the mandatory deadline, they have to request authorization from the Housing Service (Servicio de Vivienda y Urbanismo, SERVIU). This rule increases the probability that those families lived for at least 5 years near the toxic waste.

Table 8. Distance from Home to Site F and Parental Background

Variable	
Mother absence	.101
	(.141)
Father absence	.087
	(.103)
Mother with 8–11 years of education	.113
	(.103)
Mother with 12 years of education	.118
	(.095)
Mother with more than 12 years of education	.241***
	(.091)
Father with 8–11 years of education	−.093
	(.120)
Father with 12 years of education	−.055
	(.110)
Father with more than 12 years of education	.202*
	(.105)
Male	.001
	(.057)
Constant	2.110***
	(.095)
Observations	1,076
R^2	.0284

Note.—Source: 2008 PSU. Distances are measured in kilometers. Parental absence is equal to one if the biological parent or stepfather/stepmother does not live with the student. Parental education was tabulated only if parents were present. Standard errors in parentheses.

* $p < .10$.

** $p < .05$.

*** $p < .01$.

containing the entire city of Arica. With the vertices, we set the limits of a bivariate uniform distribution and sample latitude and longitude coordinates.

2. We randomly allocate 1,000 false pollution sites to Población Cardenal Raúl Silva Henríquez. This neighborhood is located 1.5 kilometers north from Site F, but it shares similar socioeconomic characteristics to those located in its vicinity (Los Industriales and Cerro Chuño).

With these sets of false locations, we repeat the analysis of section 3.3. In particular, we compute the distances of households to each of these sites and reestimate the associated reduced form models for math and language test scores. Table 9 pre-

Table 9. Robustness Checks, Randomizing Site F Location

	Math	Language
Random Site F (all the city)	.7667	1.501
	(4.563)	(4.736)
Random Site F (alternative poor neighborhood)	6.456	3.806
	(4.080)	(4.605)

Note.—Robustness check. Estimates reflect the effect of distance of household to Site F on PSU score (as in table 6) using a random location of Site F based on 1,000 draws from uniform distributions for latitude and longitude. The first row includes locations everywhere in the city of Arica. The second row restricts to random samples from Población Cardenal Raúl Silva Henríquez, a poor neighborhood with similar family background as Los Industriales or Cerro Chuño. Standard errors in parentheses.

* $p < .10$.

** $p < .05$.

*** $p < .01$.

sents the results. It displays the estimated mean effects and the associated standard errors. The first row shows the results of the reduced form equation when the location of Site F is randomly located throughout the entire city of Arica. The second row reports the results when the location of Site F is drawn from Población Cardenal Raúl Silva Henríquez. In both cases the results are negligible and not statistically significant, providing supportive evidence for our previous findings.[28]

4.2. Assessing the Potential Endogeneity of Distance

Although in our empirical analysis we are controlling for a comprehensive set of family background variables, the potential correlation between the residential location decision and unobserved variables could compromise the interpretation of our results. Here we tackle this issue.

First, we isolate the impact of family background, individual, and school characteristics on PSU scores using a large sample of individuals living in three adjacent provinces to Arica but unaffected by the hazardous waste: Parinacota, Iquique, and Tamarugal. In this sample, we estimate the reduced-form model:

$$PSU_i = \gamma_0 + \gamma_2 Age_i + \gamma_3 Gender_i + \gamma_4 X_i + \gamma_5 Z_{school,i} + \eta, \tag{3}$$

which delivers consistent estimates of the association between the exogenous controls and PSU scores. We do not include $\gamma_1 \ln D_{home,i}$ since the regression is estimated with data from provinces excluding Arica and, thus, far away from Site F.

28. Figures A3 and A4 in the appendix present a more detailed analysis of the results from these two falsification tests.

