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

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Air Pollution and Migration – exploiting a natural experiment from the Czech Republic*

BY ŠTĚPÁN MIKULA AND MARIOLA PYTLIKOVÁ

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ABSTRACT

This paper examines causal effects of air pollution on migration by exploiting a unique natural experiment of desulfurization of power plants in the region of North Bohemia in the Czech Republic after the fall of communism in 1989. The results based on a difference-in-difference estimator show that the estimated effect of reduction in sulfur dioxide (SO₂) concentrations on emigration is negative and statistically significant. The effect is sizable: we find that the large reduction in air pollution due to the technology adoption decreased emigration rates from polluted municipalities by approx. 24%. The effect is non-linear in the sense that the effect is much larger for municipalities with highest pollution levels prior the desulfurization. Thus, our results suggest that high air pollution loads in the pre-desulfurization period made staying in municipality significantly less desirable, i.e., acted as a strong push factor. All the above results are validated in numerous robustness checks and supported by zero effects from placebo tests. Besides, we explore other historical experimental settings, which allow us to separate out the interplay of possible mechanisms, such as the role of economic benefits, social capital and man-made amenities. All of those channels are otherwise hard to disentangle. Our results based on a triple difference estimator show that the anti-emigration policies had no impact on emigration decisions, whereas we find that the effect of air pollution on emigration tended to be stronger in municipalities with weaker social capital and in municipalities less equipped with man-made amenities. These results suggest that strengthening social capital as well as investing into better facilities in the area of education, health and social care, as well as facilities promoting sport and cultural activities, can partially mitigate the migratory response to air pollution.

JEL Classification: Q53, J61, O15 **Keywords:** Air pollution, migration, natural experiment.

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1. INTRODUCTION

There is consensus that air pollution is harmful to human health and that it affects infant and adult mortality, based on evidence from a rich array of studies (see for instance Graff Zivin and Neidell, 2013; Currie and Neidell, 2005; Currie, Neidell and Schmeider 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 Reed Walker, 2016; among others). Recent growing literature documents detrimental impacts of air pollution in the range of socio-economic outcomes such as: health expenditures, labor supply, hours worked (Hanna and Oliva, 2015; Aragon et al., 2017), long-run earnings (Isen, Rosin-Slater and Walker, 2017), labor productivity (Graff Zivin and Neidell, 2012; Chang et al., 2019; He et al. 2019), education outcomes such as reduction in test scores, increased school absences (Currie et al. 2009; Liu and Salvo, 2017, etc.), long-term human capital accumulation (Graff Zivin and Neidel 2013; Bharadwaj et al, 2017), and cognition (Bishop et al. 2018). Given those serious adverse effects of exposure to air pollution, one would expect that people prefer to live and raise their children in environmentally clean areas, and thus move out from polluted areas. Yet, the literature investigating the role of environmental pollution in migratory behavior¹ is almost non-existent.

To the best of our knowledge, there exist only two recent studies studying the link between air pollution and migration. Specifically, Xu and Silvester (2016) examined a relationship between air pollution (approximated by PM_{2.5}) 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 of Sub-Saharan Africa and Eastern Europe. This study however was not able to identify causal effects of air pollution on migration. This is problematic, as it is difficult to separate out the effect of pollution from the economic opportunities² that might be correlated with polluted areas. The study by Chen et al (2017) tries to overcome the empirical

¹ Although the environmental migration receives growing attention in media, the research-based evidence is still rather limited and tends to focus on the role of climate change, climate variability or natural disasters on migration, such as on impacts of temperature and precipitation variability, extreme weather events, droughts, environmental degradation, crop failure on emigration (see e.g. 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). The evidence on the role of environmental pollution in migration is almost non-existent, even though the pollution could potentially act as an important push migration factor.

² Economic factors, such as wages and employment, are known to be among main drivers of migration (Sjastaad, 1962; Clark et al., 2007; Pedersen et al, 2008; Mayda, 2010; Ortega and Peri, 2013; Fidrmuc, 2004, and others).

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. Results of their analyses show that air pollution is responsible for large changes in migration inflows and outflows in regions in China.

In this paper, we contribute to the under-research area with analyses of causal impacts of extreme air pollution levels on emigration by utilizing a natural experiment of desulfurization of power plants in the region municipalities in the region of North Bohemia in the Czech Republic. The North Bohemian region is characterized by large lignite resources that encouraged construction of multiple power plants within the area throughout the history of the region. The sulfur-rich lignite-burning power plants were responsible for high-emissions of sulfur dioxide (SO₂), which resulted in enormous SO₂ pollution levels in the area. In order to underpin causal effects of air pollution on migration we exploit a natural experiment that arose from the fact that in years 1992 to 1998 the Czech power plants had to comply with an obligation set by law to install modern desulfurization technologies, which consequently led to a substantial drop in the emitted pollution, but per se did not affect economic activity in the region. The technology adoption led to a rapid decrease in levels of SO₂ concentrations in the affected areas. In fact, the reduction in SO₂ emissions in the Czech Republic was one of the most dramatic historical examples of pollution reduction in Europe ever (Vestreng et al, 2007).

The results based on a difference-in-difference estimator show that the estimated effect of reduction in SO₂ concentrations on emigration has the expected negative sign and it is statistically significant. The effect is large, causing on average 27% decrease in emigration rates from polluted municipalities after the desulfurization technologies were adopted. Further, we find the effects on emigration to be non-linear in the sense that the effect is much larger for municipalities that initially suffered heavy SO₂ levels (annual mean concentration 50 and 60 µg/m³) with a size of almost twice as large compared to municipalities that suffered lower pollution (40 µg/m³). All the above results are validated by numerous robustness checks and by placebo tests.

What's more, in our analyses, we dig deeper into possible mechanisms via which the effect of air pollution on migration might be affected. 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. For that, we exploit additional natural experiment and other historical set-ups to study channels that are otherwise hard to disentangle. Our results based on a triple difference estimator show that that anti-emigration policies

had no impact on emigration decisions. Further, we find that the effect of air pollution on emigration was far stronger in municipalities with weaker local social capital and in municipalities with poorer facilities in terms of education, health, social care, culture and sport. The results thus imply that the burden of air pollution may be partly compensated by local social capital and man-made amenities.

2. Experimental setup: History

The communist regime in the Czech Republic³ (1948–1989), similarly to its Eastern European counterparts, pushed for massive industrialization with energy-hungry heavy industry becoming a new center of the economy. The energy needs of industrialization were supposed to be fed by utilization of large lignite deposits in the North Bohemian region (see Figure 1).⁴ To reduce transportation costs, new lignite-burning power plants (see Appendix Table A.1) were built adjacent to mines, often close to large cities, and with little attention being paid to the well-being of locals. The priority of energy production was so high that the government even moved a large historical part of city of Most (a district capital) to allow mines to expand (see Figure 2, for details see e.g., Spurný 2016).

{Figure 1 around here}

{Figure 2 around here}

The power plants were consuming about 2/3 of the lignite production (Vaněk 1996), the rest was often used in heat-production plants and home furnaces. Widespread use of sulfur-rich lignite resulted in high emissions of sulfur dioxide – a typical pollutant emitted by lignite burning. High concentration of power plants and the mountains surrounding the basin (see Figure 3) limited the dispersion of unfiltered emissions and therefore further scaled up the SO₂ concentrations in the region.

{Figure 3 around here}

Figure 4 shows the long-term development of sulfur dioxide concentrations in the worst polluted districts (“*okres*”) of Teplice, Most, and Chomutov from 1970 on (see Section 3 for details on data). The concentration levels were remarkably stable from the beginning of the 1970s to the early 1990s.

³ The Czech Republic was a part of Czechoslovakia from 1918 to 1993.

⁴ We define the North Bohemian region as administrative districts (“*okres*”) of Chomutov, Most, Teplice, Ústí nad Labem, Louny, and Litoměřice.

The annual mean SO₂ concentration reached 80µg/m³ in 1970s and 89µg/m³ in 1980s surpassing even Beijing's average level of 71 µg/m³ in 2000 (UNEP 2007) and exceeding more than four times the level of 20µg/m³, which is the EU annual limit (EU 2015) and World Health Organization (WHO) guideline for maximum 24-hours exposition (WHO 2006).⁵ Winter peak SO₂ concentrations were even higher. For example, Pinto et al. (1998) compare the SO₂ concentrations in Teplice in 1993 (1600 µg/m³) to the London smog episode from December 1952, where concentrations reached 1800 µg/m³.

{Figure 4 around here}

High concentrations of pollution caused rapid deterioration of the environment. Several papers have studied the impact of air pollution on the population of North Bohemia. For example, Kotěšovec et al. (2001) analyze mortality data from 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 the association between particulate matter concentration and a higher risk of intrauterine growth retardation.

The Czechoslovak communist government was aware of the environmental problems and their impact on public health since the early 1960s (Glassheim 2006, Vaněk 1996). However, they did not take any action. The reduction in pollution via a decrease in energy production was not an option as there were no alternative power sources and planned production grew steadily through 1960s and 1970s (Glassheim 2006). The reduction of energy production and resulting reduction in mining activity could also be perceived unfavorably by miners (i.e. a prominent part of the “*working class*”) and the communist government was not willing to take the risk (Vaněk 1996). The technical means of desulfurization were also unreachable to the government as the available Soviet desulfurization technology was untested and not suitable for the Czech power plants (Kratochvíl 2011), whereas an import of western technology was too expensive for a country struggling with the permanent lack of convertible currency (Vaněk 1996). Glassheim (2006) also hypothesizes that government had only a little interest in pollution reduction as North Bohemia was treated by the central government as “*an experiment*” with a goal to produce as much energy as possible with holding costs on minimum.

5 WHO does not set an annual guideline because “*compliance with the 24-hour level will assure low annual average levels*” (WHO 2006).

