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ABSTRACT

Air Pollution and Migration: Exploiting a Natural Experiment from the Czech Republic*

This paper examines the causal effects of air pollution on migration by exploiting a natural experiment in which desulfurization technologies were rapidly implemented in coal-burning power plants in the Czech Republic in the 1990s. These technologies substantially decreased air pollution levels without *per se* affecting economic activity. The results based on a difference-in-differences estimator imply that improvements in air quality reduced emigration from previously heavily polluted municipalities by 24%. We find that the effect of air pollution on emigration tended to be larger in municipalities with weaker social capital and fewer man-made amenities. Thus, our results imply that strengthening social capital and investing in better facilities and public services could partially mitigate depopulation responses to air pollution. Finally, we look at heterogeneous migratory responses to air pollution by education and age and find some evidence that the more educated tend to be more sensitive to air pollution in their settlement behavior.

JEL Classification: Q53, J61, O15

Keywords: air pollution, migration, natural experiment

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* We would like to thank Peter Huber, Štepán Jurajda, Christian Oschner, Paolo Zacchia, participants of the IZA Workshop on Environment and Labor Markets 2019, the 2nd CReAM/ RWI Workshop on the Economics of Migration in Essen, YEM2019, SEAM2019, EEA2020, EALE2020, SMYE2021, CERGE/IAB Workshop on the Future of Labor Markets, 11th IOS/APB/EACES Summer Academy on Socioeconomic Consequences of Climate Change, Disasters, and Extreme Events and seminar participants in Padova University and University of Stavanger for their comments and suggestions. This research was funded in part by the Czech Science Foundation grant on "International migration: Drivers and Impacts" (GA20-31615S). The usual disclaimer applies.

1 Introduction

There is a general consensus that air pollution is harmful to human health and that it affects infant and adult mortality (see for instance Graff Zivin and Neidell 2013; Currie and Neidell 2005; Currie et al. 2009; Chay and Greenstone 2003; Newell et al. 2018; Selevan et al. 2000; Currie et al. 2014; Greenstone and Hanna 2014; Tanaka 2015; Schlenker and Walker 2015). A growing body of recent literature has documented the detrimental impacts of air pollution on a range of socio-economic outcomes, including health expenditures, labor supply, hours worked (Hanna and Oliva 2015; Aragon et al. 2017), long-run earnings (Isen et al. 2017), labor productivity (Graff Zivin and Neidell 2012; Chang et al. 2019; He et al. 2019), education outcomes such as test scores and school absences (Currie et al. 2009; Liu and Salvo 2017, etc.), long-term human capital accumulation (Graff Zivin and Neidell 2013; Bharadwaj et al. 2017), and cognition (Bishop et al. 2018). Given these serious adverse effects of exposure to air pollution, one would expect people to prefer to live and raise their children in environmentally clean areas, moving out of polluted areas. Yet literature investigating the role of environmental pollution in migratory behavior is almost non-existent[1].

To the best of our knowledge, there exist only a couple of recent studies exploring the link between air pollution and migration. Specifically, Xu and Sylwester (2016) examined the relationship between air pollution (approximated by PM2.5) and international migration from low and middle-income countries to OECD countries. They show that air pollution is positively associated with emigration (to OECD countries), especially from countries in Sub-Saharan Africa and Eastern Europe. However, this study was not able to identify any causal effects of air pollution on migration. This is problematic, as it is difficult to separate out the effect of pollution from that of economic opportunities[2], which might be correlated with polluted areas. A second study, by Chen et al. (2019), tries to overcome the empirical challenges of underpinning the causal relationship between air pollution and migration by using changes in the average strength of thermal inversions over five-year periods as an instrumental variable for air pollution levels. The results of their analyses show that air pollution is responsible for large changes in regional migration in China.

Our paper contributes to the under-researched relationship between environmental pollution and migration by presenting an analysis of the causal impacts of extreme air

1. Research-based evidence within the area of environmental migration has tended to focus on the role of climate change, temperature and precipitation variability, extreme weather events, droughts, crop failure, natural disasters or environmental degradation in migration (see Dillon et al. 2011; Mueller et al. 2014; Gray and Mueller 2012; Henry et al. 2004; Barrios et al. 2006; Marchiori et al. 2012; Cai et al. 2016).

2. Air pollution tends to be correlated with economic activities, which attract workers via better job opportunities and higher wages. In the migration literature, economic factors such as wages and employment are known to be among the main drivers of migration (Sjaastad 1962; Pedersen et al. 2008; Mayda 2010; Ortega and Peri 2013; Fidrmuc 2004; Clark et al. 2007, and others).

pollution levels on migration based on a natural experiment: the desulfurization of power plants in the region of North Bohemia in the Czech Republic. The North Bohemian region is characterized by multiple lignite-burning power plants, which were responsible for high-emissions of sulfur dioxide (SO_2) polluting the entire area. In order to uncover the causal effects of air pollution on migratory behavior, we exploit a natural experiment that arose from the fact that between 1992 and 1998 the Czech power plants were obliged by law to install modern desulfurization technologies, which consequently led to a substantial drop in the emitted pollution, but did not affect the economic activity in the region *per se*. In fact, this technology-driven reduction in SO_2 emissions in the Czech Republic has been shown to be one of the most dramatic historical examples of pollution reduction in Europe (Vestreng et al. 2007). By utilizing this natural experiment, we make a two-fold contribution to the literature: we add to the literature on the determinants of migration, as well as to the literature on the socio-economic impacts of air pollution.

In our analysis, we compare differences in migration rates between the municipalities with the lowest and highest pollution levels in the pre- and post-desulfurization time-period. The results, based on a difference-in-difference estimator, show that the estimated effect of reduction in SO_2 concentrations on emigration has the expected negative sign and is statistically significant. The effect is large: emigration rates from formerly very polluted municipalities were on average 24% lower after the installation of desulfurization technologies compared to the control group of the least polluted municipalities. Further, we find the effects on emigration to be non-linear in the sense that the effect is much larger – almost twice as large – for municipalities that initially suffered from heavy SO_2 levels (annual mean concentration 50 and 60 $\mu g/m^3$) than it is for municipalities that initially suffered from lower pollution (40 $\mu g/m^3$). The results on immigration are less straightforward. Overall, we do not find that air pollution has any statistically significant effect on immigration; nevertheless, in the regressions in which we dig into these effects for multiple categories of air pollution, we do find that air pollution reduction has a statistically significant positive effect on immigration into municipalities whose initial pre-desulfurization pollution levels were 50 $\mu g/m^3$ of SO_2. All these results are validated by numerous robustness checks and by placebo tests. Our findings also suggest that migratory responses to air pollution are more pronounced among the highly educated part of the population.

Furthermore, in our analysis we dig deeper into the possible mechanisms via which air pollution might affect migration. Specifically, we investigate the role of economic benefits acting as anti-emigration policy and the role of social capital and man-made amenities in counteracting the effect of environmental pollution on migration. To do this, we exploit historical set-ups to study channels that are otherwise hard to disentangle. Our results, based on a triple difference estimator, show that anti-emigration policies had no impact on emigration decisions. Further, we find that migratory responses to air pollution are stronger in municipalities with weaker local social capital and in municipalities with poorer facilities in terms of education, health, social care, culture and sport. Our results thus imply that the burden of air pollution may be partly compensated by stronger local social capital and man-made amenities.

2 Experimental setup: History

In the Czech Republic[3], as in its Eastern European counterparts, the communist regime (1948–1989) pushed for massive industrialization, with energy-hungry heavy industry at the center of the economy. The energy demands created by this industrialization were supposed to be met by making use of substantial lignite deposits in the North Bohemian region (see Appendix Figure A.1).[4] To reduce transportation costs, a new dense cluster of six lignite-burning power plant complexes (see Appendix Table A.1) was built in the vicinity of lignite mines over an area of 380 km^2, i.e. the equivalent of a 20×20 kilometer square. These power plants were often built close to large cities, and little attention was paid to the well-being of local residents. Energy production was so high a priority that the government even moved a large part of the historical city of Most (a district capital) in order to enable the local mines to expand (see Appendix Figure A.2, for details see e.g., Spurny (2016)).

Power plants consumed about 2/3 of the lignite produced (Vaněk 1996); the rest was used in heat-production plants and home heating systems. The widespread use of sulfur-rich lignite resulted in high emissions of SO_2—a typical pollutant emitted by burning lignite. The high concentration of power plants within a relatively small area and their geographical location surrounded by mountains (see Figure 1) limited the dispersion of unfiltered emissions and therefore further scaled up SO_2 concentrations in the region.

Figure 2 shows the long-term development of SO_2 concentrations in the worst polluted districts *("okres")* of Teplice, Most, and Chomutov from 1970 onwards (see Section 3 for details on our data). The concentration levels were remarkably stable from the beginning of the 1970s to the early 1990s. The annual mean SO_2 concentration reached 80 $\mu g/m^3$ in the 1970s and 89 $\mu g/m^3$ in the 1980s, surpassing even Beijing's average level of 71 $\mu g/m^3$

3. The Czech Republic was part of Czechoslovakia between 1918 to 1993.
4. We define the North Bohemian region as the administrative districts *("okres")* of Chomutov, Most, Teplice, Ústí nad Labem, Louny, and Litoměřice.

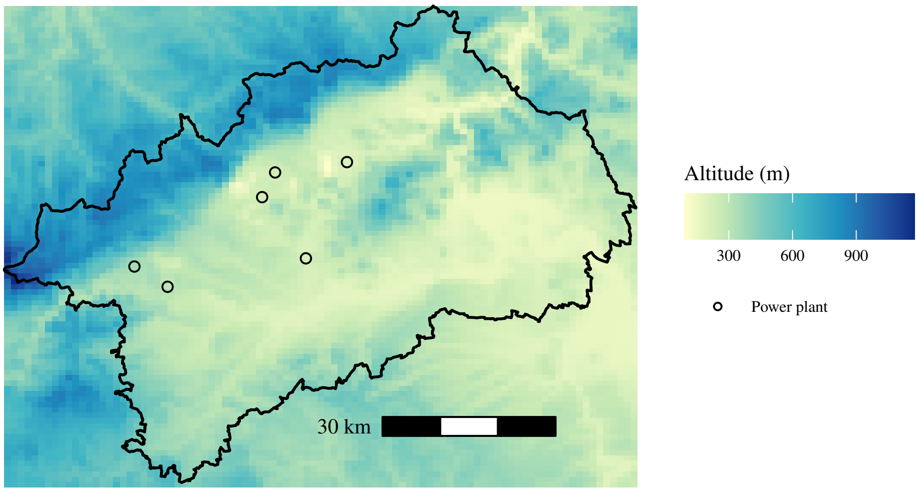


Figure 1: Altitude and power plant location in North Bohemia

Source: Shuttle Radar Topography Mission (SRTM) 1 Arc-Second Global (see Section 3).

in 2000 (UNEP 2007) and more than four times exceeding the level of 20 $\mu g/m^3$[5], which is the EU annual limit (EU 2015) and World Health Organization (WHO) guideline for maximum 24-hour SO_2 exposition (World Health Organization 2006).[6]

High concentrations of pollution caused rapid environmental deterioration. Several papers have studied how the air pollution affected the local population in North Bohemia. For instance, Kotěsovec et al. (2000) analyze mortality data from the period 1982–1998 and provide descriptive evidence of lower life-expectancy in the North Bohemian coal basin in comparison to cleaner regions of the Czech Republic (South Moravia and Prachatice). Dejmek et al. (1999) use data from Teplice (1994–1996) to show that higher particulate matter concentration is associated with a higher risk of intrauterine growth retardation.

The Czechoslovak communist government had been aware of these environmental problems and their likely impacts on public health since the early 1960s (Glassheim 2006; Vaněk 1996), yet took no action to mitigate them. Reducing pollution by decreasing energy production was not seen as an option among the communist leaders, as there were no alternative power sources available to fuel the planned industrial production, which grew steadily throughout the 1960s and 1970s (Glassheim 2006). Furthermore, any reduction in energy production that would have resulted in a reduction in mining activity might have been perceived unfavorably by miners (a prominent part of the "working class") and the

5. Winter peak SO_2 concentrations were even higher. For example, Pinto et al. (1998) compares the SO_2 concentrations in Teplice in 1993 (1600 $\mu g/m^3$) to the London smog episode of December 1952, during which concentrations reached 1800 $\mu g/m^3$.

6. WHO does not set an annual guideline because *"compliance with the 24-hour level will assure low annual average levels"* (World Health Organization 2006).

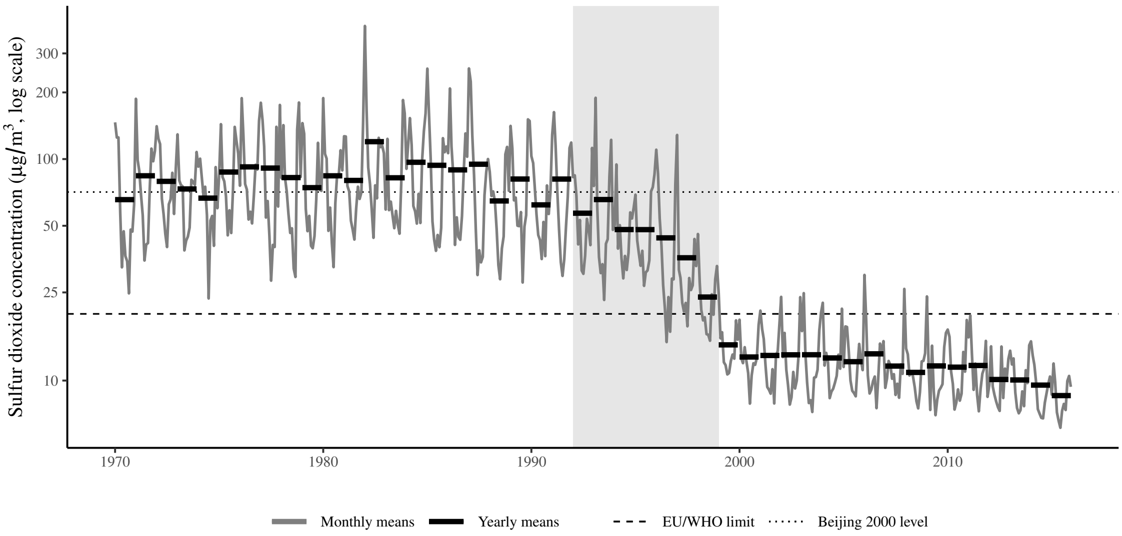


Figure 2: Development in SO_2 concentrations in the Teplice, Most, and Chomutov districts over the period 1970–2015.