Second, using the estimated parameters from equation (3) and the sample of individuals exposed to pollution in Arica, we construct predicted values for PSU scores, $\hat{P}SU_{-D}$:

$$\hat{P}SU_{-D} = \hat{\gamma}_0 + \hat{\gamma}_2 Age + \hat{\gamma}_3 Gender + \hat{\gamma}_4 X_i + \hat{\gamma}_5 Z_{school,i}.$$

Since $\hat{P}SU_{-D}$ is constructed using the estimates from the sample of individuals not exposed to pollution, we avoid the consequences of the potential biases due to the endogeneity of distance to the Site F.

Thus, we estimate the reduced form model of PSU on $\hat{P}SU_{-D}$ and distance from home to Site F using the sample exposed to pollution:

$$PSU = \gamma_0 + \gamma_1 \ln D_{home} + \tilde{\gamma}\hat{P}SU_{-D} + \varepsilon. \quad (4)$$

Note that after imposing $\tilde{\gamma} = 1$, under the null hypothesis of no correlation between family background and distance from home to Site F, the coefficient γ_1 can be compared to the one reported in table 6. Table 10 presents the results of this exercise. For math and language scores, our findings are consistent with those reported above (but with lower statistical power).

In table 11, we perform a sensitivity analysis constraining $\tilde{\gamma}$ at different values: 0.8, 1.0, and 1.2. By doing this we avoid any residual correlation between family background variables and any unobservables that determine PSU test scores.

Table 10. Estimates of PSU as a Function of Individual and School Characteristics: Sample of Individuals Living in Adjacent Providences to Arica

	Math	Language
Natural logarithm of the distance from Site F to home	8.881*	12.436***
	(5.157)	(3.975)
Family background and characteristics ($\hat{P}SU_{-D}$)	.524***	.555***
	(.133)	(.145)
Home located to the east of Site F	−3.747	−1.681
	(12.271)	(10.907)
Constant	237.515*	203.567**
	(75.890)	(76.208)
Observations	1,076	1,076

Note.—Robustness check. Estimates of the effect of distance to Site F on 2008 PSU scores (eq. [3]). We consider the sample of individuals living in the three northern provinces not affected by lead (Parinacota, Iquique, and Tamarugal). Hence these parameters are consistent and not affected by correlation between unobservables and distance from Site F. Standard errors in parentheses.

* $p < .10$.

** $p < .05$.

*** $p < .01$.

Table 11. Constrained Estimates of PSU as a Function of $\hat{P}SU_{-D}$: Sample of Individuals Living in Arica

	Math			Language		
Variable	$\tilde{\gamma}$ = .8 (1)	$\tilde{\gamma}$ = 1 (2)	$\tilde{\gamma}$ = 1.2 (3)	$\tilde{\gamma}$ = .8 (4)	$\tilde{\gamma}$ = 1 (5)	$\tilde{\gamma}$ = 1.2 (6)
Site F	6.344	4.507	2,670	10.283***	8.524***	6.765***
	(5.874)	(5.975)	(6.149)	(3.422)	(3.218)	(3.129)
Family background and characteristics ($\hat{P}SU_{-D}$)	.8	1	1.2	.8	1	1.2
	(.)	(.)	(.)	(.)	(.)	(.)
Home located to the east of Site F	–.907	1.149	3.2050	.546	2.367	4.187
	(11.407)	(10.914)	(10.460)	(10.532)	(10.062)	(9.616)
Constant	102.66***	4.005	–94.057*	85.251***	–11.473	–108.198***
	(13.384)	(13.158)	(12.956)	(9.521)	(9.231)	(8.964)
Observations	1.076	1.076	1.076	1.076	1.076	1.076

Note.—Constrained least squares (CLS) for different values of $\tilde{\gamma}$ (eq. [4]). $\hat{P}SU_{-D}$ represents the predicted value of PSU scores from eq. (3). Thus, by fixing $\tilde{\gamma}$ and estimating by CLS, we avoid any residual correlation between family background and unobservables determining the PSU score. Standard errors in parentheses.