The pollution imposed a considerable burden on locals. Nevertheless, they were willing to bear it – at least to some degree. Glassheim (2006) puts their attitude into the context of the post-World War II resettlement of the region. The area of the region was originally populated by ethnic Germans, who were, however, forcibly expelled from the country in the aftermath of the war.⁶ The emptied municipalities were resettled by inhabitants mostly from inland regions of today’s Czech Republic with little or no tie to the region (see Guzi et al. 2019 for details on resettlement process). Glassheim (2006) claims, that coal and coal mining, became, with the help of the communist government propaganda, pillars of the newly established regional identity. Such an identity could increase the willingness of locals to bear the environmental burden caused by coal mining and burning. Despite the fact that inhabitants of North Bohemia might have been relatively more tolerant towards the pollution because of the perceived identity, the region was still experiencing negative net immigration rates throughout 1970s and 1980s (see Figure 5). This might have threaten the production goals of the regime.

{Figure 5 around here}

The government was aware of the problem and implemented a series of policies that resulted in a number of various forms of monetary and non-monetary benefits. In particular, the policies aimed to attract newcomers into the region were substantial and targeted high-skilled professionals. For instance, newcomers could receive a house-building subsidy (up to 186% of average annual wage as of 1985)⁷ or recruitment benefits (up to 29% of average annual wage as of 1985).⁸ On the other hand, benefits designed to keep workers in the region were more universal but far from being that generous. All who worked in basin districts (four out of six districts in the region) for at least 10 years were eligible for an annual monetary benefit of 5.7% of average annual wage as of 1985. Locals used to call it a “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 late 1980s wages in median slowly converged to the country levels. According to Vaněk (1996) the convergence increased the frustration of population, which grew under the lid of the authoritarian regime and which boiled over in 1989. The first environmental

⁶ See Section 3.2 for a detailed description.

⁷ 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).

⁸ For a comprehensive list of monetary and non-monetary benefits Appendix Textbox A.1.

demonstration in Czechoslovakia took place on May 1989. A call for demonstrations in North Bohemia came at the time of a heavy inversion on November 8th 1989. Over a thousand of locals attended a series of demonstrations, which took place in Teplice between 11th and 13th November 1989. They demanded action on air pollution reduction under slogans “*We want healthy children!*” or “*We want clean air!*”. Later other cities in the North Bohemian coal basin joined the protests (see Vaněk 1996). Shortly after the series of demonstrations in Teplice, on November 17th 1989, the major anti-regime demonstration, which started the so-called Velvet revolution and the overthrow of the communist regime in Czechoslovakia, took place in Prague. Therefore, it was not the Communist Party to resolve the pollution problems, but in fact the first non-communist government, which sworn in on 10th December 1989. The new government started a complex process of political and economic transition. A fundamental part of the transition process was to draw a legislation, which would introduce policies aimed at improving the environment and living conditions of the population. At that time, there were two major policies adopted: (a) regulation of SO₂ emissions and (b) limitation of lignite mining, which helped as well the environment in North Bohemia.

Furthermore, law No. 309 passed in 1991 set an obligation for government to provide full and up-to-date information on air quality and emission sources to general public and established a framework for regulation of emissions and immissions. The law effectively set an obligation to install modern desulfurization technologies before December 31st 1998 – i.e. within 7 years.⁹ The strict deadline forced existing power plants to swiftly introduce desulfurization technologies. The first power plant (Komořany) started desulfurization in 1993. Others followed in 1994 or 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) limited mining activity by setting mining limits. The introduction of limits, along the drop in demand caused by economic downturn during the transition period, led to a decrease in coal production in the 1990s from 67 million metric tons in 1989 to 40 million metric tons in 2000 (see Figure A.1 in the Appendix). These regulations were later loosened (in 2008 and 2015), but never abolished.

These newly adopted policies resulted in a rapid decline in SO₂ concentrations (see Figure 4). The mean concentrations in the most heavily polluted districts dropped below the EU/WHO limit of

⁹ The law set an obligation for all emission sources to meet emission limits designed for newly build emission sources equipped with modern up-to-date technology by December 31st 1998.

20 $\mu\text{g}/\text{m}^3$ by 1999. The concentrations level reached after desulfurization remained stable throughout the 2000s and 2010s.

{Figure 6 around here}

Figure 6 shows the spatial distribution of SO₂ concentrations in North Bohemia at the beginning of desulfurization programs in 1994 (older data are not available) and after their completion in 2000. Despite the fact that SO₂ concentrations were already declining in 1994 (see Figure 4), the EU/WHO limit of 20 $\mu\text{g}/\text{m}^3$ was not met in any municipality in 1994. However, there was a substantial variation in the pollution load. The average SO₂ concentrations in municipalities ranged from 30 to 70 $\mu\text{g}/\text{m}^3$. After the desulfurization, the average concentrations in the region dropped below 20 $\mu\text{g}/\text{m}^3$ and so it did in individual municipalities. The dispersion model of the Czech Hydrometeorological Institute (CHMI) shows that all municipalities benefited from this substantial decrease in SO₂ emissions with all of them meeting the EU/WHO 20 $\mu\text{g}/\text{m}^3$ SO₂ limit by year 2000.

The government policies that aimed to support immigration and prevent emigration, which we discuss in the text above, were abandoned along the introduction of the new environmental regulation. The benefits for long-term stayers were initially guaranteed in 1991 (by Acts No. 276/1991 and 471/1991). However, these benefits were soon abolished by law No. 1/1992 in early 1992 (the law was passed in December 1991).

3. Data

The primary datasets 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 the administrative records on permanent residence changes in the period from 1971 on.¹⁰ People in the Czech Republic were and are legally obliged to register their permanent residency. Moreover, they are motivated to keep their registration up to date given that a preferential access to some public services (such as kindergartens, elementary schools or health care) is granted on its basis. The dataset contains number of people who moved in and out in each year. For our analyses we calculate annual municipality-level emigration and immigration rates

¹⁰ Data are available at <https://www.czso.cz/csu/czso/databaze-demografickych-udaju-za-obce-cr> (last accessed on February 6th 2019).

as the number of movers per resident using those gross emigration and immigration levels, and population as of January 1st. Some records on residential migration, mostly from small municipalities, are missing as they were lost before records digitization.

The concentrations of SO₂ and other pollutants are measured by a network of stations run by the Czech Hydrometeorological Institute (CHMI). Daily mean concentrations from individual measuring stations are available from CHMI yearbooks for the period from 1997 forward.¹¹ We have supplemented this publicly available data with monthly means of SO₂ concentrations from selected stations located in worst polluted districts (Most, Teplice and Chomutov) for the period 1970-1996.¹² This data allows us to observe the long-term development of overall SO₂ concentrations in the area (as depicted in Figure 4). For the spatial distribution of SO₂ concentration, we use data from a CHMI proprietary dispersion model with spatial resolution of 1 km squared. Such a detailed resolution allows us to capture pollution at level of municipalities. We have purchased data from two iterations of the model: for year 1994 (oldest iteration available) and year 2000. The CHMI dispersion model calculates 5 levels of mean sulfur dioxide concentrations in 1994: 30, 40, 50, 60, and 70 µg/m³; and 4 levels in 2000: 5, 10, 15, and 20 µg/m³ (see Figure 6). With SO₂ concentration being a continuous variable, we interpret calculated levels as centers of 10 respectively 5 µg/m³ wide bins. The concentrations at individual municipalities are defined as calculated SO₂ concentrations at municipality reference points. These reference points, defined by the CZSO, are placed in social center points of municipality such as in the front of a church or a town hall.

For our analyses, we also utilize information on population characteristics of municipalities. The primary source of the data are decennial population censuses. The municipality-level census data on population, education and age structure are available for 1980, 1991, 2001, and 2011 censuses. For the period from 1991 on, the CZSO publishes yearly data on municipality population structure

11 Yearbooks are available at http://portal.chmi.cz/files/portal/docs/uoco/isko/tab_roc/tab_roc_CZ.html (last accessed on February 6th 2019).

12 These additional data were purchased from CHMI. Frequent changes in measuring network (in locations, number of stations, and technology used) do not allow us to construct consistent long-term time series for individual measuring stations.

compiled from census and registry data.¹³ Furthermore, we exploit information from 1930 Census on ethnic composition of population in municipalities in 1930.¹⁴

In addition, we employ other datasets in our analyses. For instance, we use a map collection ArcČR 500 v3.3 to define administrative borders of municipalities and to make geospatial visualizations.¹⁵ Further, we obtain the altitude data from remotely sensed elevation grid data from Shuttle Radar Topography Mission (SRTM) 1 Arc-Second Global.¹⁶ Altitude for individual municipalities is defined as an altitude at the reference point. The driving distances between municipalities are calculated using Open street map (OSM) data.¹⁷ To capture the yearly municipality-level unemployment rate we use administrative data on registered unemployment. This data are available unfortunately only from 2001 on.¹⁸ The data on equipment with man-made amenities come from MOS database administered by CZSO.¹⁹

3.1. Estimation sample

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

The spatial distribution of SO₂ concentration is available only from the CHMI dispersion model. The oldest iteration of the model is available for 1994: the first year of widespread implementation of desulfurization technologies. With no other data available, we use this iteration to capture pre-desulfurization levels of SO₂ concentration in municipalities. The representativeness of the spatial distribution in 1994 for the pre-desulfurization period is limited by changes in emission sources. Therefore, we limit our sample to the period after the construction of the last coal-burning power plant in the area, which was finalized in 1982. From 1983 to 1993 there were no changes in the

¹³ 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.

¹⁴ The data were digitized by Guzi et al. (2019). They use aggergation rules provided by CZSO to match current and historical municipalities.

¹⁵ Map collection developed by a company ARCDATA PRAHA is available at <https://www.arcdata.cz/produkty/geograficka-data/arccr-500> (last accessed on June 26th 2019).

¹⁶ For data access see <https://www2.jpl.nasa.gov/srtm/dataprod.htm> (last accessed on December 4th 2019).

¹⁷ OSM database for the Czech Republic was downloaded from geofabrik.de on May 30th 2019.

¹⁸ 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).

¹⁹ Historical records from MOS database are not publicly accessible, but can be purchased from CZSO.

structure (i.e. in the number, location or power output) of major emission sources. Use of 1994 pollution levels for the whole pre-desulfurization period is further justified by remarkable stability of SO₂ levels in pre- and post-desulfurization period (see Figure 4).