Source: Czech Hydrometeorological Institute (CHMI, see Section 3); Limits by: World Health Organization (2006); Beijing pollution levels: UNEP (2007).

communist government was not willing to take that risk (Vaněk 1996). Technical means of desulfurization were also unavailable: the Soviet desulfurization technology was untested and not suitable for the Czech power plants (Kratochvíl 2011), while importing western technology would have been too expensive for a country struggling with a permanent lack of convertible currency (Vaněk 1996). Glassheim (2006) also hypothesizes that the government had rather little interest in reducing pollution and that the central government treated North Bohemia as "an experiment" in producing as much energy as possible with minimal costs.

The pollution associated with this "experiment" imposed a considerable burden on the local population, but they were willing to bear it—at least to some degree. Glassheim (2006) explains this attitude in the context of the post-World War II resettlement of the region: the North Bohemian region was originally primarily populated by ethnic Germans, who were forcibly expelled from the country in the aftermath of the Second World War.[7] The empty towns and villages were then resettled, largely by inhabitants from inland regions of today's Czech Republic who had little or no ties to the region (see Guzi et al. 2021, for details on this resettlement process). Glassheim (2006) claims that, with the help of communist government propaganda, coal and coal mining, became pillars of the newly established regional identity. That identity may in turn have increased the new local population's willingness to bear the environmental burden caused by heavily mining and

7. See Section 5.3.2 for a more detailed description.

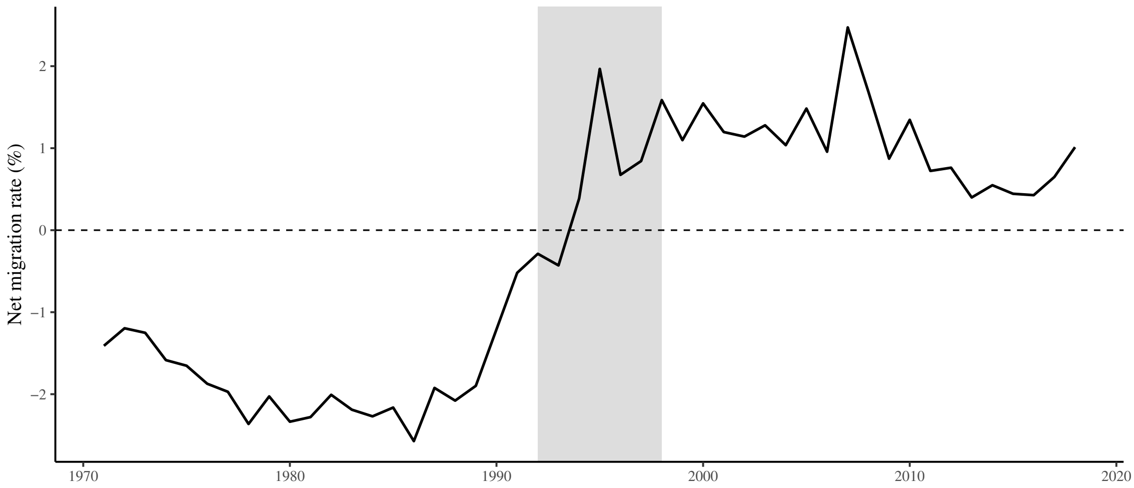


Figure 3: Net migration rate in North Bohemian municipalities (1971–2015)

Source: CZSO (see Section 3)

burning coal. However, despite the fact that North Bohemia's inhabitants may have been relatively more tolerant towards pollution than others, the region continued to experience negative net immigration rates throughout the 1970s and 1980s (see Figure 3).

This steady de-population tendency posed a threat to the regime's production goals. Consequently, the government implemented a series of policies designed to quell it, in the form of various monetary and non-monetary benefits. Policies with the aim of attracting newcomers into the region were substantial and targeted high-skilled professionals in particular. For instance, newcomers could receive house-building subsidies (up to 186% of the average annual wage in 1985)[8] or recruitment benefits (up to 29% of the average annual wage in 1985).[9] On the other hand, the benefits designed to keep workers in the region were more universal, but far less generous. Anyone who worked in the basin districts (four of the six districts in the region) for at least 10 years was eligible for an annual monetary benefit of 5.7% of the average annual wage in 1985. Locals used to refer to this as "burial benefit" *("pohřebné")*.

In total, the various benefits paid raised the income of workers in North Bohemia above the country-wide level (Vaněk 1996). However, in the late 1980s, median wages slowly converged to the country level. According to Vaněk (1996) this convergence increased the North Bohemian population's frustration, which grew under the lid of the authoritarian regime and eventually boiled over in 1989. The first environmental demonstration in Czechoslovakia took place on May 1989. A strong temperature inversion on November 8th 1989 then led to a call for demonstrations in North Bohemia and more than a thousand locals

8. Historical data on wages in Czechoslovakia are available at https://www.czso.cz/csu/czso/casove-rady-zakladnich-ukazatelu-statistiky-prace (last accessed on February 7th 2019).

9. For a comprehensive list of monetary and non-monetary benefits see Appendix Textbox A.1.

attended a series of demonstrations in Teplice between 11th and 13th November 1989. They demanded action to reduce air pollution, with slogans such as “We want healthy children!” and “We want clean air!”. Other cities in the North Bohemian coal basin later joined the protests (Vaněk 1996). On November 17th 1989, shortly after the series of demonstrations in Teplice, the major anti-regime demonstration which marked the beginning of the Velvet revolution and the fall of the communist regime in Czechoslovakia took place in Prague. It was thus not the Communist Party but rather the new government, sworn in on 10th December 1989, whose task it was to respond to these demands. The new government launched a complex process of political and economic transition, a fundamental part of which was to draw up legislation introducing policies that would improve the environment and the Czech population’s living conditions. Two major policies were adopted in the early years after the revolution that helped to reduce pollution in North Bohemia: (a) regulation of SO_2 emissions and (b) limitation of lignite mining.

Act no. 309, passed in 1991, set an obligation for the government to provide the general public with full and up-to-date information on air quality and emission sources and established a framework for the regulation of emissions and immissions. The law effectively required the installation of modern desulfurization technologies before December 31st 1998—i.e. within seven years.[10] This strict deadline forced existing power plants to implement desulfurization technologies swiftly. The first power plant (Komořany) commenced desulfurization in 1993. Others followed in 1994 and later. The last power plant in the region implemented desulfurization technologies in early 1999 (see Table A.1 in the Appendix).

The government (by Government Act no. 444/1991) also set limits on mining activity which, together with the drop in demand caused by the economic downturn during the transition period, led to a decrease in coal production during the 1990s, from 67 million metric tons in 1989 to 40 million metric tons in 2000 (see Figure A.3 in the Appendix). These regulations were later loosened (in 2008 and 2015), but never abolished.

These policies resulted in a rapid decline in SO_2 concentrations (see Figure 2). The mean concentrations in the most heavily polluted districts had dropped below the EU/WHO limit of $20\,\mu g/m^3$ by 1999. SO_2 concentrations then remained stable throughout the 2000s and 2010s.

Figure 4 shows the spatial distribution of SO_2 concentrations in North Bohemia in 1994, at the beginning of the desulfurization period (older data are not available) and after the completion of the desulfurization period, in 2000. Despite the fact that SO_2 concentrations were already slightly declining in 1994 (see Figure 2), the EU/WHO limit of $20\,\mu g/m^3$ was

10. The law set an obligation for all emission sources to meet emission limits designed for newly built emission sources equipped with modern up-to-date technology by December 31st 1998.

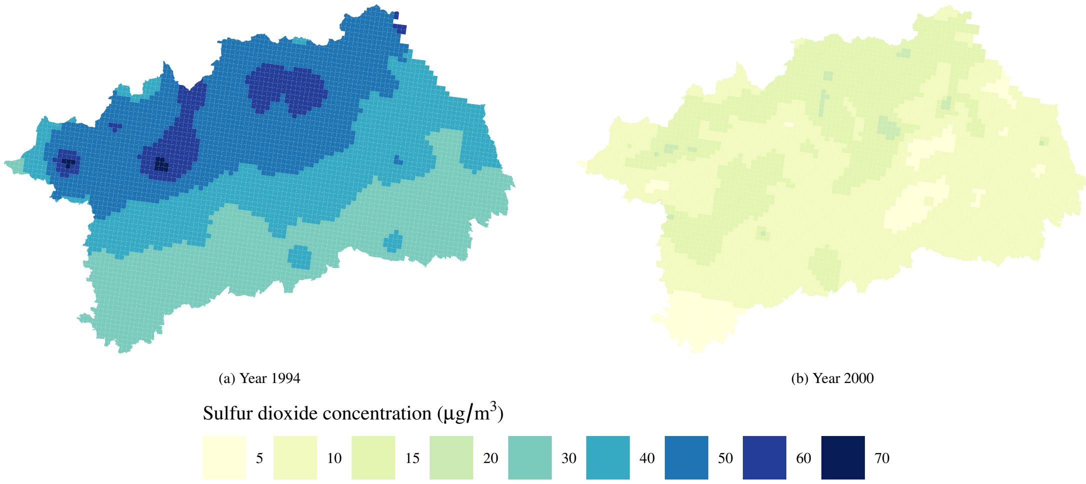


Figure 4: Spatial distribution of SO_2 concentrations in North Bohemia, year 1994 and 2000
Source: Czech Hydrometeorological Institute (CHMI, see Section 3)

not met in any municipality in the region at that time. There was substantial variation in the pollution load between municipalities, with average SO_2 concentrations ranging from 30 to 70 $\mu g/m^3$. After desulfurization, the average concentrations in the region dropped below 20 $\mu g/m^3$. The Czech Hydrometeorological Institute (CHMI) dispersion model shows that all municipalities benefited from this substantial decrease in SO_2 emissions, as in the year 2000 the SO_2 concentrations ranged from 5 to 20 $\mu g/m^3$ and all the municipalities in the region met the EU/WHO 20 $\mu g/m^3$ SO_2 limit, regardless of how high their pollution loads had been in the pre-desulfurization period (see Figure A.4 in the Appendix).

The government policies that had been introduced previously to support immigration to North Bohemia and prevent emigration, which we discussed above, were abandoned along with the introduction of the new environmental regulations. The benefits for those who remained in the region long-term were initially maintained (via Acts No. 276/1991 and 471/1991), but were then abolished in early 1992 (via Act no. 1/1992, passed in December 1991).

3 Data

The primary data sets used in our empirical analysis are municipality-level data on residential migration and sulfur dioxide concentrations. The annual data on residential migration are compiled by the Czech Statistical Office (CZSO) from administrative records on permanent residence changes in the period from 1971 onwards.[11] People in the Czech Republic were and are legally obliged to register their place of permanent residence. Moreover, they are motivated to keep this registration up to date, as preferential access to some public services is granted on the basis of permanent residence (such as kindergartens, elementary schools or local health care). The dataset contains information on the numbers of people who moved in and out of each municipal area in each year. For the purposes of our analysis, we calculate annual municipality-level emigration and immigration rates as the number of movers per resident population, using those gross emigration and immigration levels, and population as of January 1st. Some records on residential migration, mostly from smaller municipalities, are missing due to changes in municipality boundaries or because they were lost before the records were digitized.

We utilize two sources of data on municipality-level air pollution. First, concentrations of SO_2 and other pollutants are measured by a network of stations run by the Czech Hydrometeorological Institute (CHMI). This network is unfortunately too sparse to provide reliable municipality-level pollution data and therefore not optimal for our empirical analysis, but it does at least enable us to observe the long-term development of overall SO_2 concentrations in the region for our descriptive evidence (as depicted in Figure 2).[12] Our second source of data on municipality-level pollution concentration comes from a proprietary CHMI dispersion model, which takes into account local meteorological and topographic conditions as well as pollution source characteristics. The detailed resolution of the dispersion model on a 1 km grid allows us to capture pollution distribution at municipality level, represented by coordinates of their reference points, and provides us with the richer data we need for our empirical analysis.[13] We have purchased data from two iterations of the model: for 1994 (the oldest iteration available) and for the year 2000. The CHMI dispersion model categorizes municipalities into 5 categories by mean SO_2

11. Data are available at https://www.czso.cz/csu/czso/databaze-demografickych-udaju-za-obce-cr (last accessed on February 6th 2019).

12. Daily mean concentrations from individual measuring stations are available from CHMI yearbooks for the period from 1997 forward. We have supplemented this publicly available data with monthly means of SO_2 concentrations from selected stations located in the worst polluted districts (Most, Teplice and Chomutov) for the period 1970–1996. These additional data were purchased from CHMI. However, frequent changes in the measuring network (in the locations, number of stations, and technology used) do not allow us to construct consistent long-term time series for the individual measuring stations.

13. The municipal reference point, as defined by the CZSO, is placed at a social central point within each municipality (such as in the front of a church or town hall).

concentrations in 1994: 30, 40, 50, 60, and 70 $\mu\text{g/m}^3$; and 4 categories in 2000: 5, 10, 15, and 20 $\mu\text{g/m}^3$ (see Figure 4).

We also make use of data on municipalities' population characteristics from decennial population censuses. Municipality-level census data on population, education and age structure are available for the 1980, 1991, 2001, and 2011 censuses. For the period from 1991 onwards, the CZSO has also published yearly data on municipalities' population structure, compiled from census and registry data.[14] Furthermore, we exploit information from the 1930 Census on the ethnic composition of the municipalities' population in 1930.[15]

Lastly, we employ several other datasets in our analysis. We use the ArcČR 500 v3.3 map collection to define the administrative borders of the examined municipalities and to make geospatial visualizations.[16] Further, we obtain altitude data from remotely sensed elevation grid data from the Shuttle Radar Topography Mission (SRTM) 1 Arc-Second Global.[17] The altitude of each municipality is defined as the altitude at the municipality reference point. The driving distances between the municipalities are calculated using Open street map (OSM) data.[18] To capture the yearly municipality-level unemployment rate we use administrative data on registered unemployment. These data are unfortunately only available from 2001 onwards.[19] Our data on man-made amenities come from the MOS database on regions and municipalities, administered by the CZSO.[20]

3.1 Estimation sample

Our identification exploits the variation of SO_2 concentration over time and space – i.e. among municipalities in North Bohemia (which are our units of observation) and between the pre- and post-desulfurization period.

The spatial distribution of SO_2 concentration is taken from the CHMI dispersion model, the oldest available iteration of which is for the year 1994—the first year of the widespread implementation of desulfurization technologies. With no other data available, we use this iteration to capture pre-desulfurization levels of SO_2 concentration across the North

14. Census data are accessible at the website of the CZSO (https://www.czso.cz/csu/sldb/home) or are available upon request. The yearly data on age structure are not publicly available.

15. The data were digitized by Guzi et al. (2021). They use aggregation rules provided by the CZSO to match current and historical municipalities.

16. This map collection, developed by ARCDATA PRAHA, is available at https://www.arcdata.cz/produkty/geograficka-data/arccr-500 (last accessed on June 26th 2019).