* $p < .10$.

** $p < .05$.

*** $p < .01$.

Interestingly, even when the family background parameter is set to 1.2, that is, when the role of family background is "amplified," the estimated effects of distance to Site F are consistent with the results presented in table 6.

Finally, we evaluate the robustness of our results by analyzing the association between distance to Site F and test scores for two specific samples: PSU takers residing in Arica in 2008 who reported a different region of residence in 2004 SIMCE, and SIMCE takers residing in Arica in 2004 but reporting to have taken 2008 PSU in another region. In the first case we obtain positive but insignificant effects, whereas for the second group we obtain ambiguous signs and insignificant effects. These results are presented in tables A2 and A3 in the appendix, available online.

5. MONETARY LOSSES

5.1. Effects of Exposure to Waste on Earnings

We next quantify the monetary consequences of exposure to toxic waste. Surprisingly, there is little previous literature documenting these consequences.[29] We attempt to extend this literature by documenting the effects of early lead exposure on future earnings at a disaggregated level. As we show below, the results can be used to estimate monetary compensations for the serious (and irreversible) damage to the health of residents of Cerro Chuño and Los Industriales.

To obtain an estimate of the effect of early exposure on earnings we first link administrative records on earnings and the results from the Chilean college admission test for a different but similar sample. More precisely, we use monthly earnings between 2010 and 2011 from the Unemployment Insurance Database (UI) and PSU scores from 2004 to estimate the following Mincer-type regression model:[30]

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29. Landrigan et al. (2002) estimate the annual costs of the incidence, prevalence, mortality, and pediatric assistance produced by environmental pollution on the health of American children. Their results show that the annual costs of children's lead poisoning in the United States correspond to US$43.4 billion, a figure higher than the estimated annual cost of asthma (US$2 billion), cancer (US$0.3 billion), and mental disability (US$9.2 billion). Muennig and Bao (2009) extends the estimated costs of lead exposure in children in New Jersey to include special education costs, direct medical costs associated with treatment and hospitalization, social costs for juvenile and adult crime, and dropout graduate rates. The results indicate that if blood lead levels in a single cohort of children between 0 and 6 years were reduced to less than 1 microgram per deciliter of blood, the contribution to the society of New Jersey would be at least US$27 billion.

30. The UI data contain information on individual labor market histories in the formal sector (approximately 80% of the employment in the country) on a monthly basis since November 2002. We merge individual-level data on earnings with PSU test scores. Given that a sizable fraction of individuals who took the PSU in 2008 do not show up in the UI system yet, we use information from the first PSU (2004) instead. This ensures the compa-

$$\ln w_i = \beta_0 + \beta_1 PSU_{i,math} + \beta_2 PSU_{i,lang} + \beta_3 Q_i + \varepsilon_i, \quad (5)$$

where w_i corresponds to the average monthly wage obtained by individual i between 2010 and 2011 and $PSU_{i,j}$ denotes her/his PSU test scores ($j = \{math, language\}$).[31] We also include a vector of observable characteristics, Q_i, which includes gender, age, age squared, parent education, high school characteristics, and regional dummies. Table 12 presents our results. We find positive and significant effects of math and language scores on monthly earnings. Our estimates suggest that each additional point in the math test score increases earnings approximately by 0.17%. In the case of language scores, the effect is 0.01%. These imply that one extra point in the PSU increases monthly earnings by 745 and 60 Chilean pesos (or US$1.49 and US$0.12) for math and language PSU scores, respectively.[32]

With the previous information, we are able to identify the effect of proximity to a source of pollution on individual earnings. In particular, we analyze the effect of the distance from home to Site F on average monthly earnings between 2010 and 2011 using the following expression:

$$\frac{\partial W}{\partial D_{home}} = \frac{\frac{\partial W}{\partial PSU_{lang}} \times \frac{\partial PSU_{lang}}{\partial \ln(D_{home})}}{D_{home}} + \frac{\frac{\partial W}{\partial PSU_{math}} \times \frac{\partial PSU_{math}}{\partial \ln(D_{home})}}{D_{home}}. \quad (6)$$