As we mentioned above, one of issues of 1989 protests were the environmental concerns. 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 period 1990–1991 from our estimation sample. We also exclude the desulfurization period (1992–1999) as we do not have data on the spatial distribution of SO₂ concentrations during the period. As a result, we define the pre-desulfurization period as years 1983–1989 and post-desulfurization period as years 2000–2015.

The CHMI dispersion model calculates SO₂ concentrations between 30 and 70 µg/m³ in 1994. The highest level of 70 µg/m³ is calculated only for one municipality: a district capital Chomutov. As we use non-linear specification in our estimates the effect for this pollution level would be estimated using one independent observation. Therefore, we exclude Chomutov from the estimation sample used in the main analyses²⁰. Our baseline estimation sample thus contains 6,229 data-points for 301 municipalities.

3.2. Descriptive evidence

The specific topography of the region and the location of lignite deposits determined the relationship between pollution load and characteristics of municipalities. Mines and power plants were located at the foot of the mountains on the border with (East) Germany. These mountains limited emissions dispersion. As a result, more polluted municipalities tended to be located in higher altitudes and closer to the country border. As can be seen in Table 1 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 Appendix section, Tables A.2 and A.3). More polluted municipalities were also more affected by post-war expulsion and resettlement as the pre-war share of ethnic Germans was more than twice as

²⁰ However, we re-run our analyses with all data including Chomutov under the robustness analyses.

high in highly polluted municipalities compared to the least polluted municipalities in our sample (see Table 1).

{Table 1 around here}

Figure 5 and Table 2 show 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. The net immigration rate turned to positive with the start of desulfurization programs in 1993. The mean net immigration rate in the post-desulfurization period rose by 3.3 percentage points to 1.1%.

Both emigration and immigration rates differed in-between the pre- and post-desulfurization periods. The mean emigration rate in the pre-desulfurization period reached 5.2% and immigration rate 3.1%. After the desulfurization, which reduced the sulfur dioxide concentration below EU/WHO limits, the emigration rate dropped by 1.7 percentage points, and immigration rate rose by 1.5 percentage points (see column (1) in Table 2). This evidence suggests that a substantial reduction in air pollution increased the attractiveness of the region.

{Table 2 around here}

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

If we focus on changes in emigration and immigration rates within municipality-groups between pre- and post-desulfurization period, the Table 2, third rows in Panels A and B, show that least-polluted municipalities experienced smallest decrease in emigration rate relative to worse-polluted municipalities whereas increase in immigration rate in least-polluted municipalities was comparable to other groups of municipalities with higher pollution levels. These changes signal possible higher relative increase in attractiveness in formerly highly polluted municipalities.

Figures 7 and 8 show development in emigration and immigration rates, respectively, by pollution levels, from year 1983, throughout the desulfurization period (1994–1999) up to year 2015. As can be seen from Figure 7, there is a strong decline in emigration rates shortly after the fall of communism, with the decline being particularly sharp in 1991, when the new environmental legislation was adopted. The emigration rates fell in all groups of municipalities despite pollution levels being still high. This could be due to expectations of the future reduction in pollution loads supported by the new legislation.

{Figure 7 around here}

{Figure 8 around here}

On the contrary, the fall of communism seems not to have a clear immediate effect on immigration rates as seen in Figure 8. The overall increase in immigration rates did not start until mid-nineties, characterized by the implementation of desulfurization technology by the power-plants.

4. Identification strategy and empirical specification

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

$$mig_{it} = \gamma period_t SO_{ip} + \theta_t + \theta_i + \theta_A * \theta_t + \varepsilon_{it} \quad (1)$$

where mig_{it} is an outcome (migration rate at municipality i and at year t)²¹, $period_t$ is a dummy variable equals 1 for the post-desulfurization period (2000-2015) and 0 for the pre-desulfurization

²¹ The adoption of desulfurization technologies coincides with abolition of pro-immigration and anti-emigration policies in early 1990s. The pro-immigration policies were selective and targeted highly-skilled professionals while anti-emigration were general and targeted all workers from basin districts. As we do not have access to individual migration data, we cannot disentangle the effect of air pollution and benefits on immigration rate. Therefore, we focus in our main causal analysis on the impact of air pollution on emigration. Results of analyses of immigration together with a discussion of results on potential impact of benefits on immigration rate is presented in Section 6.1.

period (1983-1989). To capture the potentially non-linear effect of air pollution we include pre-desulfurization SO_2 concentrations as a vector of dummy variables (SO_{ip}) for individual pollution levels: 40, 50, and 60 $\mu\text{g}/\text{m}^3$, obtained from the 1994 iteration of CHMI dispersion model (see the Data Section above). The lowest level of 30 $\mu\text{g}/\text{m}^3$ serves a reference level. Conditional on our identification assumptions, parameters γ capture the causal effect of desulfurization, i.e. decline to exposure to air pollution on emigration rates. The reference level exceeds 20 $\mu\text{g}/\text{m}^3$ EU/WHO limits for developed countries on the mean yearly sulfur dioxide concentration by 50%. The parameters γ present therefore a lower bound of the true effect of desulfurization, which decreased pollution levels to or below 20 $\mu\text{g}/\text{m}^3$ limit in all municipalities.

The baseline specification (1) also contains a full set of municipality fixed effects θ_i including the constant, which controls for all time-invariant differences (such as geographical location, natural amenities or heritage of post-World war II resettlement) and ensures that we estimate the effect of SO_2 concentrations within a municipality. We also include year fixed effects θ_t , which control for events affecting all municipalities in the region alike – such as changes in the institutional environment, macroeconomic development, or accession of the Czech Republic to the EU. To capture possible time-variant regional characteristics, we divide the region into three areas orthogonal to pollution levels²² and include an interaction term of year and area (θ_A) fixed effects.

Key assumption underlying validity of our DD estimate is that differences in emigration rates between treated and not-treated group of municipalities would have remained constant in absence of treatment. In order to test for the assumption we perform the parallel trends assumption test, which is presented in the Appendix Figure A.3. The test shows no divergence in trends in pre-desulfurization period (1983–1989).

²² The areas are defined using the border between basin and other districts in the region (i.e., the South-West to North-East axis of the region). We divide this border into three equally long segments and assign all municipalities to the nearest one. Area is then defined as set of municipalities nearest to a specific segment. For details see Figure A.2 in Appendix.

5. Empirical Results

5.1. Main Results

Table 3 shows the main results on the impacts of air pollution reduction on emigration. Estimates from our primary regression (1) show the expected negative effect of SO₂ concentrations' decline on emigration rates with the effect being highly non-linear. The first column of Table 3 presents estimate of our parameter of interest γ capturing the interaction of post-desulfurization period and municipalities that suffered 40 $\mu\text{g}/\text{m}^3$ or higher SO₂ concentration levels and measuring the overall average impact of SO₂ decline due to the technology adoption in power plants on emigration rates. The results show that the technology adoption leading to a substantial decline in SO₂ air pollution significantly reduced emigration. The effect is statistically significant and large; the lower pollution has reduced the average emigration rate from polluted municipalities by an average of 1.4 p.p., i.e. approx. 23.6% lower emigration rates. Furthermore, we find that the effect is highly non-linear as shown in the column 2 of Table 3. In particular we find that the effect of SO₂ concentrations' decline on emigration from municipalities that suffered initially heavy SO₂ pollution levels (50 and 60 $\mu\text{g}/\text{m}^3$) is statistically significant and about two times higher that of the municipalities in the category of 40 $\mu\text{g}/\text{m}^3$ of SO₂ concentrations. Specifically, the emigration rate in these municipalities drops by 1.7 and 1.6 p.p. respectively relative to the reference group, which corresponds to 26.3% and 27.2% lower emigration rates, respectively.

{ Table 3 around here }

For the sake of completeness, we estimate regression (1) with the immigration and net immigration rates as dependent variables, and we report the estimates in the Appendix Table A.4. The results show that both rates increased relative to the reference group in municipalities with initial pollution above 40 $\mu\text{g}/\text{m}^3$ of SO₂ concentrations. Municipalities with pre-desulfurization SO₂ concentrations at 50 $\mu\text{g}/\text{m}^3$ experienced statistically significant increase by 1.1 and 2.8 p.p. in immigration and net immigration rate respectively. The estimates for municipalities with pre-desulfurization SO₂ levels at 60 $\mu\text{g}/\text{m}^3$ are somewhat lower; For immigration rate there is not effect – as the estimate of 0.2 p.p. is statistically insignificant, whereas the results show 1.8 p.p. increase in net immigration rate for those extremely polluted municipalities prior desulphurization compared to the reference group of municipalities. However, we acknowledge that these estimates cannot be interpreted as causal effects

of decrease in air pollution as we cannot disentangle effects of air pollution and pro-immigration benefits. On the other hand, one can expect that more polluted municipalities were also more affected by abolition of pro-immigration benefits. If this is the case, the estimates would suggest that there is potentially a migratory response to reduction in air pollution in terms of increased immigration.

5.2. Robustness analysis and placebo tests

Economic factors and unemployment

There is a concern with respect to the main findings that the environmental policies introduced in the early 1990s pushed for desulfurization as well as limited lignite mining. The desulfurization was achieved by the adoption of new technologies, and therefore *per se* had no or little impact on the labor market. On the other hand, limitation of lignite mining, together with overall decline during the so-called transition recession, led to closures of mines, which could adversely affect local labor markets. Especially in more polluted municipalities adjacent to mines and power plants. In effect, such a negative shock could increase emigration rates and decrease the effect of air pollution on migration, which we find based on regression (1) and which we report in the result Table 3.

In order to tackle these concerns, we re-estimate regression (1) with additional controls of municipality-level unemployment rate, defined as a share of registered unemployed on working-age population (15–64) in the given municipality in the previous year. We show the results in Table 4, in column (1). The availability of consistent municipality-level unemployment data limits our post-desulfurization period to years 2002–2012, and thus the number of observations drops by 25%. We assume the unemployment rate being equal to zero before the fall of communism – i.e., in the pre-desulfurization period. Results reported in Table 4 in column (1) show no deviation from our baseline estimates (presented in Table 3) with the coefficient for the unemployment rate being insignificant and close to zero.