17. For data access see https://www2.jpl.nasa.gov/srtm/dataprod.htm (last accessed on December 4th 2019).

18. The OSM database for the Czech Republic was downloaded from geofabrik.de on May 30th 2019.

19. The data collected by the Czech Labor Office is available from https://portal.mpsv.cz/sz/stat/nz/uzem (last accessed on June 26th 2019).

20. Historical records from the MOS database are not publicly accessible, but can be purchased from the CZSO – see https://vdb.czso.cz/mos/.

Bohemian municipalities. The validity of the spatial distribution in 1994 for the spatial distribution in the entire pre-desulfurization period is limited by changes in emission sources over time. Therefore, we limit our sample to the period after the construction of the last coal-burning power plant in the area was completed in 1982. Between 1983 and 1993 there were no changes in the structure (i.e., in the number, location or power output) of the region's major emission sources. The use of spatial distribution of pollution levels from 1994 for the whole pre-desulfurization period is further justified by the remarkable stability of SO_2 levels in both the pre- and post-desulfurization periods evidenced in the data from the CHMI network of stations (see Figure 2).

As we mentioned above, environmental concerns were one of the issues central to the 1989 protests. People expected the new government to take decisive measures to improve the environment. The government swiftly addressed this demand by passing several laws and regulations in 1991. To ensure that our results are not driven by (legitimate) expectations for the future improvement of the environment, we exclude the period 1990–1991 from our estimation sample. Moreover, migration behavior in the 1990s is likely to have been driven by expectations of a future cleaner environment, fueled by the ongoing desulfurization process, rather than by actual pollution levels. As a result, we define the pre-desulfurization period as the years 1983–1989 and the post-desulfurization period as the years 2000–2015.

The CHMI dispersion model calculates SO_2 concentrations in five levels between 30 and 70 $\mu g/m^3$ in 1994, which we use to essentially categorize municipalities based on their pre-desulfurization pollution levels. The highest level of 70 $\mu g/m^3$ is calculated for only one municipality: the district capital Chomutov. As we estimate the effect of desulfurization for each pollution level to reflect the potentially non-linear effect of air pollution, the effect for this pollution level would be estimated using only one independent observation. Therefore, we exclude Chomutov from the estimation sample used in our main analysis, and work with only four 1994 SO_2 concentration levels (30, 40, 50 and 60 $\mu g/m^3$) to categorize the municipalities according to pollution[21]. Overall, our baseline estimation sample thus contains data for 301 municipalities for the years 1983–1989 and 2000–2015, a total of 6,229 data-points.

21. However, we re-run our analysis with all the data, including Chomutov, as part of our robustness checks.

Table 1: Descriptive statistics: Population, pollution load, and other time-invariant characteristics by SO_2 concentration

	Year	Municipalities in estimation sample				
		All	By SO_2 concentration (1994)			
			30 μg/m^3	40 μg/m^3	50 μg/m^3	60 μg/m^3
		(1)	(2)	(3)	(4)	(5)
SO_2 concentration (μg/m^3)	1994	40.63	30.00	40.00	50.00	60.00
		(0.56)	(0.00)	(0.00)	(0.00)	(0.00)
	2000	11.11	9.68	10.16	13.42	13.89
		(0.17)	(0.19)	(0.28)	(0.35)	(0.41)
Population	1980	2189.87	880.11	1526.87	4129.21	3771.27
		(457.29)	(182.86)	(438.12)	(1476.15)	(2062.93)
	1991	2327.62	886.37	1615.58	4748.40	3598.15
		(530.05)	(176.41)	(497.38)	(1848.96)	(2016.66)
	2001	2110.81	824.90	1393.43	4355.64	3656.07
		(464.42)	(162.69)	(402.67)	(1654.62)	(1973.76)
	2011	2145.70	865.46	1409.48	4394.44	3722.59
		(457.30)	(162.45)	(387.07)	(1630.81)	(1944.76)
Altitude (m)		286.33	242.93	266.61	350.29	357.58
		(8.11)	(9.38)	(12.33)	(19.48)	(37.45)
Share of ethnic Germans (%)	1930	54.24	26.81	60.56	77.84	79.28
		(2.23)	(3.73)	(3.60)	(2.11)	(3.30)
Municipalities (n)		301	108	93	73	27

Notes: Table reports means and robust standard errors clustered by municipality in parentheses. Differences are tested for statistical significance: *, ** and *** denote statistical significance at 10%, 5% and 1%.

3.2 Descriptive evidence

The region we examine has a specific topography which, together with the location of lignite deposits, determined the relationship between pollution load and municipalities' characteristics. Mines and power plants were located at the feet of the mountains on the border with (East) Germany. These mountains limited the dispersion of emissions. As a result, more polluted municipalities tended to be located in higher altitudes and closer to the border.

As can be seen in Table 1, the more polluted municipalities also seem to be substantially larger in terms of population. Despite the existing differences in population size, the population structure in terms of education and age across the groups of municipalities is comparable (see Tables A.2 and A.3 in Appendix). The more polluted municipalities were more heavily affected by post-war expulsion and resettlement: the pre-war share of ethnic Germans was more than twice as high in highly polluted municipalities as in the least polluted municipalities in our sample (see Table 1).

Regarding population movement, both emigration and immigration rates differed between the pre- and post-desulfurization periods, see Table 2, Panel A and B. The mean emigration rate in the pre-desulfurization period reached 5.2‰ and the immigration rate 3.1‰. After desulfurization, which reduced the SO_2 concentration to below EU and WHO limits, the emigration rate dropped by 1.7 percentage points, while the immigration rate rose by 1.5 percentage points (see column (1) in Table 2).

These changes in emigration and immigration are reflected in the development of the net migration rates[22], see Table 2, Panel C, which shows that in the pre-desulfurization period, the region experienced a negative net immigration rate with a mean of −2.2‰ per year despite the pro-immigration and anti-emigration policies in place at the time. The mean net migration rate in the post-desulfurization period rose by 3.3 percentage points to 1.1‰. Further, Figure 3 shows long-term development in the average net migration rate over the years 1971–2015. As can be seen, the net migration rate turned to positive in 1993, at the beginning of the desulfurization process. This evidence suggests that the substantial reduction in air pollution brought about through desulfurization increased the region's attractiveness.

The same patterns hold for differences between the least- and the worst- polluted municipalities in the estimation sample. The emigration rate from the worst-polluted municipalities exceeded the emigration rate from the least-polluted municipalities by between 1.3 and 2.7 p.p. in the pre-desulfurization period. This gap substantially narrowed, to 0.5–0.7 p.p., after desulfurization. The development of the immigration rate was less dynamic. In the pre-desulfurization period, the worst-polluted municipalities experienced slightly higher immigration rates (by 0.4 up to 0.9 p.p.) relative to the least-polluted municipalities. After desulfurization the gap slightly increased (by 0.5 up to 1.2 p.p.).

If we look at changes in the emigration and immigration rates within municipality-groups between the pre- and post-desulfurization periods, the third rows in Panels A and B of Table 2 show that the least-polluted municipalities experienced the smallest decrease in emigration rate relative to more heavily-polluted municipalities, whereas the increase in immigration rate in the least-polluted municipalities was only slightly lower or comparable to other groups of municipalities with higher pollution levels. These changes signal a possible higher relative increase in attractiveness in formerly highly polluted municipalities than in formerly less polluted municipalities, after the environment had become cleaner. Developments in net migration, shown in Panel C of Table 2, again mirror the development in emigration and immigration rates. Clearly, the more polluted a particular municipality was in the past, the more attractive it became for re-population after the air had become

22. Defined as immigration minus emigration by population.

Table 2: Migration rates by period and SO_2 concentration

	Municipalities in estimation sample				
	All	By SO_2 concentration (1994)			
		$30\,\mu g/m^3$	$40\,\mu g/m^3$	$50\,\mu g/m^3$	$60\,\mu g/m^3$
	(1)	(2)	(3)	(4)	(5)
	Panel A: Emigration rate				
Post-desulfurization period (%)	3.46	3.09	3.56	3.84	3.62
	(0.07)	(0.09)	(0.12)	(0.20)	(0.21)
Pre-desulfurization period (%)	5.21	3.77	5.08	6.46	5.89
	(0.22)	(0.15)	(0.41)	(0.48)	(0.69)
Difference (p.p.)	-1.74^{***}	-0.68^{***}	-1.52^{***}	-2.62^{***}	-2.27^{***}
	(0.20)	(0.15)	(0.40)	(0.42)	(0.54)
	Panel B: Immigration rate				
Post-desulfurization period (%)	4.58	4.05	4.54	5.26	5.01
	(0.11)	(0.13)	(0.19)	(0.32)	(0.27)
Pre-desulfurization period (%)	3.05	2.59	3.48	2.99	3.46
	(0.12)	(0.18)	(0.27)	(0.22)	(0.43)
Difference (p.p.)	1.53^{***}	1.46^{***}	1.06^{***}	2.27^{***}	1.55^{***}
	(0.17)	(0.21)	(0.32)	(0.39)	(0.55)
	Panel C: Net migration rate				
Post-desulfurization period (%)	1.12	0.96	0.99	1.42	1.39
	(0.07)	(0.08)	(0.12)	(0.22)	(0.19)
Pre-desulfurization period (%)	−2.16	−1.18	−1.60	−3.47	−2.43
	(0.25)	(0.19)	(0.41)	(0.57)	(0.89)
Difference (p.p.)	3.28^{***}	2.14^{***}	2.58^{***}	4.89^{***}	3.82^{***}
	(0.29)	(0.21)	(0.46)	(0.71)	(0.94)
Municipalities (n)	301	108	93	73	27

Notes: Table reports means and robust standard errors clustered by municipality in parentheses. Differences are tested for statistical significance: *, ** and *** denote statistical significance at 10%, 5% and 1%.

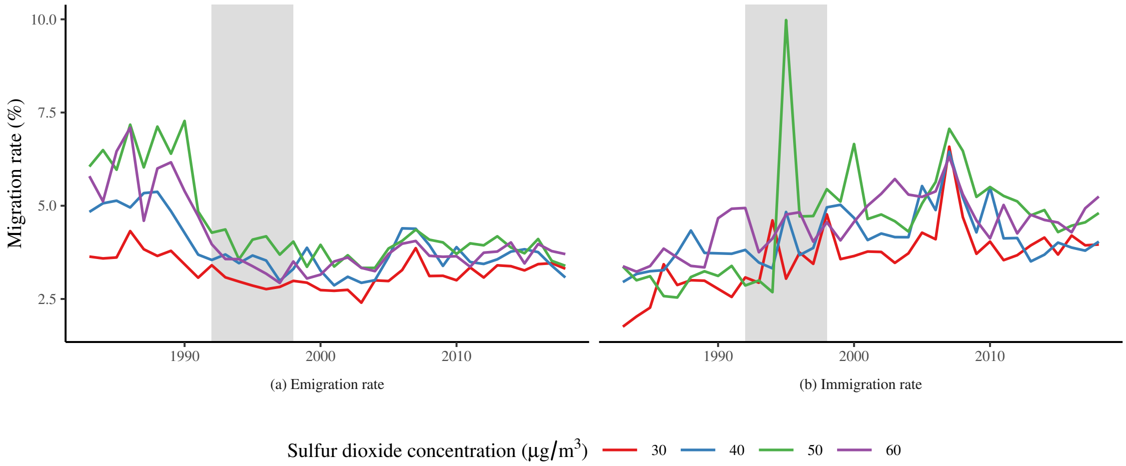


Figure 5: Migration rates in municipalities in North Bohemia by 1994 SO_2 concentration, years 1983–2015

Source: CZSO (see Section 3)

substantially cleaner thanks to the implementation of desulfurization technology at the power plants.

Figure 5 shows development in the emigration and immigration rates, respectively, by pollution levels, from 1983 through to 2015, including the whole of the desulfurization period (1994–1999). As Figure 5 reveals, there was a strong decline in emigration rates shortly after the fall of communism; that decline was particularly sharp in 1991, when the new environmental legislation was adopted. The emigration rates dropped at this stage for all groups of municipalities, even those whose pollution levels were still high at that time. This could be due to expectations of a future reduction in pollution supported by the new legislation.

On the contrary, the fall of communism seems not to have any clear immediate effect on immigration rates, as can be seen in Figure 5: the overall increase in immigration rates did not start until mid-nineties, once the implementation of desulfurization technology at the power-plants was already effective.

4 Identification strategy and empirical specification

Our identification strategy rests on comparing differences in migration rates between municipalities with the lowest and highest levels of pollution in the pre- and post-desulfurization periods. To do so, we employ the difference-in-differences (DID) framework, which ensures that our estimates are not driven by substantial country-wide changes that affected all municipalities alike (such as the fall of communism and institutional changes in the transition period). To estimate the impacts of pollution on migration, we estimate the following regression:

$$mig_{it} = \gamma \mathrm{SO40}_i p_t + \sum_k \beta_k l_k + \theta_p + \theta_i + \varepsilon_{it} \tag{1}$$

where mig is the migration rate in municipality i and in year t (we estimate separate models for emigration, immigration and net migration rate), p_t is a a dummy variable, which is equal to 1 for the post-desulfurization period (2000–2015) and 0 for the pre-desulfurization period (1983–1989).

To capture the overall effect of the reduction in air pollution due to desulfurization, we interact the dummy variable for the post-desulfurization period with an indicator variable ($SO40$) for municipalities whose SO_2 concentrations in the pre-desulfurization period were greater than or equal to $40\,\mu\mathrm{g/m}^3$.[23][24] Specification (1) also contains a full set of municipality fixed effects, including a constant that controls for all time-invariant differences (such as geographical location, natural amenities or post-World War II resettlement heritage) and hence ensures that we are estimating the effect of the municipality's SO_2 concentrations. We also include an indicator variable for the post-desulfurization period (θ_t). To capture possible time-variant regional characteristics, we divide the region into three areas orthogonal to pollution levels[25] and include a linear trend (l) specific for each area and period.

23. The pre-desulfurization SO_2 concentrations are a good approximation for the reduction in air pollution, since desulfurization reduced pollution levels to below the EU and WHO limits in all municipalities (see Figure 4).

24. Furthermore, we also estimate two alternative model specifications: 1) a simple reduced form model with the municipality-level migration rate on the left hand side and SO_2 concentrations on the right hand side, and 2) a regression in pre- and post- mean outcome changes i.e., $\Delta mig_i = \gamma \Delta \mathrm{SO}_i + \theta_\alpha$, where Δmig_i is the difference between mean migration rates in the post- and pre-desulfurization periods, ΔSO is the difference in SO_2 concentrations, and θ_α is an area fixed effect. Further, in the second alternative specification, we also instrument the change in SO_2 concentrations with the pre-desulfurization SO_2 levels. The results from the regression on the estimated coefficients of interest for all three specifications are in line with the reported findings from our main DID analyses. The result tables are available from the authors upon request.

25. The areas are defined using the border between the basin and the remainder of the region (i.e., the South-West to North-East axis); we divide this border into three equally long segments and assign each municipality to the nearest one. Area is then defined as the set of municipalities nearest to a specific segment.