From the parameters in equations (2) and (5) (presented in tables 6 and 12, respectively), we evaluate the partial derivative $\partial W / \partial D_{home}$ for different values of initial distance. The estimated coefficients of this relationship are presented in table 13. The first row shows that for each kilometer increase in distance from a base of 0.1 km, individual monthly earnings increase by US$145.75 (18.4% increase). The impact decreases for individuals located far away from Site F.

5.2. Compensation for Lead Intoxication

Here we present back-of-the-envelope calculations for appropriate compensation for lead intoxication. First, we compute the effect of lead on test scores and then use our estimates from table 12 to link test scores and wages.

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rability of our results. See table A4 in the appendix for descriptive statistics of the sample of individuals who took the PSU in 2004 and for whom we have data on monthly earnings between 2010 and 2011.

31. We use data for the first version of the PSU (2004) linked with UI wage data because a sizable fraction of students who took the PSU in 2008 are still enrolled in tertiary institutions in 2010–11.

32. Given that the dependent variable is expressed as the natural logarithm of the monthly wages, under the assumption of normality, we can write the marginal effect of an increase in PSU score on monthly earnings as $\hat{\beta}_1 \times \exp(\hat{\beta}_0 + \hat{\beta}_1 PSU_{math} + \hat{\beta}_2 PSU_{lang} + \hat{\beta}_3 Q + \hat{\sigma}2/2)$, where we evaluate the regressors at the respective sample means. We use $1 = 500 pesos.

Table 12. PSU 2004 Scores on Average Monthly Wages 2010–11

Variable	(1)
Math PSU 2004 score	.0017***
	(.000)
Language PSU 2004 score	.0001***
	(.000)
Constant	11.7713***
	(.106)
Region fixed effect	Yes
Family background	Yes
Age and gender	Yes
School-level variables	Yes
Observations	65,497

Note.—Source: 2004 PSU and Unemployment Insurance Database. *Region* corresponds to the region in which the student took the test in 2004. Standard errors in parentheses.
* $p < .10$.
** $p < .05$.
*** $p < .01$.

The empirical strategy is carried out following a data-combination strategy. Consider first the following system of equations:

$$PSU_i = \beta_0 + \beta_1 Pb_i + \beta_2 X_i + \beta_3 Z_{school,i} + \varepsilon_i, \tag{7}$$

$$Pb_i = \alpha_0 + \alpha_1 \ln D_{home,i} + \alpha_2 Age_i + \alpha_3 Gender_i + \eta_i. \tag{8}$$

We interpret equation (7) as the structural equation describing the effect of blood lead levels, Pb_i, on individual's test scores, PSU_i. This idea is related to the empirical strategy in Nilsson (2009), which exploits the phase-out of leaded gasoline in Sweden to show that reduced lead exposure early in life (as measured by municipality air lead levels) improves cognitive and noncognitive ability, as well as labor market outcomes among young adults.[33] Equation (8), on the other hand, represents our model for blood lead levels as a function of distance to the source of pollution. We assume that the only channel in which toxic waste exposure affects test scores is lead.

As discussed above, we use the LCCI data to estimate equation (8). These results were reported in table 3. However, we do not have blood lead levels (Pb_i) and test scores (PSU_i) for the same sample of individuals, so equation (7) cannot be

33. See also Grönqvist, Nilsson, and Robling (2014) for evidence on the effects of lead on criminal behavior.

Table 13. Marginal Effects of Distance from Home to Site F on Monthly Wages

	Math		Language		Math+Lang		
Distance	(CLP)	(US$)	(CLP)	(US$)	(CLP)	(US$)	%
.1 km	65,480	130.96	7,393	14.79	72,873	145.75	18.4
.5 km	13,096	26.19	1,479	2.96	14,575	29.15	3.7
1.5 km	4,365	8.73	493	.99	4,858	9.72	1.2
2.5 km	2,619	5.24	296	.59	2,915	5.83	.9