Post-desulfurization pollution levels

The environmental policies decreased SO₂ concentrations to meet EU/WHO limits in the post-desulfurization period. Still, even when meeting the administratively set limit, there was a variation in the pollution load across municipalities (see Figure 6 and Table 1). To test whether the post-desulfurization pollution levels played a role in migration behavior, we re-estimate regression (1)

with controlling for the post-desulfurization SO₂ concentrations. Results reported in column (2) of the Table 4 do not deviate significantly from the baseline estimates for variables of interest.

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, which might affect migration behavior. We re-estimate regression (1) with the following additional controls lagged by one year: share of secondary educated, share of tertiary educated, the share of age cohorts (20–29, 30–39, 40–49, 50–59, 60–69) on population. We obtain the data on population characteristics from decennial censuses held in 1980, 1991, 2001, and 2011. In order to make use of the entire wealth of our data, we interpolate yearly values for years in-between census years using nearest-neighbor interpolation and piecewise linear interpolation. The results from our main regression (1) controlling for the municipality-level population characteristics are reported in columns (3) and (4) in Table 4. The results show that coefficients estimated for higher pollution levels do not significantly differ from our baseline results for both interpolation methods, while coefficients for municipalities with 40 µg/m³ SO₂ concentrations are marginally larger when controlling for the population characteristics.

Other robustness checks

In the next step, we run a number of further robustness checks and re-estimate regression (1) using differently specified samples. First, we include the only municipality (Chomutov) with SO₂ concentration at 70 µg/m³ into our data sample. We then define the category with the highest air pollution loads as municipalities with SO₂ concentration greater or equal to 60 µg/m³. Results reported in column (5) of Table 4 do not differ from our baseline results.

Next, we restrict our data sample to balanced panel of municipalities and exclude municipalities with missing migration records. Balancing the panel has no impact on our results (see column (6) Table 4).

In the last robustness checks, we test the robustness of our results to the presence of potential outliers. These outliers may occur due to mine expansions (as was the case of the city of Most) or other unobserved factors such as natural disasters. In order to check whether our results are not driven by those outliers, we re-estimate the regression (1) using sample without top 1% observations for each

year. The results are shown in the column (7) of Table 4. The estimated coefficients are similar and statistically significant although somewhat lower in magnitude (by 0.2 to 0.4 p.p.).

{Table 4 around here}

Placebo tests

In the analysis, we treat the desulfurization period of 1992–1999 as an event that triggered the change in residential migration. However, the identified effect could be caused by another event coinciding with desulfurization. To exclude that possibility, we perform two placebo tests. Specifically, we split true pre- and post-desulfurization periods into (a) placebo pre- (1983–1986, and 2000–2007 respectively) and (b) placebo post-desulfurization (1987–1989, and 2008–2015 respectively) periods and re-estimate regression (1) separately for each of those two “placebo” periods as if the desulfurization tech adoption happened in 1986 with analyses limited to years 1983-1989, and in year 2006 with analyses limited to years 2000-2015. The idea is of course that if there is an “effect” of “placebo desulfurization” on migration, there are reasons to be suspicious about the main estimates. We present estimates from the placebo analyses in Table 5, with estimates from sample of years 1983-1989 shown in Column (1), and estimates from sample of years 2000-2015 shown in Column (2). As can be seen from the results, none of the placebo estimates are statistically significant, which supports results from our analyses presented above.

{Table 5 around here}

5.3. Mechanisms

The role of anti-emigration government policies

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

The eligibility for benefits was determined by place and length of work. Only those who worked in municipalities in basin districts for more than 10 years were eligible for benefits in the form once-per-year monetary transfer of 2,000 Czechoslovak crowns (i.e. 5.7% of average annual wage in 1985). This monetary benefit was abolished in early 1992 along the introduction of new environmental regulations.

To disentangle the role of anti-emigration government policies from the effects of air pollution on emigration, we utilize the fact that some of the municipalities, as listed in legal documents, constituted eligibility of workers for the benefit (hereafter “*municipalities eligible for benefits*”), whereas others did not (hereafter “*municipalities not eligible for benefits*”). Figure 9 shows that municipalities eligible for benefits created a compact area in the northern part of North Bohemia. The eligibility was correlated with pollution load: all municipalities in areas with SO₂ concentration above 40 µg/m³ were eligible for benefits, but there was a variation in eligibility in less polluted municipalities. The share of eligible municipalities in our estimation sample is 32% (n = 35) among least polluted and 74% (n = 69) among municipalities with SO₂ concentrations equal to 40 µg/m³. All more polluted municipalities were eligible for benefits.

{Figure 9 around here}

To disentangle the effects of air pollution and benefits we extend the baseline specification (1) to triple DID using the eligibility for benefits as an additional dimension yielding the following specification:

$$mig_{it} = \gamma_{1ip}period_tSO_{ip} + \gamma_{2ip}period_tSO_{ip}benefits_i + \gamma_{3ip}period_tbenefits_i + \theta_t + \theta_i + \theta_A * \theta_t + \varepsilon_{it} \quad (2)$$

Where $benefits_i$ is an indicator variable for municipalities eligible for benefits. We estimate equation (2) on sample limited to municipalities with pre-desulfurization SO₂ concentrations equal or below 40 µg/m³.

{Table 6 around here}

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.

The municipality of residence could be however different from municipality of workplace, which in fact constituted eligibility for benefits of individual workers. To account for potential distortions, we construct a continuous measure reflecting an importance of benefits for each municipality (i.e. treatment intensity measure). Using 1991 census data we calculate shares of economically active residents working in municipalities eligible for benefits for each municipality. Figure 10 shows minimum variation in intensity measure across all groups of municipalities except those with pre-desulfurization SO_2 concentrations at $40 \mu\text{g}/\text{m}^3$. This is not surprising as those are typically located on the border between areas eligible and non-eligible for benefits (see Figure 9). It also suggest that people in the region were commuting on short distances (i.e. they faced similar pollution levels in municipality of work and residence).

Thus in the next step, we re-estimate regression (2) with the alternative continuous measure of $benefits_i$ defined as intensity measure in a municipality i . The results of the regression with the alternative measure of benefits shown in column (2) in Table 6 do not differ substantially from results obtained with $benefits_i$ defined as a binary variable (shown in column (1) Table 6). The triple difference term is somewhat lower, but still statistically insignificant. None of our results, therefore, indicates that benefits influenced the effect of pollution on the emigration rate.

The role of social capital

The migratory response of residents to pollution depends on willingness of an individual to suffer the negative amenity, and at the same time to deal with utility losses related to emigration such as the psychological costs of migration of leaving their familiar place, their family and friends. Higher attachment of residents to their communities could increase such utility losses or the migration costs and therefore it should decrease the migratory responses to air pollution. To dig deeper into this link we exploit another natural experiment, which came out of the history of the region.

North Bohemia was one of the regions of the Czech Republic 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 11), allowed ethnic Czechs to come to emptied municipalities, seize German properties, and settle there. However, these settlers had no or little ties to the region and among themselves.

{Figure 11 around here}

The government propaganda, as noted above, sought to base their new regional identity on coal and coal mining. Such an identity could increase tolerance to the coal-related pollution. However, the regional identity was not the only phenomenon missing in resettled municipalities. The expulsion of residents destroyed local social capital (i.e., social ties among people living in a municipality) in affected municipalities.²³ 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 stable equilibrium characterized by lower levels of social capital and higher migration.

Guzi et al. (2019) 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.²⁴ They find expulsion and resettlement to increase emigration and immigration rates in most affected municipalities (municipalities with a pre-war share of ethnic Germans above 90%) by 0.6–0.7 p.p. and 0.4–0.5 p.p. respectively relative to comparable least affected municipalities (municipalities with a pre-war share of ethnic Germans below 10%) located nearby. Guzi et al. (2019) also suggest that lower social capital is the driving mechanism of the causal effect. In their study the authors document that people in resettled municipalities do not differ in terms of values and general pro-social behavior (such as tendency to give donations, participate in voluntary work or in propensity to attend social events), but in terms of having less local social capital as they are less likely to be a member a local club, or to organize local public events.

Building on Guzi et al. (2019), 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 the North Bohemia, the variable could also capture the effect of propaganda-fueled regional identity. We assume that these effects should go in the opposite directions. To test the impact of local social capital in the pollution migration link, we split the sample by the cutoff of 50% of ethnic Germans in the local

²³ The affected municipalities were resettled mostly by ethnic Czech from various regions of the Czech Republic. Larger groups of settlers moving together from the same origin could be able to establish higher initial level of local social capital in resettled municipalities. To our knowledge, there is no evidence that such movements of settlers was a common phenomenon. Čapka et al. (2005) present Sobotín, North Moravia, as an example of a municipality resettled from one dominant source. Even in this case the share of settlers from the same origin comprised less than 20%. Guzi et al. (2019) use data from a rich agricultural region of South Moravia and show, that on average 11.7% settlers came from the most important municipality of origin.

²⁴ Guzi et al. (2019) use the same source dataset on residential migration as we do.

population in 1930 and re-estimate the regression (1) for both samples. Results reported in Table 7, columns (1) and (2), show the tendency of migratory responses to air pollution to be 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 the disutility caused by the air pollution.

The chosen cutoff of 50% provides only a few municipalities for estimation of the effect of higher levels of pollution in municipalities below the cutoff (six municipalities for pre-desulfurization SO_2 concentration $50 \mu\text{g}/\text{m}^3$ and two municipalities for $60 \mu\text{g}/\text{m}^3$, see the lower part of the Figure 11). In order to base the 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 sample of 29 municipalities with SO_2 concentration $50 \mu\text{g}/\text{m}^3$ and 11 municipalities for $60 \mu\text{g}/\text{m}^3$ below the cutoff of 75%. Table 7, columns (3) and (4) provide the results of our main estimation model (1) for municipalities being below- and above- the threshold of 75% share of ethnic Germans in 1930, respectively. The coefficients show similar pattern as in the first two columns defined by 50% threshold, and in line of what we would expect; the effect of air pollution on emigration seem to be stronger in municipalities with weaker social capital.