As the effect of desulfurization could potentially be non-linear in the pre-desulfurization SO_2 concentrations, we also estimate the following specification (2):

$$mig_{it} = \sum_j \gamma_j \text{SO}_i p_t + \sum_k \beta_k l_k + \theta_p + \theta_i + \varepsilon_{it} \tag{2}$$

where the effect is estimated separately for each category of municipalities (a vector of indicator variables SO) defined by pre-desulfurization SO_2 concentrations (40, 50, and $60\,\mu\text{g/m}^3$). The category of the least polluted municipalities ($30\,\mu\text{g/m}^3$) is our reference group in both specifications. The reference category exceeds the EU/WHO $20\,\mu\text{g/m}^3$ limits for developed countries by 50%. The parameters therefore represent a lower bound estimate of the true effect of desulfurization, which decreased pollution levels to or below the $20\,\mu\text{g/m}^3$ limit in all municipalities.

We further perform the parallel trends assumption test, which we discuss and present in the Appendix section B. Figures B.5, B.6 and B.7 report the results of the parallel assumption test for emigration, immigration and net migration rates, respectively. As the figures show, the test reveals no divergence in trends in the pre-desulfurization period (1983–1989) for emigration and net migration rate, whereas for immigration rate the test is weaker.

5 Empirical Results

5.1 Main Results

Table 3 presents estimates of our parameters of interest from (1) and (2) for interaction term of post-desulfurization period and dummies for categories of municipalities that suffered higher SO_2 concentrations in the pre-desulfurization period, capturing the impacts of air pollution reduction—thanks to the adoption of new technology in power plants—on migration rates.

The estimates from regression (1), presented in Panel A, show that the adoption of desulfurization technology affected emigration from municipalities with pre-desulfurization SO_2 concentrations of $40\,\mu\text{g/m}^3$ or higher. The desulfurization of powerplants and the resulting cleaner environment in these formerly heavily polluted areas decreased emigration rates by 1.4 percentage points, which corresponds to an approx. 24% decline in emigration rate. The impact on the immigration rate is statistically insignificant. Overall, desulfurization contributed to the re-population of the region as it led to an increase in the net migration rate by 1.7 percentage points (approx. 78%) relative to the comparison

Table 3: Main results

	Dependent variable		
	Emigration rate (%)	Immigration rate (%)	Net migration rate (%)
	(1)	(2)	(3)
Panel A: One category for municipalities with pre-desulfurization SO_2 concentrations > 30 μg/m^3			
Pre-desulfurization SO_2 concentration ≥ 40 μg/m^3	-1.381^{***}	0.313	1.695^{***}
× Post-desulfurization period	(0.282)	(0.335)	(0.470)
Adjusted R^2	0.337	0.139	0.133
Observations	6,229	6,229	6,229
Panel B: Multiple categories for municipalities with pre-desulfurization SO_2 concentrations > 30 μg/m^3			
Pre-desulfurization SO_2 concentration = 40 μg/m^3	-0.879^{**}	-0.533	0.346
× Post-desulfurization period	(0.397)	(0.378)	(0.562)
Pre-desulfurization SO_2 concentration = 50 μg/m^3	-1.700^{***}	1.061^{**}	2.760^{***}
× Post-desulfurization period	(0.419)	(0.484)	(0.729)
Pre-desulfurization SO_2 concentration = 60 μg/m^3	-1.588^{***}	0.171	1.760^{**}
× Post-desulfurization period	(0.469)	(0.567)	(0.856)
Adjusted R^2	0.339	0.142	0.140
Observations	6,229	6,229	6,229

Notes: Table reports γ coefficients from Equation (1) in Panel A, and γ_j coefficients from Equation (2) in Panel A. All model specifications include constant, municipality and post-desulfurization fixed effects, and linear trends for each area and period. Robust standard errors clustered by municipality are reported in parentheses: *, ** and *** denote statistical significance at 10%, 5% and 1%. The reference category for SO_2 concentration is 30 μg/m^3.

group. These results suggest that the reduction in air pollution made previously heavily polluted municipalities more attractive for people to live in.

The estimates of the non-parametric regression (2), presented in Panel B, show that the impacts of air pollution reduction tend to be non-linear in pre-desulfurization pollution levels. In particular, we find that the effect of the decline of SO_2 concentrations on emigration from municipalities with heavy initial SO_2 pollution levels (50 and 60 μg/m^3) is statistically significant and about two times higher than the effect on emigration from municipalities in the category with 40 μg/m^3 SO_2 concentrations. Specifically, the emigration rate in the two initially most heavily polluted categories of municipalities drops by 1.7 and 1.6 p.p. respectively, relative to the initially least polluted category; this corresponds to 26% and 27% lower emigration rates, respectively.

The results for immigration and net migration rates show that both rates increased relative to the reference group in municipalities whose initial SO_2 concentration exceeded 40 $\mu g/m^3$. Municipalities whose pre-desulfurization SO_2 concentrations were as high as 50 $\mu g/m^3$ experienced a statistically significant increase in immigration and net immigration rate, by 1.1 and 2.8 p.p. respectively. The estimates for municipalities whose pre-desulfurization SO_2 levels were 60 $\mu g/m^3$ are somewhat lower and statistically insignificant for immigration rate; our results show that they experienced an 1.8 p.p. increase in net immigration rate compared to the reference group of the least polluted municipalities.

We acknowledge that estimates must be interpreted with caution as the reduction in air pollution took place in parallel to the abolition of anti-depopulation policies. The analysis presented in section 5.3.1 shows that the abolition of these policies had no impact on emigration rates. Therefore, we interpret our estimates on emigration rates as causal effects. However, our estimates for immigration and net migration rates cannot be interpreted as such, as we cannot disentangle the effects of reducing air pollution from the effects of abolishing substantial pro-immigration benefits due to the lack of individual-level data. The estimates for immigration rates suggest two possible explanations: (a) The substantial pro-immigration benefits provided in pre-desulfurization period were sufficient to compensate (to some extent) for the disutility from air pollution; or (b) The poor environment in pre-desulfurization period gave the region a bad reputation, which deterred people from moving into the region even after pollution levels had radically decreased.

5.2 Robustness analysis and placebo tests

5.2.1 Economic factors and unemployment

There is a concern with respect to our main findings that the environmental policies introduced in the early 1990s both pushed for desulfurization and, at the same time, limited lignite mining. Desulfurization was achieved through the adoption of new technologies, and therefore *per se* had no or little impact on the labor market. On the other hand, new limits on lignite mining, together with the overall decline during the so-called transition recession, led to mine closures, which may have adversely affected local labor markets, in particular in the more polluted municipalities situated close to mines and power plants. In effect, such a negative shock could affect the migratory responses to air pollution reduction we find in our baseline estimates, as reported in Table 3.

In order to tackle these concerns, we re-estimate regression (2) with additional controls consisting of the municipality-level unemployment rate, defined as the share of registered unemployed on the working-age population (15–64) in the given municipality in the previous year. We report the results in Table 4, in column (1). The municipality-level unemployment data are available only for the periods 2001–2011 and 2013–2015, which limits our post-desulfurization period, and thus the number of observations drops by 15%. We assume the unemployment rate to have been equal to zero before the fall of communism – i.e., in the pre-desulfurization period. The results reported in Table 4, column (1), show no deviation from our baseline estimates (presented in Table 3); the coefficient for the unemployment rate is insignificant and close to zero.

5.2.2 Post-desulfurization pollution levels

The environmental policies introduced in the 1990s decreased SO_2 concentrations to below the EU/WHO limits in the post-desulfurization period. Still, although these administrative limits were met, some variation in the pollution load across the examined municipalities remained (see Figure 4 and Table 1). To test whether post-desulfurization pollution levels played any role in migration behavior, we re-estimate regression (2) with controls for post-desulfurization SO_2 concentrations. The results reported in Table 4, column (2), do not deviate significantly from the baseline estimates for the variables of interest.

5.2.3 Population and education structure

Even though the municipalities in our sample were comparable in education and demographic structure throughout the observation period, we try in the next step to take care of possible differences in population structure that might have affected migration behavior. We re-estimate regression (2) with a number of additional demographic controls, such as the share of secondary and tertiary educated and the share of age cohorts (20–29, 30–39, 40–49, 50–59, 60–69) on the population. All those controls enter the regression lagged by one year. We obtain the data on population characteristics primarily from decennial censuses held in 1980, 1991, 2001, and 2011. In order to make use of the entire wealth of our data, we use interpolate yearly values for the years between census years. For the population structure between 1991 and 2015, we use census data adjusted with population registry data from the CZSO.[26] We interpolate the remaining missing values using nearest-neighbor interpolation.[27] The results from our main regression (2) controlling for these municipality-level demographic characteristics are reported in column (3) of Table 4 and show that the estimated coefficients do not differ when controlling for these demographic characteristics.

26. The dataset is not publicly available, but can be purchased from the CZSO for academic use.
27. The results obtained with piece-wise linear interpolation do not deviate significantly; these results are available upon request.

Table 4: Robustness analysis

	Unemploy. rate	SO_2 conc. in post-desulf. period	Education and age structure	Inclusion of Chomutov	Balanced panel	Exclusion of outliers	Adjusted standard errors
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
				Panel A: Emigration rate			
Pre-desulf. SO_2 concentration = 40 $\mu g/m^3$ × Post-desulfurization period	−0.859**	−0.839**	−0.924**	−0.877**	−0.854**	−0.646**	−0.879**
	(0.406)	(0.375)	(0.415)	(0.396)	(0.413)	(0.307)	(0.413)
Pre-desulf. SO_2 concentration = 50 $\mu g/m^3$ × Post-desulfurization period	−1.738***	−1.570***	−1.665***	−1.703***	−1.645***	−1.336***	−1.700**
	(0.439)	(0.519)	(0.427)	(0.419)	(0.429)	(0.270)	(0.791)
Pre-desulf. SO_2 concentration = 60 $\mu g/m^3$ × Post-desulfurization period	−1.615***	−1.307**	−1.509***	−1.457***	−1.546***	−1.176***	−1.588**
	(0.468)	(0.589)	(0.458)	(0.468)	(0.473)	(0.278)	(0.771)
Adjusted R^2	0.352	0.340	0.349	0.338	0.374	0.341	0.339
Moran's Z							0.745
Observations	5,326	6,229	6,229	6,252	4,485	6,148	6,229
				Panel B: Immigration rate			
Pre-desulf. SO_2 concentration = 40 $\mu g/m^3$ × Post-desulfurization period	−0.500	−0.566	−0.471	−0.534	−0.469	−0.302	−0.533
	(0.385)	(0.382)	(0.383)	((0.377)	(0.383)	(0.324)	(0.489)
Pre-desulf. SO_2 concentration = 50 $\mu g/m^3$ × Post-desulfurization period	0.983**	0.908*	1.086**	1.062**	1.303***	0.873***	1.061
	(0.447)	(0.509)	(0.488)	(0.484)	(0.493)	(0.330)	(0.733)
Pre-desulf. SO_2 concentration = 60 $\mu g/m^3$ × Post-desulfurization period	0.161	−0.128	0.166	0.100	0.335	0.336	0.171
	(0.587)	(0.747)	(0.540)	(0.554)	(0.569)	(0.509)	(0.642)
Adjusted R^2	0.161	0.142	0.147	0.142	0.155	0.186	0.142
Moran's Z							1.020
Observations	5,326	6,229	6,229	6,252	4,485	6,148	6,229
				Panel C: Net migration rate			
Pre-desulf. SO_2 concentration = 40 $\mu g/m^3$ × Post-desulfurization period	0.360	0.272	0.453	0.343	0.386	0.330	0.346
	(0.565)	(0.545)	(0.571)	(0.559)	(0.584)	(0.511)	(0.517)
Pre-desulf. SO_2 concentration = 50 $\mu g/m^3$ × Post-desulfurization period	2.721***	2.478***	2.752***	2.764***	2.948***	2.555***	2.760***
	(0.674)	(0.831)	(0.750)	(0.729)	(0.748)	(0.609)	(0.918)
Pre-desulf. SO_2 concentration = 60 $\mu g/m^3$ × Post-desulfurization period	1.776**	1.179	1.674**	1.558*	1.881**	2.136***	1.760**
	(0.877)	(1.077)	(0.789)	(0.847)	(0.865)	(0.792)	(0.892)
Adjusted R^2	0.168	0.142	0.154	0.139	0.177	0.240	0.140
Moran's Z							0.066
Observations	5,326	6,229	6,229	6,252	4,485	6,148	6,229

Notes: Table reports γ_j coefficients from Equation (2). All model specifications include constant, municipality, year and area by year fixed effects. In column (1) the baseline specification (2) is extended with the one-year-lagged unemployment rate in the municipality, in column (2) with SO_2 concentrations in the post-desulfurization period (with 5 $\mu g/m^3$ as the reference level), and in columns (3) and (4) with lagged interpolated values for age structure (shares of age groups 20–29, 30–39, 40–49, 50–59, and 60–69 on total population) and education structure (shares of secondary and teriary educated on the population aged 15+). Column (3) uses the nearest-neighbor interpolation, and column (4) the piece-wise linear interpolation of census-based covariates. In column (5) the estimation sample includes the city of Chomutov in the 60 $\mu g/m^3$ category, redefining this category as $\geq 60\,\mu g/m^3$. In column (6) the estimation sample is balanced by excluding municipalities for which migration records are missing. In column (7) municipality-year data-points within each year's top 1% emigration rate are excluded from the sample. Robust standard errors clustered by municipality are reported in parentheses: *, ** and *** denote statistical significance at 10%, 5% and 1%. The reference category for SO_2 concentration in the pre-desulfurization period is 30 $\mu g/m^3$.

5.2.4 Other robustness checks

In the next step, we run a number of further robustness checks and re-estimate regression (2) using differently specified samples. First, we include the only municipality with a pre-desulfurization SO_2 concentration of 70 μg/m^3 (the district capital Chomutov) into our data sample. We then define the category with the highest air pollution loads as municipalities with SO_2 concentration greater than or equal to 60 μg/m^3. Including the district capital in the sample somewhat lowers the estimated migratory responses in the category with the highest pre-desulfurization pollution concentrations, see column (4) of Table 4.

Next, we restrict our data sample to a balanced panel of municipalities and exclude municipalities for which migration records are missing. As can be seen from Table 4, column (5), balancing the panel has no impact on our results.

We then proceed to test the robustness of our results to the presence of potential outliers. These outliers may occur due to mine expansions (as in the case of the city of Most) or other unobserved factors such as natural disasters. To the best of our knowledge, there is no comprehensive database of such events that would enable us to control for them. In order to check that our results are not driven by such outliers, we re-estimate regression (2) using a sample without the top 1% observations for each year. As can be seen from Table 4, column (6), the estimated coefficients are similar and statistically significant, although slightly lower in magnitude by 0.2 to 0.4 p.p.