Note.—In order to analyze the effect of lead exposure (measured through the distance from home to the main source of pollution in Arica) on wages, we develop an expression that relates: (1) the marginal effect of distance from home to Site F on PSU scores and (2) the marginal effect of PSU scores on wages (i.e.,

$$\frac{\partial W}{\partial D_{home}} = \frac{\frac{\partial W}{\partial PSU_{lang}} \times \frac{\partial PSU_{lang}}{\partial \ln(D_{home})}}{D_{home}} + \frac{\frac{\partial W}{\partial PSU_{math}} \times \frac{\partial PSU_{math}}{\partial \ln(D_{home})}}{D_{home}}.$$

Using the estimated coefficients of equation (2), we obtain the effect in terms of PSU points of an increase of 1 kilometer of the distance from student's home to Site F. Then, using a sample of wages and PSU 2004 scores, we explore the relationship between PSU scores and earnings (i.e., $\partial W/\partial PSU$). In particular, we estimate a Mincer equation, taking as dependent variable the natural logarithm of the average monthly earnings obtained between 2010 and 2011 by the students who took the PSU in 2004. The estimated coefficients of this relationship are presented in table 12. Then, combining both estimated effects ($\partial W/\partial PSU$ and $\partial PSU/\partial D_{home}$), we obtain the effect of an increase of 1 kilometer in the distance from a student's home to Site F on monthly wages. The first row of the table shows these results for Distance equal to .1 km (people living very close to Site F). Then, for each increase of 1 kilometer in the distance to Site F, on his (her) monthly wage will increase in CLP 72,873 pesos (or equivalently US$145.75 dollars).

estimated directly. This is where the data combination strategy is useful. By substituting expression (8) into (7) we can derive the reduced-form equation (2), linking PSU scores to distance to Site F. In this context, it is straightforward to show that γ_1 in equation (2) is equal to $(\beta_1 \times \alpha_1)$. Given that the model is exactly identified, we can estimate the (structural) effect of lead exposure on academic achievement, β_1, from equations (2) and (8) as:

$$\hat{\beta}_1 = \frac{\hat{\gamma}_1}{\hat{\alpha}_1}.$$

Table 14 presents the estimated effect of lead blood level on math and language test scores. We obtain standard errors using the delta method.[34] The estimated $\hat{\beta}_1$ implies a reduction of 13.81 (or 0.15 standard deviations) points for one microgram of lead per deciliter of blood for math and 19.37 (or 0.21 standard deviations) points for one microgram of lead per deciliter of blood for language. Overall our

34. Assuming that $\text{Cov}(\hat{\gamma}_1, \hat{\alpha}_1)=0$, the variance of $\hat{\beta}_1$ is giving by the following expression: $\text{Var}(\hat{\beta}_1)=\text{Var}(\hat{\gamma}_1)/\hat{\alpha}_1^2- + (\hat{\gamma}_1^2-/\hat{\alpha}_1^4-) \times \text{Var}(\hat{\alpha}_1)$.

Table 14. The Empirical Relationship between Lead Levels and PSU Test Scores

Stage	Math (1)	Language (2)
First stage ($\hat{\alpha}_1$)	−.636**	−.636**
	(.318)	(.318)
Reduced form ($\hat{\gamma}_1$)	8.783**	12.325***
	(3.951)	(4.074)
$\hat{\beta}_1 = \hat{\gamma}_1/\hat{\alpha}_1$	−13.810	−19.379*
	(9.288)	(11.615)
Observations	1,076	1,076

Note.—Standard errors are calculated using the delta method. Assuming that $\mathrm{Cov}(\hat{\gamma}_1, \hat{\alpha}_1) = 0$, the variance of $\hat{\beta}_1$ is giving by the following expression: $\mathrm{Var}(\hat{\beta}_1) = \mathrm{Var}(\hat{\gamma}_1)/\hat{\alpha}_1^2 + (\hat{\gamma}_1^2/\hat{\alpha}_1^4)\cdot\mathrm{Var}(\hat{\alpha}_1)$. Standard errors in parentheses.