{Table 7 around here}

Testa (2019) and Daněk (1995) show differences in population structure between areas affected and unaffected by the post-war events. To check, whether these differences drive our results, we re-estimate regressions reported in Table 7 with additional controls for education and age structure (see Section 5.2 for details on data and interpolations of values for in-between census years). Results reported in Table A.5 in Appendix do not substantially deviate from those reported in Table 7 for both types of additional census variables interpolation (i.e., nearest-neighbor interpolation and piecewise linear interpolation).

The role of man-made amenities

Similarly to the local social capital, the man-made amenities availability, such as availability of 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. To investigate this mechanism, 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 a municipality using 1993 data collected by the Czech Statistical Office, CZSO.²⁵ We categorize man-made amenities into three groups: (a) Education, health and social care facilities (number of hospitals, retirement homes, etc.), (b) Culture and sports facilities (number of libraries, cinemas, football fields, etc.), and (c) Public administration facilities and public utilities (number of job centers, courts, etc.; and presence of a sewerage, water supply system, etc.).²⁶

Figure 12 shows spatial distribution of man-made amenities availability. Number of facilities and public utilities is raising in population (with Spearman's rho between 0.72 and 0.85). The availability of amenities is also correlated between amenities groups with Spearman's rho between 0.67 and 0.75.

The man-made amenities in centrally planned socialist economy could be allocated to compensate for the air pollution. We cannot exclude this option. However, the man-made amenities endowment is only weakly correlated with SO₂ concentration levels in pre-desulfurization period (with Spearman's rho between 0.06 and 0.24). Similarly, one can imagine that municipalities richer in local social capital could be able to lobby more efficiently and to get more (often government-funded) man-made amenities. However, the pre-war share of ethnic Germans is not correlated with man-made amenities availability either (with Spearman's rho between 0.06 and 0.12).

{Figure 12 around here}

To see 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 (1) for all six resulting sub-samples.

{Table 8 around here}

Table 8 provides the results for each amenity group and municipalities split into being below- and above- the median for each amenity group. The Table 8 is also divided into panel A and panel B based on two different alternative ways of calculation of amenities. In the panel A, we calculate man-made amenities availability as sum of amenities located in the respective municipalities. In an alternative specification, presented in panel B, we allow residents to use man-made amenities located in nearby

²⁵ The 1993 is the first iteration of the source database available. For number of public administration facilities, we use 1994 data as data for 1993 are not available.

²⁶ For the full list see Appendix Textbox A.2.

municipalities in the Czech Republic. The alternative amenities availability measure is calculated as a sum of man-made amenities within 20 km driving distance. Results estimated in baseline and alternative specification effectively set bounds for estimates which would be obtained for man-made amenities availability measures calculated using weights decreasing in distance and leveling off at 0 for distance greater than 20 km.

Estimated effects of air pollution reported in panel A tend to be higher for municipalities with lower availability education and health facilities as well as public administration facilities and utilities. If also man-made utilities outside the municipality are considered the same pattern also appears in the case of culture and sports facilities (columns (3) and (4) in panel B). These results suggest that man-made amenities availability can compensate disutility caused by the air pollution.

6 CONCLUSIONS

Using unique natural experiment of modern technology adoption in power plants that lead to a massive air pollution reduction in the area, this paper examines the effect of air pollution on migratory behaviour. In particular, we look at residential emigration rates from municipalities in the region of North Bohemia in Czechia that suffered extreme pollution levels. In order to examine the causal effects of air pollution on emigration we exploit the fact that in years between 1992–1999 Czech power plants had to comply with the obligation set by law to install desulfurization technologies. This led to a massive reduction in SO₂ concentrations in the air in the area to values below EU/WHO limits.

The results based on a difference-in-difference estimator show that the estimated effect of reduction in SO₂ concentrations on emigration is as expected negative. The effect is large and statistically significant, bringing about 27% decrease in emigration rates from polluted municipalities after the desulfurization technologies were adopted compared to less polluted baseline group of municipalities. Further, the effects of air pollution on emigration seem to be non-linear. The effect of reduction in air pollution in municipalities that initially suffered extreme SO₂ pollution levels (at 50 and 60 µg/m³ of SO₂) is about twice as large than the effect in municipalities with initial pollution load of 40 µg/m³. Our main results are supported by a number robustness checks and by placebo tests.

Furthermore, we dig deeper into possible mechanisms, which might influence the migratory responses to air pollution. In our analyses, we find that anti-emigration policies in the form of benefits do not seem to affect the air pollution- migration link. However, we find that the effect of air pollution

on emigration was far stronger in municipalities with weaker local social capital and scanty man-made amenities and facilities.

To sum up, our paper brings a novel evidence of environmental pollution acting as a strong push migration factor. The push effect does not seem to be counteracted by the existence of anti-emigration economic benefits provided by the government. Further, our results suggest that strengthening social capital as well as investing into better facilities in the area of education, health and social care, as well as facilities promoting sport and cultural activities, can partially mitigate the migratory response to air pollution. Overall, policies aiming at prevention of regional de-population should target policies towards cleaner environments, stronger social capital and city amenities.

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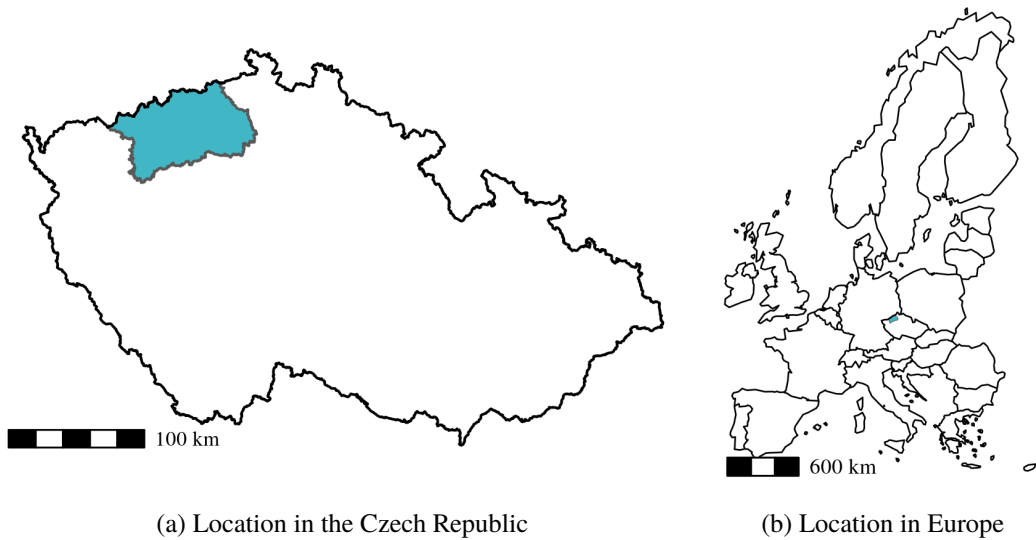


Figure 1: North Bohemia region

Source: ArcČR 500 v3.3, Eurostat (see Section XXX)



(a) Most in 1964

(b) Most in 1987

Figure 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).