In our final robustness check, we adjust standard errors for spatial auto-correlation with a procedure suggested and implemented by Kelly (2020). Despite the Moran's Z-scores being below the indicative threshold of two, the spatial auto-correlation adjusted standard errors are larger than the robust clustered standard errors, see Table 4, column (7). The estimates for emigration and net migration rate remain statistically significant at 5% level. However, the inflation of the standard errors might be, especially in the case of emigration rate, driven by outliers than can distort the spatial adjustment (Kelly 2020). With the 5% largest residuals removed, the standard errors for the emigration rate only increase by up to 0.2 (see Table A.5 in the Appendix).

5.2.5 Placebo tests

In our main analysis, we treat the 1992–1999 desulfurization period as an event that triggered changes in residential migration. However, the identified effect could be caused by some other event that coincided with desulfurization. To exclude that possibility, we perform two placebo tests. Specifically, we split the true pre- and post-desulfurization periods into (a) placebo pre- (1983–1986,) and (b) placebo post-desulfurization (2008–2015 respectively)

Table 5: Placebo tests

	Dependent variable		
	Emigration rate (%)	Immigration rate (%)	Net migration rate (%)
	(1)	(2)	(3)
Panel A: Pre-desulfurization period (placebo cutoff at 1987)			
Pre-desulfurization SO_2 concentration = 40 $\mu g/m^3$	0.156	0.125	−0.032
× Placebo post-desulfurization period	(0.281)	(0.391)	(0.406)
Pre-desulfurization SO_2 concentration = 50 $\mu g/m^3$	0.062	−0.534	−0.596
× Placebo post-desulfurization period	(0.448)	(0.340)	(0.523)
Pre-desulfurization SO_2 concentration = 60 $\mu g/m^3$	−0.455	−0.489	−0.035
× Placebo post-desulfurization period	(0.340)	(0.331)	(0.467)
Adjusted R^2	0.579	0.344	0.502
Observations	1,413	1,413	1,413
Panel B: Post-desulfurization period (placebo cutoff at 2008)			
Pre-desulfurization SO_2 concentration = 40 $\mu g/m^3$	−0.046	−0.224	−0.178
× Placebo post-desulfurization period	(0.161)	(0.289)	(0.241)
Pre-desulfurization SO_2 concentration = 50 $\mu g/m^3$	−0.039	0.106	0.145
× Placebo post-desulfurization period	(0.211)	(0.486)	(0.495)
Pre-desulfurization SO_2 concentration = 60 $\mu g/m^3$	−0.167	−0.429	−0.263
× Placebo post-desulfurization period	(0.155)	(0.314)	(0.253)
Adjusted R^2	0.257	0.164	0.052
Observations	4,816	4,816	4,816

Notes: Table reports γ_j coefficients from Equation (2). All model specifications include constant, municipality and post-desulfurization fixed effects, and linear trends for each area and period. Robust standard errors clustered by municipality are reported in parentheses: *, ** and *** denote statistical significance at 10%, 5% and 1%. The reference category for SO_2 concentration is 30 $\mu g/m^3$.

periods and re-estimate regression (2) separately for each of those two "placebo" periods as if the desulfurization tech adoption had happened in 1986 with analysis limited to the years 1983–1989, or in 2006 with analysis limited to the years 2000–2015. The idea is that if we find that"placebo desulfurization" had any effect on migration, there would be reason to be suspicious about our main estimates. We present estimates from these placebo analyses in Table 5, with estimates for the 1983–1989 period shown in Panel A, and estimates for the 2000–2015 period shown in Panel B. As can be seen from the results, none of the placebo estimates are statistically significant, which supports the results of our main analysis presented above.

5.3 Factors shaping the migratory response to air pollution

5.3.1 The role of anti-emigration government policies

The baseline results in Table 3 suggest that higher pollution loads made staying in the given municipality less desirable, i.e., acted as a strong push factor. This effect could, however, have been partially affected by the government policies in place in the pre-desulfurization era, which were designed to keep workers in the area and may have compensated the disutility from air pollution.

Eligibility for anti-emigration benefits was determined by location and length of work. Only those who worked in municipalities in the basin districts for a period of more than 10 years were eligible for benefits in the form of an annual monetary transfer of 2,000 Czechoslovak crowns (i.e., 5.7% of the average annual wage in 1985). This monetary benefit was abolished in early 1992 along with the introduction of new environmental regulations.

To disentangle the role of these anti-emigration government policies from the effects of air pollution reduction on emigration, we utilize the fact that workers were eligible for these benefits in some of the municipalities in our sample (hereafter "qualifying municipalities"), whereas workers based in other municipalities were not eligible (hereafter "non-qualifying municipalities"). Figure 6 shows that the qualifying municipalities were clustered in a compact area within the northern part of North Bohemia. Eligibility was correlated with pollution load: all the municipalities in areas with initial SO_2 concentrations with 50 $\mu g/m^3$ and higher were eligible for benefits, whereas there was variation in eligibility among the less polluted municipalities. The share of qualifying municipalities in our estimation sample is 32% (n = 35) among the least polluted and 74% (n = 69) among municipalities with SO_2 concentrations equal to 40 $\mu g/m^3$.

To disentangle the effects of air pollution and anti-emigration benefits, we extend the baseline specification (2) to triple DID using eligibility for benefits as an additional dimension, yielding the following specification:

$$mig_{it} = \sum_j \gamma_j \mathrm{SO}_i p_t + \sum_j \delta_j \mathrm{SO}_i p_t b_i + \alpha p_t b_i + \sum_k \beta_k l_k + \theta_p + \theta_i + \varepsilon_{it} \tag{3}$$

where b_i is an indicator variable for qualifying municipalities. We estimate equation (3) on a sample limited to municipalities whose pre-desulfurization SO_2 concentrations were equal to or below 40 $\mu g/m^3$.

The results of our triple difference empirical specification are presented in column (1) of Table 6. As can be seen, the triple difference term is insignificant, suggesting that anti-emigration policies had no impact on emigration decisions.

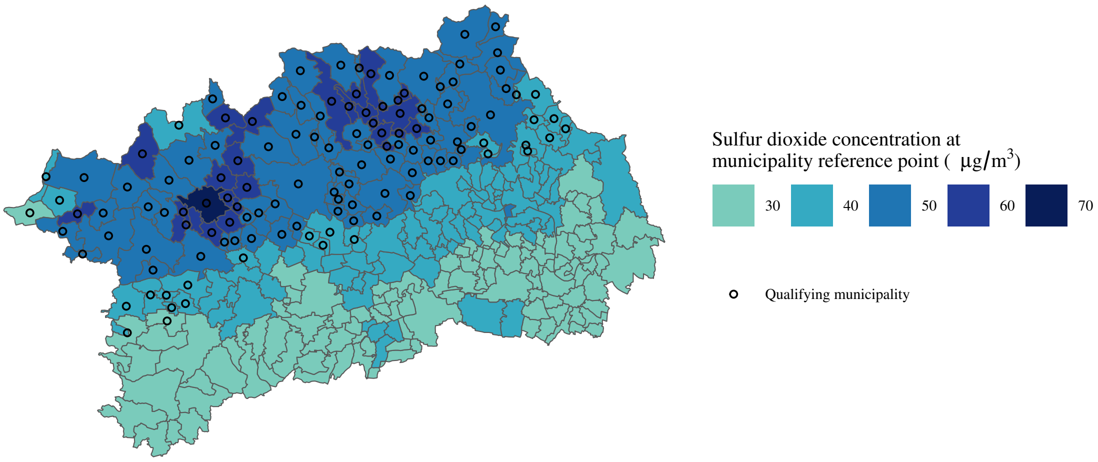


Figure 6: SO_2 concentrations in 1994 and qualifying municipalities in the pre-desulfurization period

Source: Czech Hydrometeorological Institute (CHMI), ArcČR 500 v3.3, see Section 3.

Table 6: Impact of monetary benefits on migratory response to air pollution

	Eligibility for benefits	
	Indicator variable	Treatment intensity
	(1)	(2)
Pre-desulfurization SO_2 concentration = 40 μg/m^3 × Eligibility for benefits × Post-desulfurization period	−1.138 (1.619)	−0.587 (1.933)
Pre-desulfurization SO_2 concentration = 40 μg/m^3 × Post-desulfurization period	−0.683** (0.314)	−0.583* (0.313)
Post-desulfurization period × Eligibility for benefits	0.500 (1.150)	−0.422 (1.346)
Adjusted R^2	0.245	0.245
Observations	4,007	4,007

Notes: Table reports γ_j coefficients from Equation (3) with the emigration rate as a dependent variable. All model specifications include constant, municipality and post-desulfurization fixed effects, and linear trends for each area and period. Robust standard errors clustered by municipality are reported in parentheses: *, ** and *** denote statistical significance at 10%, 5% and 1%. The reference category for SO_2 concentration is 30 μg/m^3.

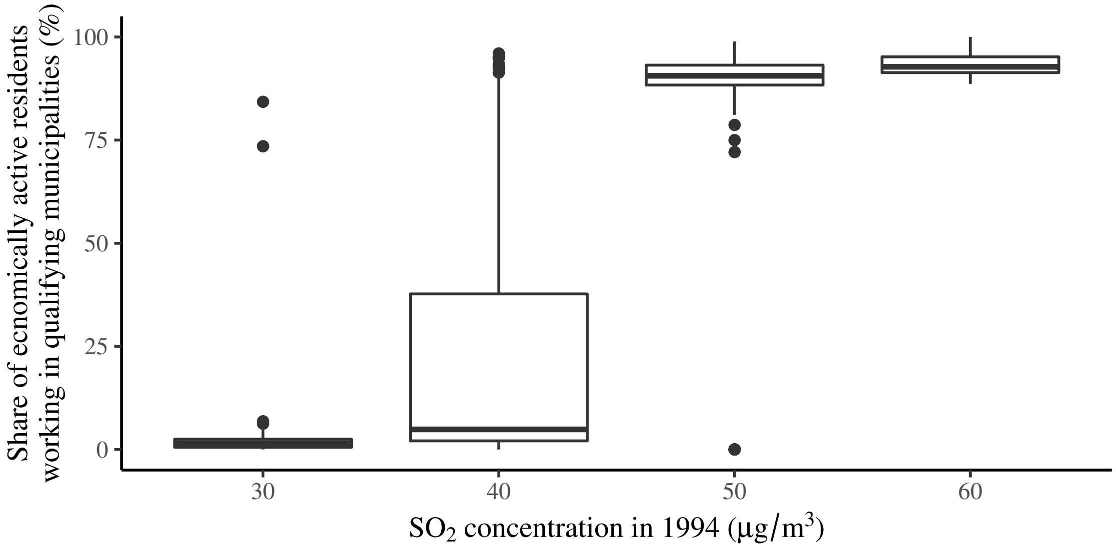
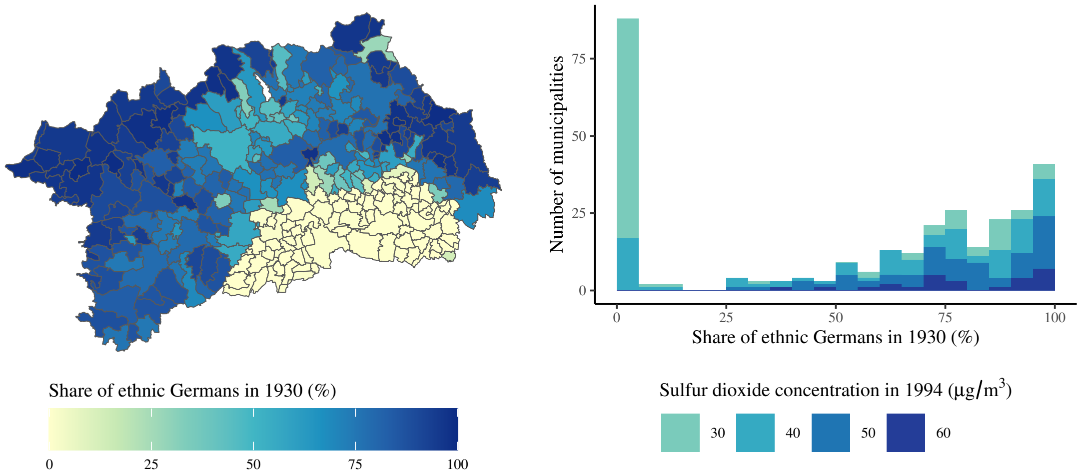


Figure 7: Share of population working in qualifying municipalities on economically active population (1991) by SO_2 concentration in municipality of residence (1994).

Workers' municipality of residence could, however, have been different from the municipality in which they worked, and it was the latter that in fact influenced the workers' eligibility for benefits. To account for potential distortions, we construct a continuous treatment intensity measure reflecting the importance of benefits for each municipality. For each municipality, we use 1991 census data to calculate the share of economically active residents working in municipalities eligible for benefits. Figure 7 shows minimum variation in the intensity measure across all groups of municipalities except those with pre-desulfurization SO_2 concentrations of $40\,\mu g/m^3$. This is not surprising, since those municipalities are typically located on the border between qualifying and non-qualifying areas (see Figure 6). This outcome suggests that the region's inhabitants commuted short distances (i.e., their municipalities of work and residence had similar levels of pollution).

In the next step, we re-estimate regression (3) with b_i being the treatment intensity measure in municipality i. The results are shown in column (2) in Table 6.

The triple difference term is statistically insignificant for both specifications. None of our results, therefore, indicates that benefits influenced the observed effect on the emigration rate.



(a) Spatial distribution of ethnic Germans in 1930

(b) Municipalities by share of ethnic Germans in 1930 and SO_2 concentration in 1994

Figure 8: Distribution of ethnic Germans in 1930

Source: Czech Hydrometeorological Institute (CHMI), ArcČR 500 v3.3, Guzi et al. (2021). For details see Section 3.

5.3.2 The role of social capital and attachment to local communities

Residents' migratory response to pollution depends on their willingness to suffer the negative amenity, and on their willingness to accept the utility loses related to emigration, such as the costs of leaving their familiar place, their family and friends. Greater attachment to their communities could increase residents' utility losses from migration, or migration costs, and should therefore decrease migratory responses to air pollution. To dig deeper into this link, we exploit another natural experiment offered by the history of the examined region.

North Bohemia was one of the regions of Czechoslovakia affected by the post-war expulsion of ethnic Germans (64% of the population of the region in 1930). The expulsion of ethnic Germans, who lived in ethnically well-segregated municipalities (see Figure 8), in turn allowed ethnic Czechs to come to the vacated municipalities, seize German properties, and settle there. However, these settlers had minimal ties to the region and among themselves.