* $p < .10$.

** $p < .05$.

*** $p < .01$.

results suggest negative and large effects of proximity to the pollution site on test scores.

Although we find significant results for $\hat{\gamma}_1$ and $\hat{\alpha}_1$, as expected, we lose power when computing their ratio. Nevertheless, we obtain significant results (at the 10% level) in the case of language test scores. This finding is in line with the results for the effect of lead on verbal IQ as reported in Needleman, Geiger, and Frank (1985).[35]

We extend the analysis to compute the individual-level monetary impact of lead exposure. To do so, we combine our previous results with the marginal effect of lead on PSU test scores. Formally, we compute:

$$\frac{\partial W}{\partial Pb} = \frac{\partial W}{\partial PSU_{lang}} \times \frac{\partial PSU_{lang}}{\partial Pb} + \frac{\partial W}{\partial PSU_{math}} \times \frac{\partial PSU_{math}}{\partial Pb}. \quad (9)$$

Table 15 presents these partial derivatives obtained using the results in table 6 ($\partial PSU/\partial Pb$) and from table 12 we can obtain ($\partial W/\partial PSU$). We estimate that for

35. Also, we perform linear regression models to study the effect of the school's proximity to Site F on the academic achievement of the students of Arica using SIMCE scores between 2003 and 2006. As we previously described, in SIMCE we only have the distance from schools to Site F. Tables A5 and A6 in the appendix present descriptive statistics of SIMCE 2003–6 scores and the results from the linear regression models, respectively. The findings confirm our main results. Even after controlling for gender, parental education, school characteristics, we obtain positive effects from (natural logarithm) distance between the school and Site F on school-level math and language test scores.

Table 15. Marginal Effect of Blood Lead Levels (1μg/dL) on Monthly Wages (Pesos)

			Math	Language	Total Effect
(1)	$\frac{\partial W}{\partial Pb}$	$\frac{Pesos}{\mu g/dL}$	−10,296	−1,162	−11,458
(2)	$\%\frac{\partial W_{mean}}{\partial Pb}$	$\%\left(\frac{Pesos}{\mu g/dL}\right)$	−2.6%	−.3%	−2.9%

Note.—In order to analyze the effect of lead exposure on wages, we develop an expression that relates (1) the marginal effect of blood lead concentration on PSU scores and (2) the marginal effect of PSU scores on wages, i.e.,

$$\frac{\partial W}{\partial Pb} = \frac{\partial W}{\partial PSU_{lang}} \times \frac{\partial PSU_{lang}}{\partial Pb} + \frac{\partial W}{\partial PSU_{math}} \times \frac{\partial PSU_{math}}{\partial Pb}.$$

Using data from blood tests taken to residents of the neighborhoods nearest to Site F (main source of exposure to lead in Arica) during 2000 and PSU scores in the subjects of math and language, we obtain the effect in terms of PSU points of an increase of 1 microgram of lead per deciliter of blood (i.e., $\partial PSU/\partial Pb$). Table 14 presents these results differentiated by subject (math and language). Then, using a sample of wages and 2004 PSU scores, we explore the relationship between scores PSU and wages (i.e., $\partial W/\partial PSU$). In particular, we estimate a Mincer equation, taking as dependent variable the natural logarithm of the average monthly wages obtained between 2010 and 2011 by the students who took the PSU in 2004. The estimated coefficients of this relationship are presented in table 12. Then, combining both estimated effects ($\partial W/\partial PSU$ and $\partial PSU/\partial Pb$), we obtain the effect of an increase of one microgram of lead per deciliter of blood (1μg/dL) on monthly wages. The first row of the table shows these results. Then, for each increase of 1 microgram on an individual's blood lead level, his (her) monthly wage will decrease in CLP 11,458 pesos (or equivalently US$22.92). Finally, row 2 shows the marginal effect of lead on annual wages as percentage of the average monthly wage of the sample used (CLP 395,447 pesos per month).