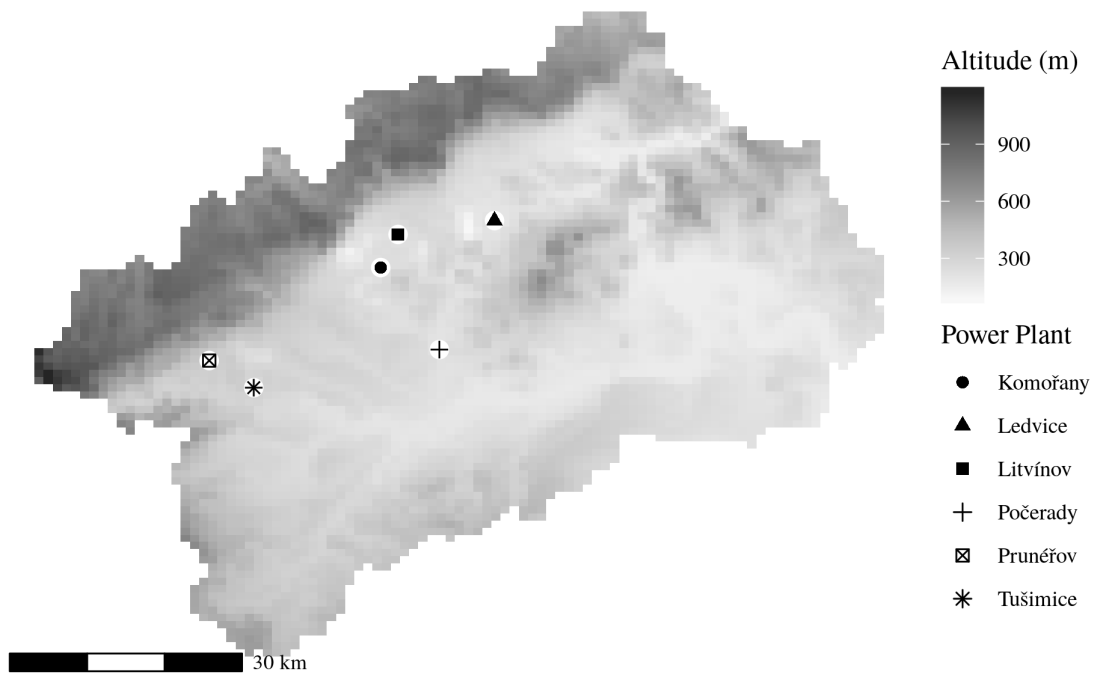


Figure 3: Altitude and power plants location in North Bohemia

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

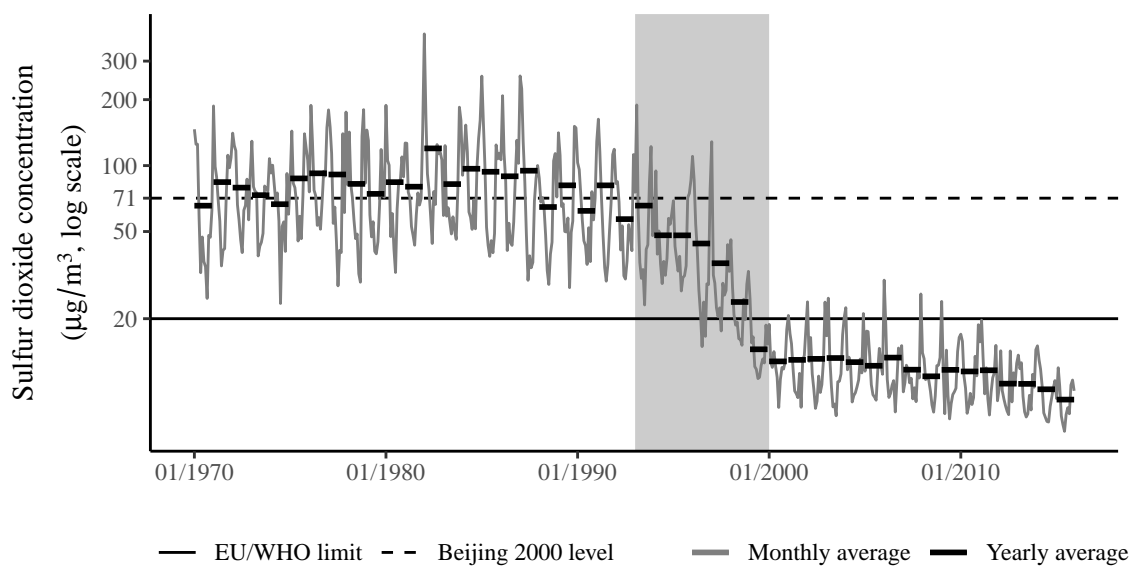


Figure 4: Development in SO_2 concentrations in districts of Teplice, Most, and Chomutov over the period 1970–2015.

Source: Czech Hydrometeorological Institute (CHMI, see Section XXX); Limits by: WHO, 2006; Beijing pollution levels: UNEP, 2007.

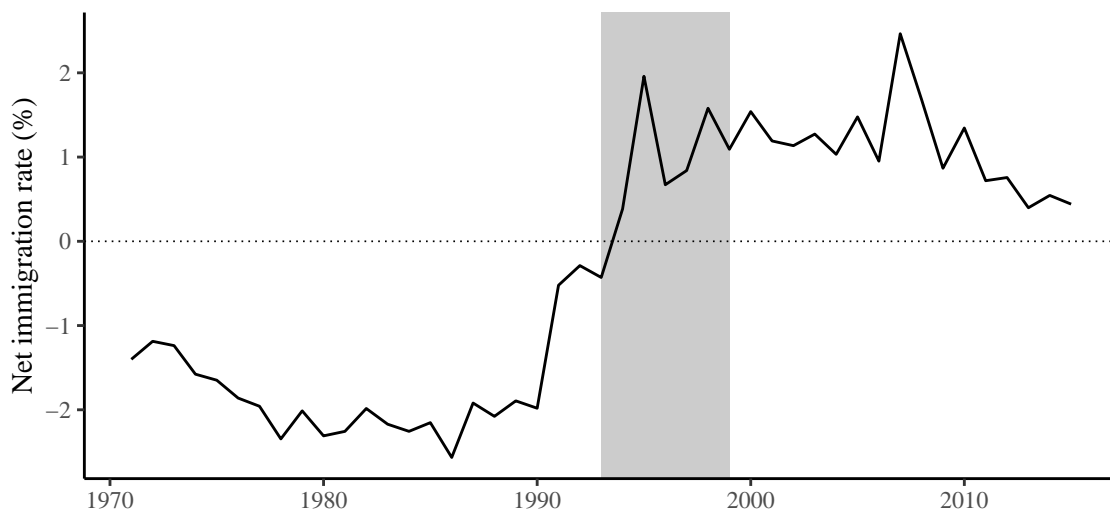


Figure 5: Average net immigration rate in municipalities in North Bohemia (1971–2015)

Source: CZSO (see Section XXX)

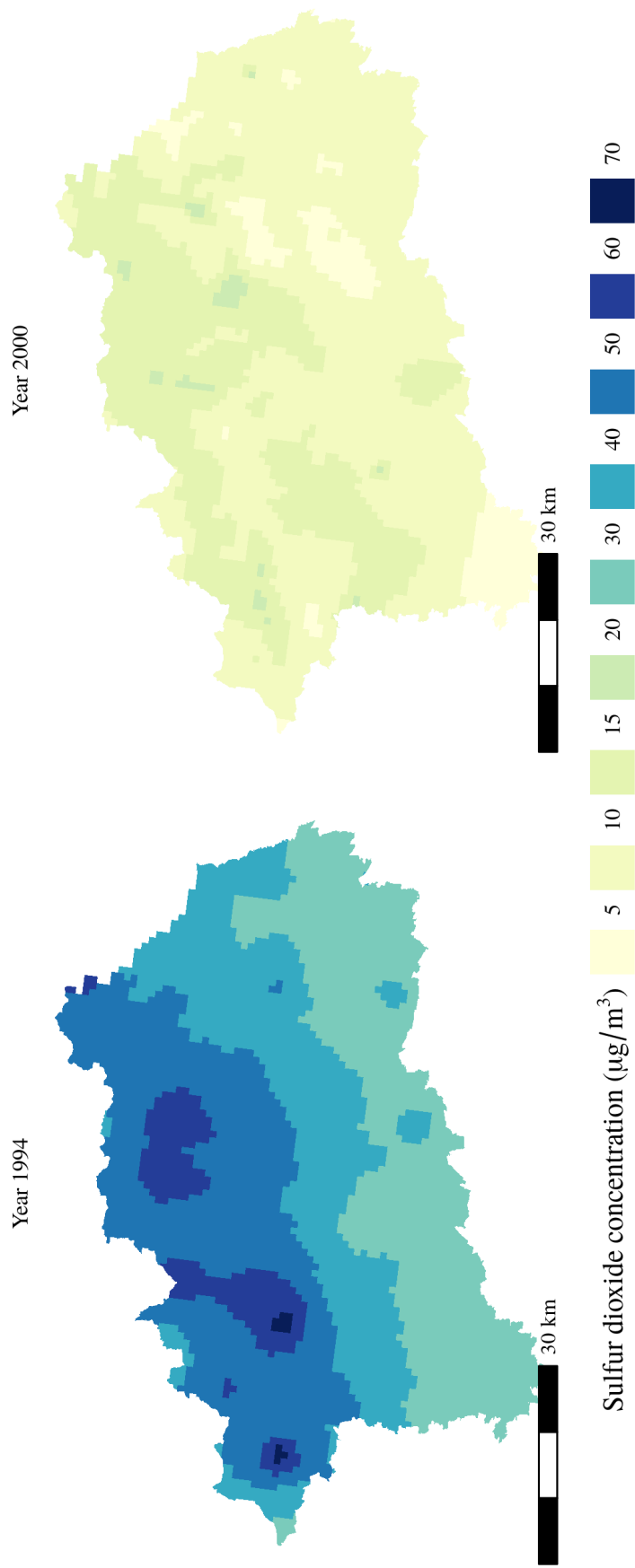


Figure 6: Spatial distribution of SO₂ concentrations in North Bohemia, year 1994 and 2000

Source: Czech Hydrometeorological Institute (CHMI, see Section XXX)

Table 1: Time-invariant characteristics and population by SO₂ concentration in 1994

	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 (0.56)	30.00 (0.00)	40.00 (0.00)	50.00 (0.00)	60.00 (0.00)
	2000	11.11 (0.17)	9.68 (0.19)	10.16 (0.28)	13.42 (0.35)	13.89 (0.41)
Altitude (m)		286.33 (8.11)	242.93 (9.38)	266.61 (12.33)	350.29 (19.48)	357.58 (37.45)
Distance to the country border (km)		26.53 (0.77)	39.32 (0.65)	27.00 (0.79)	12.77 (0.81)	10.40 (0.90)
Population	1980	2135.09 (440.09)	889.72 (166.55)	1419.06 (376.37)	4347.51 (1544.73)	3601.19 (1991.46)
	1991	2119.29 (477.95)	808.80 (161.38)	1403.56 (417.50)	4421.36 (1706.60)	3602.44 (2014.18)
	2001	2110.81 (463.89)	824.89 (162.46)	1393.49 (402.13)	4354.25 (1652.48)	3659.63 (1972.97)
	2011	2099.10 (447.16)	852.23 (160.11)	1390.89 (380.02)	4279.08 (1593.83)	3631.96 (1904.93)
Share of ethnic Germans (%)	1930	54.24 (2.23)	26.81 (3.73)	60.56 (3.60)	77.84 (2.11)	79.28 (3.30)
Municipalities (n)		301	108	93	73	27

Notes: Table reports means and standard errors in parentheses.

Table 2: Migration rates by period and SO₂ concentration

	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)
<i>Panel A: Emigration rate</i>					
Pre-desulfurization (%)	5.21 (0.22)	3.77 (0.15)	5.08 (0.41)	6.46 (0.48)	5.89 (0.69)
Post-desulfurization (%)	3.46 (0.07)	3.09 (0.09)	3.56 (0.12)	3.84 (0.20)	3.62 (0.21)
Difference (p.p.)	-1.74*** (0.20)	-0.68*** (0.15)	-1.52*** (0.40)	-2.62*** (0.42)	-2.27*** (0.54)
<i>Panel B: Immigration rate</i>					
Pre-desulfurization (%)	3.05 (0.12)	2.59 (0.18)	3.48 (0.27)	2.99 (0.22)	3.46 (0.43)
Post-desulfurization (%)	4.58 (0.11)	4.05 (0.13)	4.54 (0.19)	5.26 (0.32)	5.01 (0.27)
Difference (p.p.)	1.53*** (0.17)	1.46*** (0.21)	1.06*** (0.32)	2.27*** (0.39)	1.55*** (0.55)
<i>Panel C: Net immigration rate</i>					
Pre-desulfurization (%)	-2.16 (0.25)	-1.18 (0.19)	-1.60 (0.41)	-3.47 (0.57)	-2.43 (0.89)
Post-desulfurization (%)	1.12 (0.07)	0.96 (0.08)	0.99 (0.12)	1.42 (0.22)	1.39 (0.19)
Difference (p.p.)	3.28*** (0.29)	2.14*** (0.21)	2.58*** (0.46)	4.89*** (0.71)	3.82*** (0.94)
	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%.