As noted above, government propaganda sought at the time to build up a new regional identity based on coal and coal mining. Such an identity may have increased the inhabitants' tolerance to coal-related pollution. However, regional identity was not the only phenomenon missing in the resettled municipalities. The expulsion of the original residents had destroyed local social capital (i.e., social ties among municipal inhabitants) in the affected municipalities. Theoretical models developed by David et al. (2010), and

Bräuninger and Tolciu (2011) suggest that a negative shock to social capital, such as this one, could shift a municipality into a stable equilibrium characterized by lower levels of social capital and higher emigration.

Guzi et al. (2021) use municipality-level data for the Czech Republic for the period 1971–2015 to identify the persistent long-run effect of resettlement on residential migration. They find that the expulsion of ethnic Germans and subsequent resettlement increased emigration rates in most affected resettled municipalities (municipalities with a pre-war share of ethnic Germans above 90%) by 0.6–0.7 p.p. relative to comparable least affected municipalities (municipalities with a pre-war share of ethnic Germans below 10%) located nearby. Guzi et al. (2021) also suggest that lower social capital is the driving mechanism behind this causal effect. They document that the inhabitants of the resettled municipalities do not differ in terms of values or general pro-social behavior, but in terms of having less local social capital: they are less likely to be members of local clubs or to organize local public events.

Building on Guzi et al. (2021), we use the share of ethnic Germans from the last pre-war census held in 1930 as a proxy variable for the stock of local social capital. We note that in the case of North Bohemia, the variable could also capture the possible effect of propaganda-supported regional identity related to coal-mining. We assume that these effects should be in opposite directions. To test the impact of local social capital on the pollution-migration link, we split the sample by the cutoff of 50% of ethnic Germans in the local population in 1930 and re-estimate the regression (2) for both samples. The results reported in Table 7, columns (1) and (2), show that the migratory responses to air pollution are stronger in municipalities with less social capital, i.e., those formerly dominated by ethnic Germans (by 0.4 to 1.3 p.p.). This suggests that local social capital can compensate for the disutility caused by air pollution.

The chosen cutoff of 50% provides a sample of only a few municipalities on which to estimate the effect of higher levels of pollution in municipalities below the cutoff (six municipalities with pre-desulfurization SO_2 concentrations of $50\,\mu g/m^3$ and two municipalities with $60\,\mu g/m^3$, see Figure 8). In order to base our inference on a larger set of observations and to test the robustness of our findings, we define an alternative cutoff of 75%. This cutoff yields a sample of 29 municipalities with SO_2 concentrations of $50\,\mu g/m^3$ and 11 municipalities with $60\,\mu g/m^3$ below the cutoff of 75%. Table 7, columns (3) and (4) provide the results of our main estimation model (2) for municipalities below- and above- the threshold of a 75% share of ethnic Germans in 1930, respectively. The coefficients show similar pattern as in the first two columns defined using a 50% cutoff, and are in line with what we would expect; the effect of air pollution on emigration seems to be stronger in municipalities with weaker social capital.

Table 7: Impact of social capital on migratory response to air pollution

	Share of ethnic Germans in 1930			
	< 50%	≥ 50%	< 75%	≥ 75%
	(1)	(2)	(3)	(4)
Pre-desulfurization SO_2 concentration = 40 $\mu g/m^3$	−0.308	−1.572*	−0.555*	−1.534
× Post-desulfurization period	(0.326)	(0.806)	(0.323)	(1.009)
Pre-desulfurization SO_2 concentration = 50 $\mu g/m^3$	−1.163*	−2.120***	−0.902***	−2.373***
× Post-desulfurization period	(0.594)	(0.696)	(0.296)	(0.833)
Pre-desulfurization SO_2 concentration = 60 $\mu g/m^3$	−1.586**	−1.994**	−0.704**	−2.234**
× Post-desulfurization period	(0.635)	(0.788)	(0.352)	(1.049)
Adjusted R^2	0.170	0.340	0.264	0.342
Observations	2,207	3,999	3,469	2,737

Notes: Table reports γ_j coefficients from Equation (2). All model specifications include constant, municipality and post-desulfurization fixed effects, and linear trends for each area and period. Robust standard errors clustered by municipality are reported in parentheses: *, ** and *** denote statistical significance at 10%, 5% and 1%. The reference category for SO_2 concentration is 30 $\mu g/m^3$.

5.3.3 The role of man-made amenities

Like local social capital, the availability of man-made amenities, such as schools, libraries, health care facilities, sports stadiums, etc., could potentially mitigate the effect of air pollution on residential migration as it could make the municipalities more attractive to live in or move into. To investigate whether this factor shapes migratory responses to air pollution, we exploit the variation in man-made amenities availability in the region.

To measure the availability of man-made amenities at the municipal level, we use the number of facilities and utilities in each municipality using 1993 data collected by the Czech Statistical Office, CZSO.[28] We categorize man-made amenities into three groups: (a) Education, health and social care facilities (hospitals, retirement homes, etc.), (b) Culture and sports facilities (libraries, cinemas, football fields, etc.), and (c) Public administration facilities and public utilities (job centers, courts, etc.; sewerage, water supply system, etc.).[29]

The number of facilities and public utilities increases in population (with Spearman's ρ between 0.72 and 0.85). The availability of amenities is also correlated between amenity groups with Spearman's ρ between 0.67 and 0.75.

In the centrally planned socialist economy, man-made amenities could have been allocated to compensate for the air pollution. We cannot exclude this option. However,

28. The dataset does not contain information on the quality or capacity of the amenities. 1993 is the first iteration of the source database available. For a number of public administration facilities, data for 1993 is not available and we therefore use 1994 data.

29. For the full list of facilities, see Appendix Textbox A.2.

man-made amenity endowment is only weakly correlated with SO_2 concentration levels in the pre-desulfurization period (with Spearman's ρ between 0.06 and 0.24). Similarly, one could imagine that municipalities richer in local social capital could be able to lobby more efficiently and to obtain more (often government-funded) man-made amenities. However, the pre-war share of ethnic Germans is not correlated with the availability of man-made amenities (Spearman's ρ between 0.06 and 0.12).[30]

To assess the impact of man-made amenities on shaping migration response to air pollution, we split the estimation sample by median amenity availability in each amenity group and re-estimate regression (2) for all six resulting sub-samples.

Tables 8 and 9 provide the results for each amenity group and municipalities split into categories below- and above- the median for each amenity group. The tables differ according to how we calculate the amenities availability. In Table 8, we calculate the availability of man-made amenities as the sum of amenities located in the respective municipalities. In the alternative specification, presented in Table 9, we allow for residents making use of the man-made amenities located in nearby municipalities in addition to their municipality of residence. The alternative amenity availability measure is calculated as the sum of man-made amenities within a 20 km driving distance. The results estimated in the baseline and alternative specifications effectively set bounds for the estimates that would be obtained for man-made amenity availability calculated using weights decreasing in distance and leveling off at 0 for a distance greater than 20 km.

In general, these estimates are in line with our main results for the impact of air pollution reduction based on regression (2) model specification. However, the estimated effects tend to be larger in municipalities with below-median availability of man-made amenities. The same pattern holds for both man-made amenities measures. These results suggest that the availability of man-made amenities can compensate in part for the disutility caused by air pollution.

30. For descriptive statistics on the availability of man-made amenities see Appendix Table A.4.

Table 8: Man-made amenities in the municipality

	Dependent variable					
	Emigration rate (%)		Immigration rate (%)		Net migration rate (%)	
	Sample		Sample		Sample	
	Below median	Above median	Below median	Above median	Below median	Above median
	(1)	(2)	(3)	(4)	(5)	(6)
Panel A: Education and health facilities						
Pre-desulfurization SO_2 concentration = 40 μg/m^3	−1.716**	−0.332	−0.850	−0.320	0.866	0.012
× Post-desulfurization period	(0.853)	(0.272)	(0.673)	(0.351)	(1.026)	(0.384)
Pre-desulfurization SO_2 concentration = 50 μg/m^3	−2.637***	−0.629**	1.277*	0.279	3.915***	0.908**
× Post-desulfurization period	(0.812)	(0.277)	(0.746)	(0.355)	(1.049)	(0.454)
Pre-desulfurization SO_2 concentration = 60 μg/m^3	−1.196*	−1.544**	−1.006	0.549	0.191	2.093
× Post-desulfurization period	(0.697)	(0.751)	(0.996)	(0.748)	(1.126)	(1.353)
Adjusted R^2	0.333	0.404	0.140	0.193	0.166	0.203
Observations	3,168	3,061	3,168	3,061	3,168	3,061
Panel B: Culture and sports facilities						
Pre-desulfurization SO_2 concentration = 40 μg/m^3	−0.735	−0.648*	−0.441	−1.159**	0.295	−0.511
× Post-desulfurization period	(0.679)	(0.350)	(0.605)	(0.453)	(0.976)	(0.432)
Pre-desulfurization SO_2 concentration = 50 μg/m^3	−2.006***	−0.956**	1.848**	−0.347	3.854***	0.609
× Post-desulfurization period	(0.601)	(0.461)	(0.735)	(0.451)	(1.053)	(0.614)
Pre-desulfurization SO_2 concentration = 60 μg/m^3	−1.525**	−0.771	0.442	−1.471	1.968*	−0.699
× Post-desulfurization period	(0.619)	(0.508)	(0.676)	(0.897)	(1.063)	(1.070)
Adjusted R^2	0.356	0.306	0.146	0.154	0.169	0.118
Observations	3,960	2,269	3,960	2,269	3,960	2,269
Panel C: Public administration facilities and public utilities						
Pre-desulfurization SO_2 concentration = 40 μg/m^3	−0.735	−0.795**	−0.441	−0.723*	0.295	0.072
× Post-desulfurization period	(0.679)	(0.312)	(0.605)	(0.372)	(0.976)	(0.409)
Pre-desulfurization SO_2 concentration = 50 μg/m^3	−2.006***	−1.328***	1.848**	0.112	3.854***	1.440***
× Post-desulfurization period	(0.601)	(0.400)	(0.735)	(0.376)	(1.053)	(0.545)
Pre-desulfurization SO_2 concentration = 60 μg/m^3	−1.525**	−1.178***	0.442	−0.508	1.968*	0.670
× Post-desulfurization period	(0.619)	(0.357)	(0.676)	(0.562)	(1.063)	(0.664)
Adjusted R^2	0.356	0.324	0.146	0.184	0.169	0.164
Observations	3,960	2,919	3,960	2,919	3,960	2,919

Notes: Table reports γ_j coefficients from Equation (2). All model specifications include constant, municipality and post-desulfurization fixed effects, and linear trends for each area and period. Robust standard errors clustered by municipality are reported in parentheses: *, ** and *** denote statistical significance at 10%, 5% and 1%. The reference category for SO_2 concentration is 30 μg/m^3.

Table 9: Man-made amenities within a 20 km driving distance

	Dependent variable					
	Emigration rate (%)		Immigration rate (%)		Net migration rate (%)	
	Sample		Sample		Sample	
	Below median	Above median	Below median	Above median	Below median	Above median
	(1)	(2)	(3)	(4)	(5)	(6)
	Panel A: Education and health facilities					
Pre-desulfurization SO_2 concentration = 40 μg/m^3	−1.250*	−0.474	−0.432	−0.580	0.818	−0.106
× Post-desulfurization period	(0.648)	(0.309)	(0.525)	(0.479)	(0.895)	(0.502)
Pre-desulfurization SO_2 concentration = 50 μg/m^3	−1.521***	−1.580***	1.513**	0.066	3.034***	1.646**
× Post-desulfurization period	(0.545)	(0.569)	(0.679)	(0.470)	(0.898)	(0.779)
Pre-desulfurization SO_2 concentration = 60 μg/m^3	−2.996**	−0.869**	2.406**	−1.410**	5.402**	−0.541
× Post-desulfurization period	(1.259)	(0.407)	(1.086)	(0.659)	(2.144)	(0.763)
Adjusted R^2	0.390	0.292	0.179	0.132	0.176	0.133
Observations	3,118	3,111	3,118	3,111	3,118	3,111
	Panel B: Culture and sports facilities					
Pre-desulfurization SO_2 concentration = 40 μg/m^3	−1.448*	−0.400	−0.605	−0.520	0.843	−0.120
× Post-desulfurization period	(0.739)	(0.287)	(0.593)	(0.443)	(1.028)	(0.458)
Pre-desulfurization SO_2 concentration = 50 μg/m^3	−2.645***	−0.940***	2.390***	−0.305	5.035***	0.636
× Post-desulfurization period	(0.782)	(0.329)	(0.882)	(0.413)	(1.357)	(0.474)
Pre-desulfurization SO_2 concentration = 60 μg/m^3	−2.345**	−1.037**	1.204	−0.632	3.549**	0.405
× Post-desulfurization period	(0.952)	(0.404)	(1.109)	(0.432)	(1.783)	(0.501)
Adjusted R^2	0.380	0.242	0.139	0.150	0.154	0.133
Observations	3,149	3,080	3,149	3,080	3,149	3,080
	Panel C: Public administration facilities and public utilities					
Pre-desulfurization SO_2 concentration = 40 μg/m^3	−1.448*	−0.485	−0.605	−0.576	0.843	−0.092
× Post-desulfurization period	(0.739)	(0.321)	(0.593)	(0.449)	(1.028)	(0.507)
Pre-desulfurization SO_2 concentration = 50 μg/m^3	−2.645***	−1.812***	2.390***	0.416	5.035***	2.228**
× Post-desulfurization period	(0.782)	(0.627)	(0.882)	(0.478)	(1.357)	(0.874)
Pre-desulfurization SO_2 concentration = 60 μg/m^3	−2.345**	−1.124**	1.204	−0.385	3.549**	0.739
× Post-desulfurization period	(0.952)	(0.439)	(1.109)	(0.498)	(1.783)	(0.644)
Adjusted R^2	0.380	0.260	0.139	0.145	0.154	0.154
Observations	3,149	3,097	3,149	3,097	3,149	3,097

Notes: Table reports γ_j coefficients from Equation (2). All model specifications include constant, municipality and post-desulfurization fixed effects, and linear trends for each area and period. Robust standard errors clustered by municipality are reported in parentheses: *, ** and *** denote statistical significance at 10%, 5% and 1%. The reference category for SO_2 concentration is 30 μg/m^3.

6 Air pollution reduction and changes in population structure by education and age

We might expect heterogeneous migratory responses to pollution by education and age, since highly educated people may have better knowledge or understanding of the detrimental effects of air pollution on health and thus may be more sensitive to air pollution. Similarly, younger people might be more concerned about settling down and raising their children in environmentally polluted areas. If this is the case, we should expect air pollution to have a a larger impact on migration among the highly educated and younger age groups in the population. In the next step, we try to shed some light on these possible heterogeneous responses. Given that our data do not allow us to pin down individuals and their characteristics, nor numbers of migrants by education, age, etc., we make use of municipality-level census data on the educational and age structure of the municipal populations. We are interested in whether the reduction in air pollution had any effect on the changes in municipal populations' educational and age composition over time. To investigate that, we re-estimate regression (2) with demographic and educational structure measures as the dependent variables. In particular, we estimate this specification for each age category within the population (20–29, 30–39, 40–49, 50–59, 60–69) as a share of the total population and with the shares of primary, secondary, and tertiary educated inhabitants on the adult population (15 years and older).