each extra microgram of lead, monthly earnings decrease by 11,458 Chilean pesos (or US$22.92). This represents a 2.9% decrease in average monthly wages (of the average monthly earnings for our sample: 395,447 pesos per month).[36]

Finally, we use our results to compute the losses in terms of lifetime earnings (present discounted value) due to the exposure to hazardous waste. Using the estimates reported in table 15, we simulate the stream of earnings of an individual exposed to the toxic waste and compare it with the simulated profile of a representative individual not exposed to it.[37] We find a difference of CLP$3 million (or US $6,000 dollars) for each microgram of lead per deciliter of blood. It is worth

36. We work with a nationwide sample to estimate the parameters for the Mincer equation. For consistency purposes, we estimate the effects of lead on earnings using the whole sample. We performed the analysis using a subsample including only Arica and found very similar results. Indeed, the average monthly wage of the subsample of Arica is CLP 381,938, very close to the national wage.

37. The predicted lifetime profile of annual earnings is generated from Mincer-type regressions estimated using the UI data. We assumed a discount rate of 4%.

mentioning that in 2007 the Chilean Supreme Court ruled that there should be a compensation payment of CLP$8 million (US$16,000) per claimant made by the Arica Health Service to 365 residents of Cerro Chuño and Los Industriales (Corte Suprema 2007). In light of our findings, at an average of 10 μg/dL in the sample, the mean compensation should have been approximately US$60,000 dollars, about 3.8 times the amount dictated by the Supreme Court in 2007.

6. CONCLUSIONS

In this paper, we estimate the effects of early exposure to mining waste on academic test scores. We exploit a massive and unfortunate pollution incident that occurred in the city of Arica in northern Chile. Between 1984 and 1989 more than 20,000 tons of chemical waste, rich in arsenic and lead, were abandoned within the city limits. Students at proximate schools and residents of nearby neighborhoods became exposed to abnormally high levels of chemical waste.

We find a strong relationship between school and home distance to the waste deposit site and test scores. A differences-in-differences approach shows that attending a school 1 kilometer farther away from the polluted area increases math and language score by 0.09 and 0.07 standard deviations, respectively. We also find significant long-run effects of mining waste exposure on student achievement. Specifically, we find that an increase of 1 microgram of lead per deciliter of blood reduces math and language scores by 0.15 and 0.21 standard deviations approximately 2 decades after the arrival of the waste.

Using administrative data on labor market outcomes, we calculate back-of-the-envelope estimates of the impact of exposure to hazardous waste on future earnings. Comparing outcomes by residential proximity to Site F, we find that a 1 kilometer increase in the distance between home and Site F increases individual monthly earnings by US$145.75. This corresponds to a 18.4% increase in monthly earnings. Alternatively, combining these estimates with information from georeferenced blood tests, we estimate that affected individuals can be expected to lose approximately $6,000 per microgram of lead per deciliter of blood over the course of their lifetime as a result of their early life exposure to toxic waste. Thus, at an average of 10 micrograms of lead per deciliter of blood in our sample, we estimate an overall monetary losses of about $60,000. This evidence may be useful to policy makers when determining appropriate compensation for individuals exposed to events such as the one in Arica.

Even though our results use information from one specific contamination event, we believe they are generally informative about the short- and long-term consequences of environmental pollution. As such, our findings of direct negative effects of hazardous waste on individual academic achievement can be used to shed light on the impact of other similarly unfortunate episodes as well as to design policies aimed at preventing and alleviating their consequences.

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