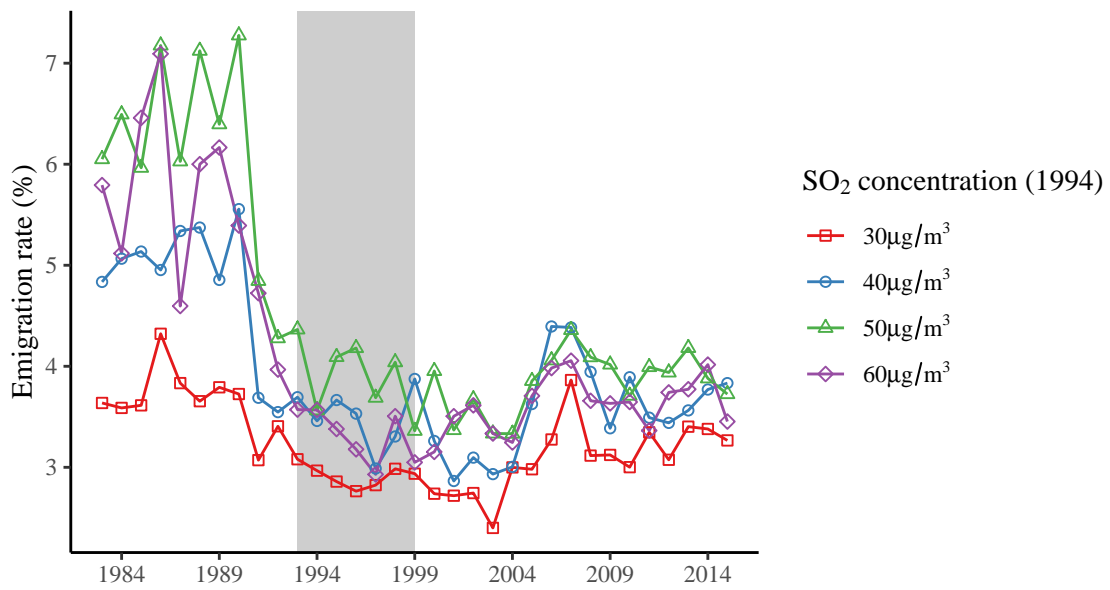


Figure 7: Emigration rate from municipalities in North Bohemia by 1994 SO₂ concentration, years 1983–2015

Source: CZSO (see Section XXX)

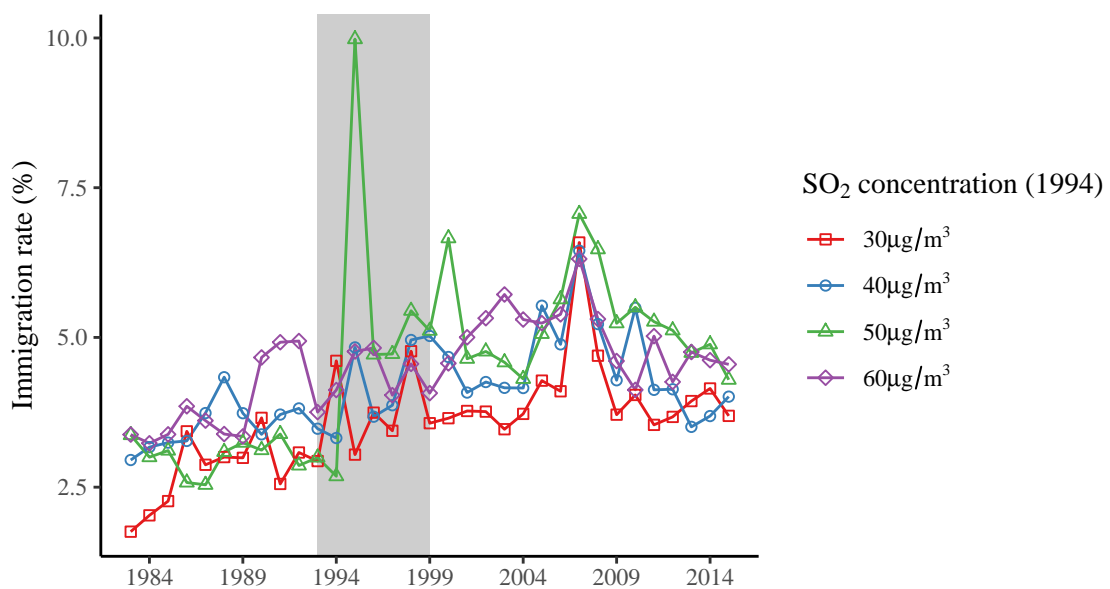


Figure 8: Immigration rate from municipalities in North Bohemia by 1994 SO₂ concentration, years 1983–2015

Source: CZSO (see Section XXX)

Table 3: Main results of SO₂ concentration' decreases on emigration rate

	(1)	(2)
Pre-desulfurization SO ₂ concentration $\geq 40 \mu\text{g}/\text{m}^3$ × Post-desulfurization period	-1.378*** (0.290)	
Pre-desulfurization SO ₂ concentration = $40 \mu\text{g}/\text{m}^3$ × Post-desulfurization period		-0.877** (0.409)
Pre-desulfurization SO ₂ concentration = $50 \mu\text{g}/\text{m}^3$ × Post-desulfurization period		-1.695*** (0.430)
Pre-desulfurization SO ₂ concentration = $60 \mu\text{g}/\text{m}^3$ × Post-desulfurization period		-1.586*** (0.484)
Adjusted R2	0.348	0.350
Observations	6,229	6,229

Notes: Table reports coefficients γ from Equation (1). All model specifications include constant, 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 SO₂ concentration is $30 \mu\text{g}/\text{m}^3$.

Table 4: Robustness analysis

	Unemployment rate	SO ₂ concentration in post-desulfurization period	Education and age structure (nearest-neighbor interpolation)	Education and age structure (linear interpolation)	Inclusion of Chomutov	Balanced panel	Exclusion of outliers
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Pre-desulfurization SO ₂ concentration = 40 $\mu\text{g}/\text{m}^3$ × Post-desulfurization period	-0.875** (0.436)	-0.837** (0.387)	-0.991** (0.412)	-1.011** (0.436)	-0.875** (0.409)	-0.854** (0.426)	-0.641** (0.312)
Pre-desulfurization SO ₂ concentration = 50 $\mu\text{g}/\text{m}^3$ × Post-desulfurization period	-1.694*** (0.464)	-1.566*** (0.533)	-1.706*** (0.429)	-1.718*** (0.436)	-1.698*** (0.429)	-1.645*** (0.442)	-1.340*** (0.279)
Pre-desulfurization SO ₂ concentration = 60 $\mu\text{g}/\text{m}^3$ × Post-desulfurization period	-1.615*** (0.480)	-1.306** (0.607)	-1.583*** (0.472)	-1.635*** (0.448)	-1.455*** (0.482)	-1.546*** (0.487)	-1.180*** (0.288)
Unemployment rate	-0.021 (0.021)						
Post-desulfurization SO ₂ concentration = 10 $\mu\text{g}/\text{m}^3$ × Post-desulfurization period		-0.263 (0.403)					
Post-desulfurization SO ₂ concentration = 15 $\mu\text{g}/\text{m}^3$ × Post-desulfurization period		-0.612 (0.715)					
Post-desulfurization SO ₂ concentration = 20 $\mu\text{g}/\text{m}^3$ × Post-desulfurization period		0.953 (0.751)					
Adjusted R2	0.381	0.351	0.357	0.379	0.349	0.383	0.354
Observations	4,724	6,229	6,229	5,326	6,252	4,485	6,148

Notes: Table reports coefficients γ from Equation (1). All model specifications include constant, municipality, year and area by year fixed effects. In column (1) the baseline specification (1) is extended with the one-year-lagged unemployment rate in the municipality, in column (2) with SO₂ concentrations in post-desulfurization period (with 5 $\mu\text{g}/\text{m}^3$ being a 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 secondary and tertiary educated on 15+ population). The column (3) uses the nearest-neighbor interpolation, and column (4) the piecewise linear interpolation of census-based covariates. In the column (5) the estimation sample includes city of Chomutov into 60 $\mu\text{g}/\text{m}^3$ category and therefore redefining this category as $\geq 60 \mu\text{g}/\text{m}^3$. In the column (6) the estimation sample is balanced by excluding municipalities with missing migration records. In the column (7) municipality-year data-points within each year top 1% of 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 SO₂ concentration in pre-desulfurization period is 30 $\mu\text{g}/\text{m}^3$.

Table 5: Placebo tests

	Pre-desulfurization	Post-desulfurization
	period	period
	(1)	(2)
Pre-desulfurization SO ₂ concentration = 40 μg/m ³ × Post-desulfurization period	0.156 (0.306)	-0.046 (0.167)
Pre-desulfurization SO ₂ concentration = 50 μg/m ³ × Post-desulfurization period	0.062 (0.489)	-0.039 (0.219)
Pre-desulfurization SO ₂ concentration = 60 μg/m ³ × Post-desulfurization period	-0.454 (0.370)	-0.167 (0.160)
Adjusted R2	0.581	0.266
Observations	1,413	4,816

Notes: Table reports coefficients γ from Equation (1). All model specifications include constant, municipality, year and area by year fixed effects. The Equation (1) is estimated separately for pre- and post-desulfurization period with placebo pre- and post-desulfurization periods. Robust standard errors clustered by municipality are reported in parentheses: *, ** and *** denote statistical significance at 10%, 5% and 1%. The reference category for SO₂ concentration is 30 μg/m³.