The age structure and education data are available only from the decennial censuses held in 1980, 1991, 2001, 2011. We associate the 1980 and 1991 census years with the pre-desulfurization period and the 2001 and 2011 censuses with the post-desulfurization period.

The results, reported in Table 10, do not show any systematic statistically significant effect on age structure. However, results on education structure show a small positive, yet weakly significant, effect on the share of tertiary educated residents, supporting the hypothesis that more educated people tend to be more sensitive to air pollution in their settlement behavior.

Table 10: Impact of air pollution on age and education structure

	Dependent variable							
	Age structure (shares of age groups on total population, %)					Education structure (shares on 15+ population, %)		
	20–29	30–39	40–49	50–59	60–69	Primary	Secondary	Tertiary
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Pre-desulfurization SO_2 concentration = 40 $\mu g/m^3$	−0.404	−0.038	0.242	0.406	0.533	0.123	−0.658	0.352
	(0.313)	(0.343)	(0.344)	(0.387)	(0.348)	(0.809)	(0.795)	(0.265)
Pre-desulfurization SO_2 concentration = 50 $\mu g/m^3$	−0.474	0.042	0.206	0.058	0.805*	−0.251	−1.070	0.556**
	(0.353)	(0.338)	(0.387)	(0.430)	(0.463)	(0.850)	(0.872)	(0.280)
Pre-desulfurization SO_2 concentration = 60 $\mu g/m^3$	−0.468	−0.220	0.807	0.313	−0.244	−0.484	−0.069	0.732**
	(0.579)	(0.552)	(0.494)	(0.404)	(0.515)	(1.148)	(1.116)	(0.350)
Adjusted R^2	0.378	0.264	0.321	0.266	0.414	0.913	0.872	0.713
Observations	1,204	1,204	1,204	1,204	1,204	1,204	1,204	1,204

Notes: Table reports γ_j coefficients from Equation (3). All model specifications include municipality, year and area by year fixed effects. Robust standard errors clustered by municipality are reported in parentheses: *, ** and *** denote statistical significance at 10%, 5% and 1%. The reference category for SO_2 concentration is 30 $\mu g/m^3$.

7 Conclusions

Using a unique natural experiment resulting from the implementation of modern technology in power plants that vastly reduced air pollution, in this paper we have examined the effect of air pollution on migratory behavior.

In particular, we have looked at residential migration rates for municipalities in the North Bohemian region of the Czech Republic that previously suffered from extreme pollution levels. In order to examine the causal effects of air pollution on migration, we exploit the fact that between 1992 and 1999, Czech power plants were required by law to install modern desulfurization technologies. This led to a massive reduction in SO_2 concentrations in the air in the area to levels below the relevant EU/WHO limits.

Our results, based on a difference-in-difference estimator, show that the reduction in SO_2 concentrations had a negative effect on emigration. This effect is large and statistically significant: emigration rates from initially highly polluted municipalities were 24% lower after the desulfurization technologies were adopted, compared to the least polluted baseline group of municipalities. Further, the effects of air pollution on emigration seem to be non-linear: the effect effect is about twice as large in municipalities that initially suffered extreme SO_2 pollution levels (50 and 60 $\mu g/m^3$ of SO_2) as it is in municipalities with an initial pollution load of 40 $\mu g/m^3$. The effect on net migration is also enormous: the adoption of desulfurization technology led to an increase by 1.7 p.p. in net migration in the initially highly polluted municipalities, which corresponds to an approx. 78% increase in net migration rate compared to the baseline group of the least polluted municipalities. This suggest that the extreme polluted areas became more attractive to live in after the air became cleaner. Our main results are supported by a number of robustness checks and placebo tests.

Furthermore, we have dug deeper into additional factors that might possibly have influenced migration in the focus period. In our analysis, we have found that anti-emigration policies in the form of benefits did not affect the air pollution – migration relationship. However, the results show also that the effect of air pollution on migration tend to be stronger in municipalities with weaker local social capital and relatively few man-made amenities and facilities. Finally, we have also found some evidence that more educated people tend to be more sensitive to air pollution in their settlement behaviour.

To sum up, in this paper we have presented novel evidence of environmental pollution acting as a strong push factor for migration. The push effect does not seem to be counteracted by the existence of anti-emigration economic benefits provided by the government, whereas the migratory response to air pollution does seems to be counteracted to some extent by the existence of strong local social capital and the availability of man-made city amenities. Overall, policies aiming to prevent regional de-population should support initiatives to clean up the region's environments and to establish stronger social capital and man-made amenities.

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A Appendix

A.1 Additional Figures and Tables

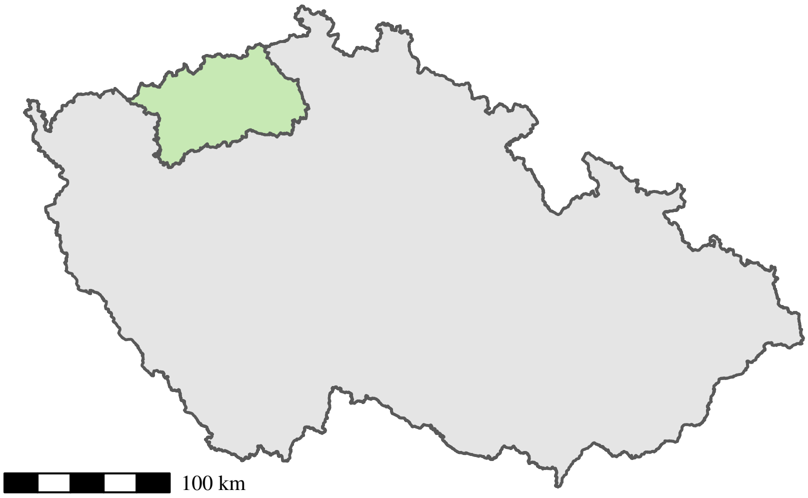

Figure A.1: Location of the region in the Czech Republic

Source: ArcČR 500 v3.3

Table A.1: Lignite-burning power plants in North Bohemia

Power plant	Construction	Desulfurization
Komořany	1951–1964	1993–1999
Ledvice	1967	1996–1998
Počerady I and Počerady II	1970–1977	1994–1996
Prunéřov	1967–1968 (second unit 1981-1982)	1995–1996
Tušimice I and Tušimice II	1963–1967 (second unit 1974–1975)	1994–1997
Litvínov T200 and T700	1942–1958	1996

Source: Power plant owners ČEZ (https://www.cez.cz/cs/vyroba-elektriny/uhelne-elektrarny/cr.html), and United Energy (https://www.ue.cz/historie-a-soucasnost). Last accessed January 30, 2019.

(a) Most in 1964 (b) Most in 1987

Figure A.2: Effect of mining on city of Most

Source: Collection of historical orthophotos available at https://mapy.mesto-most.cz/portal/WAB?cfg=most-do-minulosti (last accessed on September 4, 2019).

Table A.2: Descriptive statistics: Population structure

	Year	Municipalities in estimation sample				
		All	By SO_2 concentration (1994)			
			30 μg/m^3	40 μg/m^3	50 μg/m^3	60 μg/m^3
		(1)	(2)	(3)	(4)	(5)
Share of 20-29 age group (%)	1980	14.37	13.78	14.59	14.96	14.37
		(0.16)	(0.27)	(0.29)	(0.27)	(0.53)
	1991	11.68	11.68	11.67	11.89	11.19
		(0.16)	(0.26)	(0.28)	(0.31)	(0.67)
	2001	16.61	16.64	16.64	16.74	16.08
		(0.15)	(0.27)	(0.26)	(0.30)	(0.55)
	2011	11.98	11.94	11.93	12.25	11.61
		(0.17)	(0.25)	(0.33)	(0.35)	(0.49)
Share of 30-39 age group (%)	1980	13.75	13.08	13.91	14.28	14.50
		(0.16)	(0.24)	(0.31)	(0.30)	(0.53)
	1991	13.44	13.21	13.31	13.68	14.18
		(0.15)	(0.25)	(0.27)	(0.29)	(0.42)
	2001	12.29	11.91	12.30	12.64	12.83
		(0.13)	(0.22)	(0.27)	(0.25)	(0.39)
	2011	16.65	16.18	16.66	17.17	17.19
		(0.16)	(0.28)	(0.32)	(0.30)	(0.47)
Share of 40-49 age group (%)	1980	10.38	10.16	10.22	10.76	10.78
		(0.12)	(0.21)	(0.20)	(0.25)	(0.27)
	1991	15.21	14.66	15.34	15.61	15.85
		(0.18)	(0.27)	(0.38)	(0.38)	(0.44)
	2001	14.57	14.08	14.46	15.01	15.73
		(0.14)	(0.23)	(0.24)	(0.28)	(0.50)
	2011	13.33	12.70	13.46	13.71	14.33
		(0.14)	(0.21)	(0.31)	(0.26)	(0.26)
Share of 50-59 age group (%)	1980	12.58	12.87	12.12	12.56	13.12
		(0.15)	(0.25)	(0.26)	(0.30)	(0.39)
	1991	10.79	10.71	10.68	10.99	10.88
		(0.14)	(0.23)	(0.24)	(0.31)	(0.34)
	2001	15.13	14.85	15.05	15.38	15.80
		(0.19)	(0.28)	(0.36)	(0.45)	(0.46)
	2011	14.34	14.46	14.24	14.14	14.67
		(0.15)	(0.29)	(0.29)	(0.24)	(0.42)
Share of 60-69 age group (%)	1980	9.19	10.00	9.12	7.99	9.37
		(0.15)	(0.25)	(0.24)	(0.30)	(0.41)
	1991	11.31	12.02	11.08	10.64	11.06
		(0.19)	(0.33)	(0.36)	(0.41)	(0.40)
	2001	9.18	9.55	9.25	8.71	8.68
		(0.13)	(0.21)	(0.23)	(0.31)	(0.27)
	2011	13.49	13.94	13.43	13.13	12.87
		(0.18)	(0.26)	(0.32)	(0.48)	(0.38)
Share of 70-79 age group (%)	1980	9.68	11.91	9.19	7.67	7.85
		(0.23)	(0.43)	(0.35)	(0.32)	(0.50)
	1991	8.61	10.11	8.57	6.74	7.83
		(0.20)	(0.39)	(0.30)	(0.29)	(0.42)
	2011	8.75	9.80	9.04	7.18	7.85
		(0.17)	(0.25)	(0.35)	(0.26)	(0.42)
Municipalities (n)		301	108	93	73	27

Notes: Table reports means and robust standard errors clustered by municipality in parentheses. Differences are tested for statistical significance: *, ** and *** denote statistical significance at 10%, 5% and 1%.

Table A.3: Descriptive statistics: Education

	Year	Municipalities in estimation sample				
		All	By SO_2 concentration (1994)			
			30 μg/m^3	40 μg/m^3	50 μg/m^3	60 μg/m^3
		(1)	(2)	(3)	(4)	(5)
Share of primary educated (%)	1980	59.77	59.38	59.26	60.86	60.14
		(0.47)	(0.79)	(0.88)	(1.00)	(1.26)
	1991	47.72	46.94	48.94	47.61	46.90
		(0.45)	(0.75)	(0.88)	(0.90)	(1.19)
	2001	32.43	31.74	33.03	32.97	31.73
		(0.37)	(0.66)	(0.70)	(0.73)	(0.80)
	2011	23.65	23.30	24.11	23.78	23.13
		(0.31)	(0.51)	(0.60)	(0.61)	(0.70)
Share of secondary educated (%)	1980	37.59	38.06	38.15	36.64	36.37
		(0.45)	(0.75)	(0.80)	(0.94)	(1.24)
	1991	49.43	50.57	48.27	49.05	49.85
		(0.42)	(0.69)	(0.80)	(0.80)	(1.10)
	2001	62.76	63.86	62.21	61.93	62.47
		(0.34)	(0.55)	(0.66)	(0.64)	(0.89)
	2011	64.17	65.69	63.80	62.38	64.25
		(0.31)	(0.47)	(0.57)	(0.66)	(0.80)
Share of tertiary educated (%)	1980	1.32	1.38	1.32	1.29	1.17
		(0.07)	(0.12)	(0.13)	(0.15)	(0.19)
	1991	1.82	1.98	1.77	1.72	1.68
		(0.09)	(0.16)	(0.17)	(0.17)	(0.24)
	2001	2.99	2.94	3.02	3.03	2.99
		(0.10)	(0.17)	(0.20)	(0.21)	(0.32)
	2011	5.86	5.48	5.89	6.15	6.42
		(0.17)	(0.28)	(0.32)	(0.34)	(0.46)
Municipalities (n)		301	108	93	73	27

Notes: Table reports means and robust standard errors clustered by municipality in parentheses. Differences are tested for statistical significance: *, ** and *** denote statistical significance at 10%, 5% and 1%.

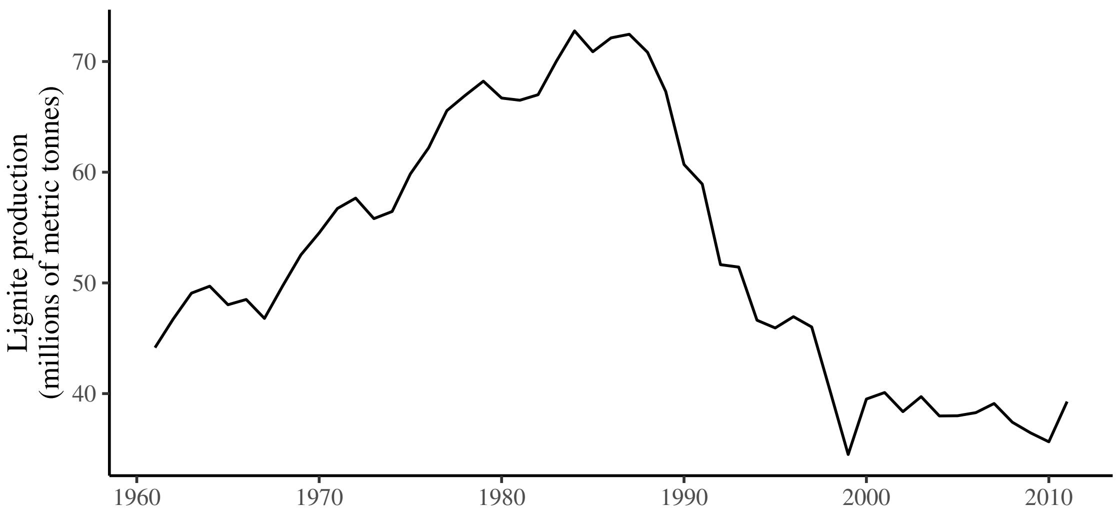

Figure A.3: Lignite mining in North Bohemia

Table A.4: Descriptive statistics: Man-made amenities

Man-made amenities	Year	Municipalities in estimation sample				
		All	By SO_2 concentration (1994)			
			30 $\mu g/m^3$	40 $\mu g/m^3$	50 $\mu g/m^3$	60 $\mu g/m^3$
		(1)	(2)	(3)	(4)	(5)
Education and health facilities in the municipality (n)	1993	5.24	2.72	4.67	8.97	7.19
		(0.95)	(0.64)	(1.42)	(3.06)	(3.57)
Education and health facilities within 20 km driving distance (n)	1993	139.76	120.50	128.19	168.88	177.89
		(5.61)	(8.24)	(9.36)	(12.87)	(19.99)
Culture and sports facilities in the municipality (n)	1993	5.70	3.44	4.28	11.42	4.11
		(1.07)	(0.38)	(0.85)	(4.14)	(1.29)
Culture and sports facilities 20 km driving distance (n)	1993	142.72	141.17	126.48	159.26	160.11
		(6.45)	(9.10)	(9.79)	(16.27)	(27.77)
Public administration and utilities in the municipality (n)	1993	6.52	5.67	6.53	7.25	7.96
		(0.21)	(0.30)	(0.35)	(0.50)	(0.63)
Public administration and utilities within 20 km driving distance (n)	1993	184.37	208.27	181.55	164.41	152.44
		(6.14)	(10.66)	(10.41)	(12.47)	(18.00)
Municipalities (n)		301	108	93	73	27

Notes: Table reports means and robust standard errors clustered by municipality in parentheses. Differences are tested for statistical significance: *, ** and *** denote statistical significance at 10%, 5% and 1%.

Table A.5: DID results with standard errors adjusted for spatial auto-correlation

	Dependent variable		
	Emigration rate (‰)	Immigration rate (‰)	Net migration rate (‰)
	(1)	(2)	(3)
Pre-desulfurization SO_2 concentration = 40 $\mu g/m^3$ × Post-desulfurization period	-0.879^{**}	-0.533	0.346
	(0.374)	(0.490)	(0.568)
Pre-desulfurization SO_2 concentration = 50 $\mu g/m^3$ × Post-desulfurization period	-1.700^{***}	1.061	2.760^{***}
	(0.636)	(0.670)	(0.858)
Pre-desulfurization SO_2 concentration = 60 $\mu g/m^3$ × Post-desulfurization period	-1.588^{**}	0.171	1.760^{**}
	(0.635)	(0.623)	(0.852)

Notes: Table reports γ_j coefficients from Equation (2). All model specifications include constant, municipality and post-desulfurization fixed effects, and linear trends for each area and period. Moran's Z is calculated using residuals from Equation (2) with spatial spatial weights set to 0.2 for five closest municipalities. Standard errors adjusted for spatial auto-correlation by procedure suggested by Kelly (2020) are reported in parentheses: *, ** and *** denote statistical significance at 10%, 5% and 1%. Adjusted standard errors were calculated using Matern kernel with smoothing parameter $\kappa \in \{0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, 1\}$. Residuals with absolute value larger than 5 are excluded from the calculation of spatial autocorrelation adjusted standard errors. Results that minimize log likelihood function are reported. The reference category for SO_2 concentration is 30 $\mu g/m^3$.

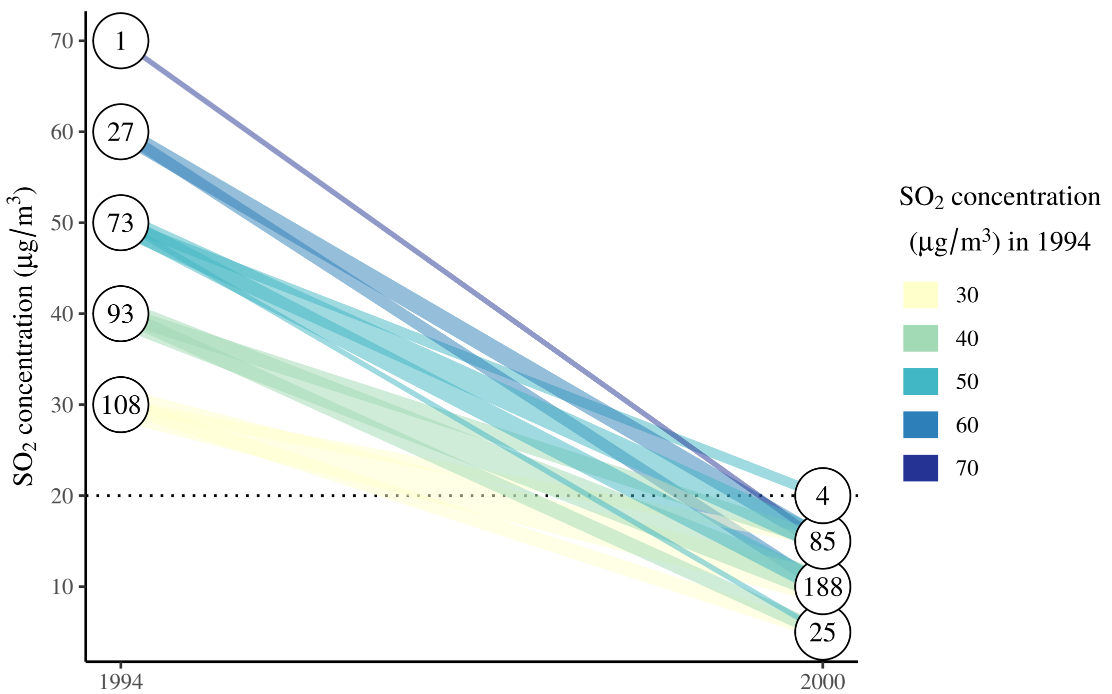

Figure A.4: SO_2 concentration in 1994 and 2000

Textbox A.1: Pro-immigration and anti-emigration measures

- The government provided house-building subsidies for newcomers in order to attract people into the region. These subsidies had a maximum value of 65,000 Czechoslovak crowns (CSK) (186% of the average annual wage in 1985). Highly-skilled professionals were also given preferential access to public housing.
- Enterprises also often paid recruitment benefits of up to 10,000 CSK (29% of the average annual wage in 1985).
- The government granted special benefits for medical doctors and pharmacists (see act of the government No. 37/1984): a recruitment benefit of 10,000 CSK to those who promised to stay in the area for at least five years, a 10,000 pay rise for high performers not available elsewhere, and special stipends for those who agreed to stay for at least six years.
- Those who had worked in the basin districts for at least 10 years were eligible for a monetary benefit of 2,000 CSK per year (5.7% of the average annual wage in 1985).
- The government limited the mobility of highly-qualified workers (medical doctors, pharmacists, teachers, and selected technical professions) from the region. Vaněk (1996) states that professionals who tried to move out of the area found themselves unable to find jobs or housing in their destination region. Vaněk (1996) claims that this policy was executed on an informal basis from the beginning of the 1980s. In 1984 the policy was incorporated into Act No. 37/1984 (only for medical doctors and pharmacists). That regulation was abolished (both *de facto* and *de iure*) in 1986.
- The authorities did not inform the public about the health risks or pollutant concentrations, although in the late 1980s, a limited warning system was implemented (e.g., yellow flags or signs were mounted on public transport vehicles during temperature inversions).
- The government provided free or heavily subsidized short-term (holiday) accommodation in clean mountain areas to children during temperature inversions.

Textbox A.2: Man-made amenities by group

- **Education, health and social care facilities:** Adult protective service facilities; Community health centers; Emergency medical service facilities; Hospitals; Child protective service facilities; Kindergartens; Language schools; Primary and secondary schools; Retirement homes; Spas; Universities; Vocational education institutes.
- **Culture and sports facilities:** Amphitheatres (natural); Athletic fields; Cinemas; Free time centers (for children); Galleries; Gyms; Museums; Other sport facilities; Public libraries; Sports stadiums; Swimming pools; Theaters; Zoos (animal parks).
- **Public administration facilities and public utilities:** Courts and legal system facilities; Firefighting squads; Firefighting facilities; Gas supply networks; Job centers; Other offices; Police stations; Post offices; Urban planning offices; Waste management facilities; Watter supply networks.

B Parallel trends in pre-treatment period

The difference-in-differences framework used in the main part of the paper assumes the presence of parallel trends in the pre-treatment period. In this part of the paper we test this assumption by estimating the following regression:

$$mig_{it} = \sum_j \gamma_{jt} \mathrm{SO}_i \theta_t + \theta_i + \xi_{it} \tag{4}$$

where air pollution level category (SO) is interacted with year fixed effects (θ_t), and the year 1989 is used as a reference. The rest of the notation is identical to (2). We estimate regression (4) on a sub-sample limited to the pre-treatment period. Point estimates with 95% confidence intervals (calculated using robust standard errors clustered by municipality) are reported in Figures B.5, B.6, and B.7. The results suggest that the parallel trends assumption holds. Only the estimate of γ for immigration rate in 40 μg/m^3 category in 1987 is significant at 5% level.

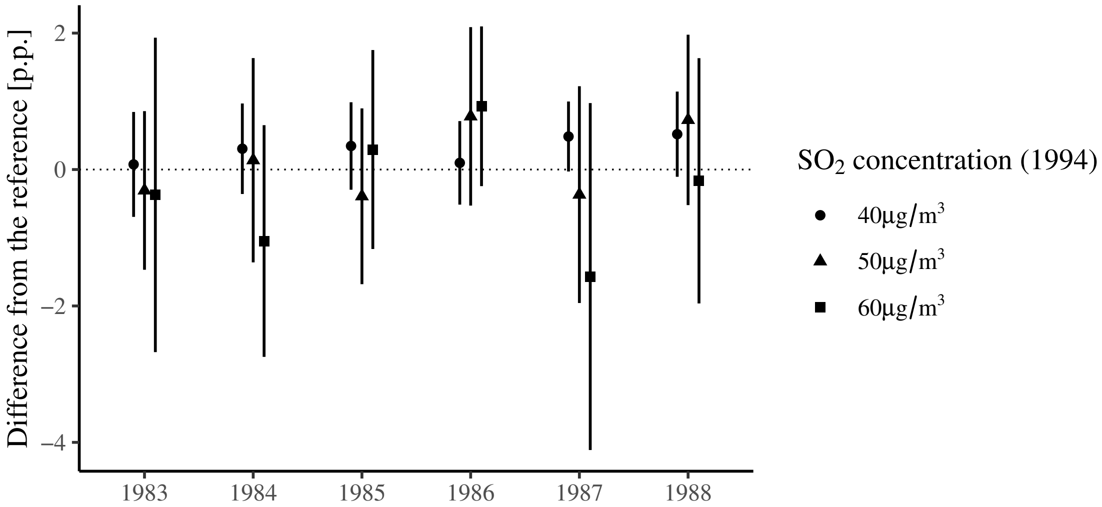

Figure B.5: Parallel trend assumption test (emigration rate)

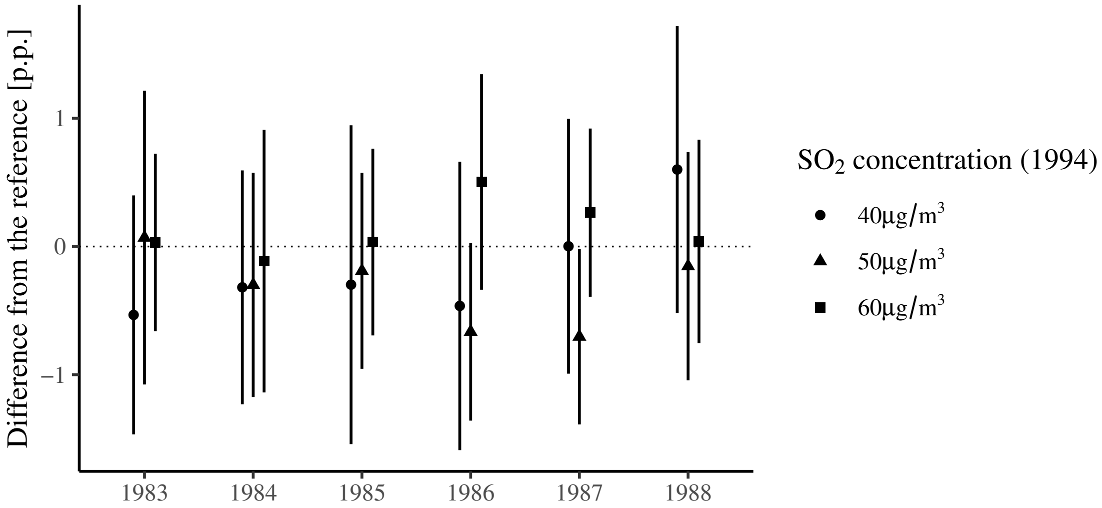

Figure B.6: Parallel trend assumption test (immigration rate)

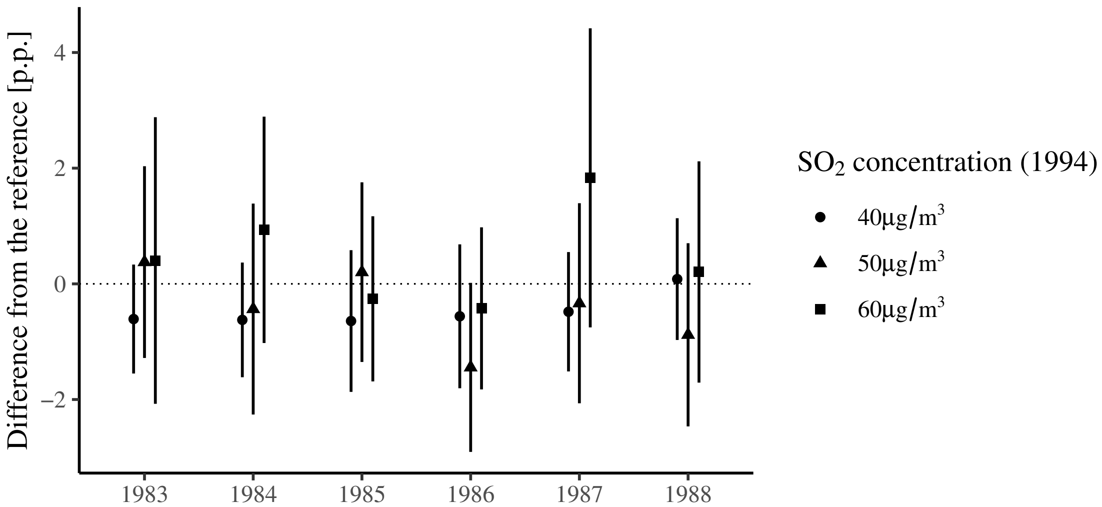

Figure B.7: Parallel trend assumption test (net migration rate)