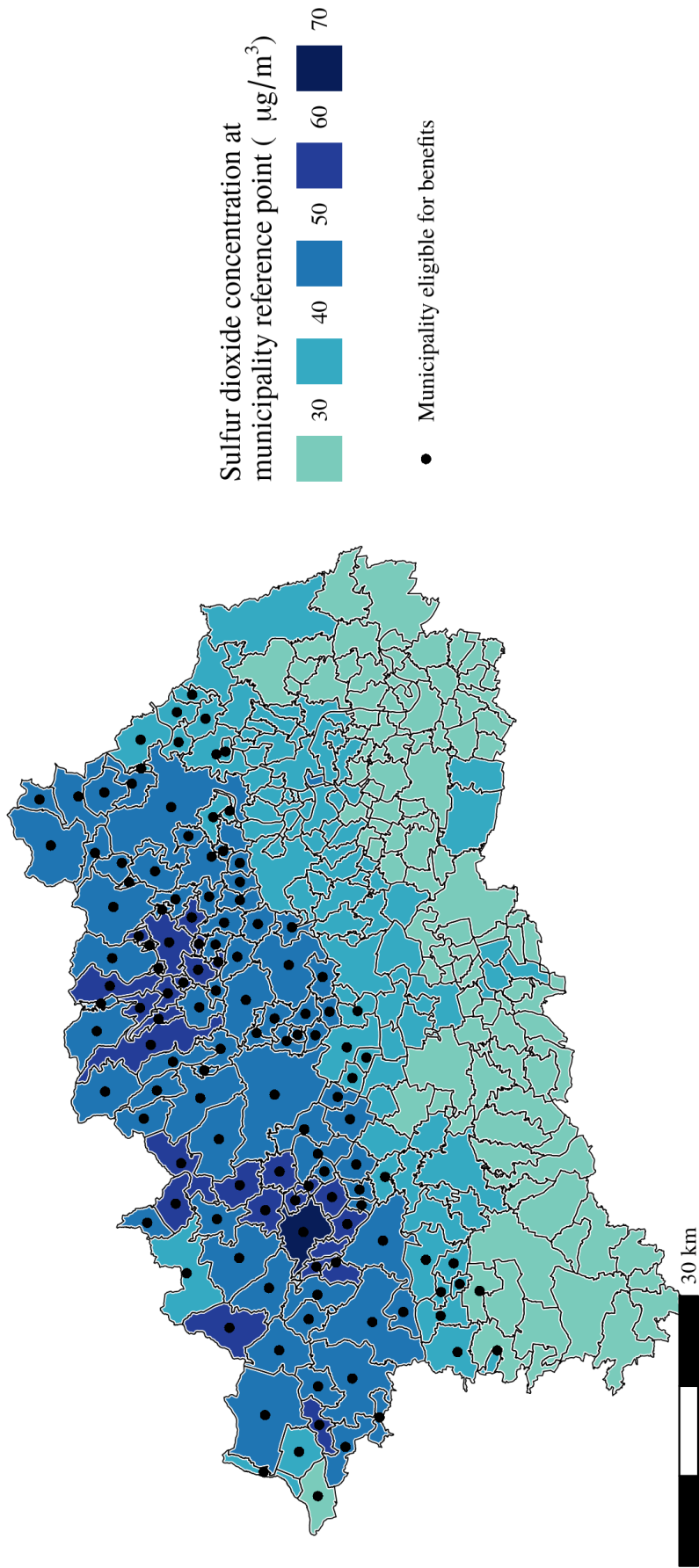


Figure 9: SO₂ concentrations in 1994 and eligibility for benefits (until 1992)

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

Table 6: Impact of eligibility for benefits on emigration rate (triple DiD strategy)

	Definition of benefits _i variable	
	Binary variable	Intensity measure
	(1)	(2)
Pre-desulfurization SO ₂ concentration = 40 μg/m ³ × Eligibility for benefits × Post-desulfurization period	-1.089 (1.652)	-0.588 (1.999)
Pre-desulfurization SO ₂ concentration = 40 μg/m ³ × Post-desulfurization period	-0.689** (0.325)	-0.589* (0.324)
Eligibility for benefits × Post-desulfurization period	0.453 (1.161)	-0.413 (1.390)
Adjusted R2	0.263	0.264
Observations	4,007	4,007

Notes: Table reports coefficients γ from Equation (2). All model specifications include constant, 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 SO₂ concentration is 30 μg/m³.

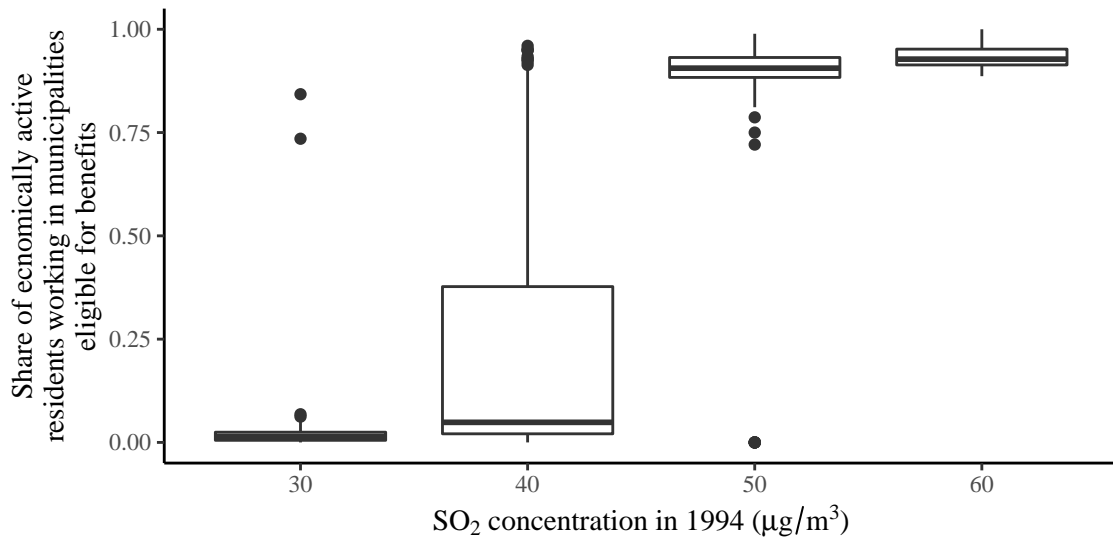
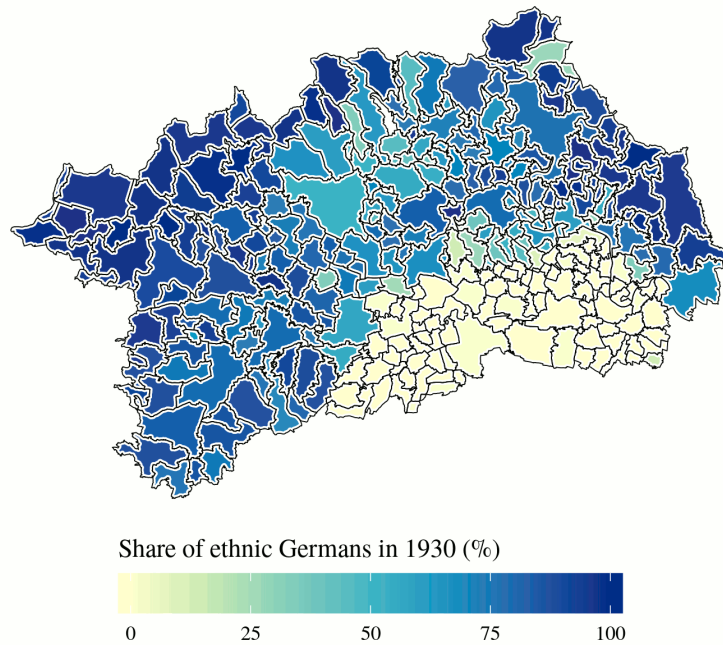
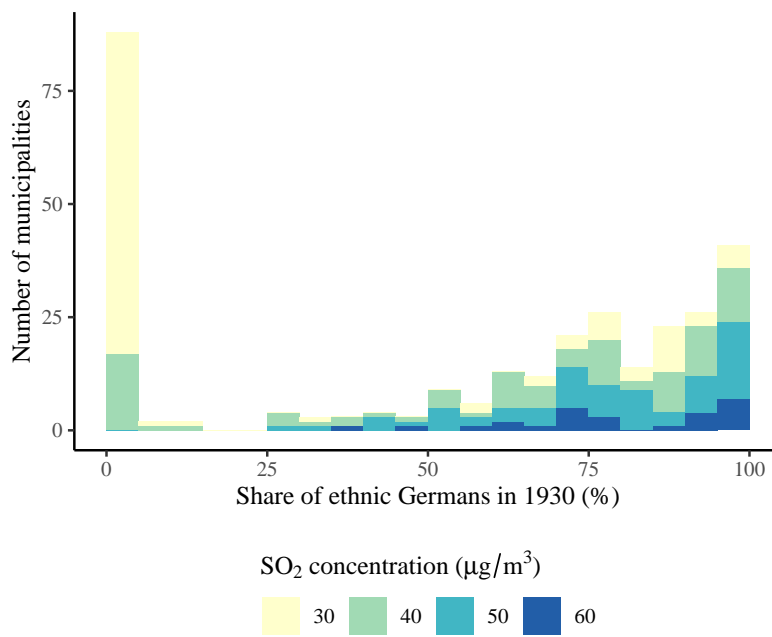


Figure 10: Share of population working in municipalities eligible for benefits on economically active population (1991) by SO₂ concentration in municipality of residence (1994).

Notes: Three outliers (in 50 μg/m³ category) with values above 1 are excluded from the Figure.



(a) Spatial distribution of ethnic Germans in 1930



(b) Municipalities by share of ethnic Germans in 1930 and SO₂ concentration in 1994

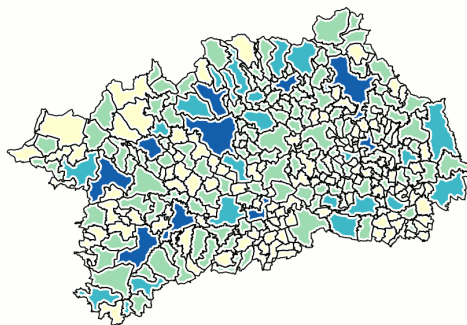
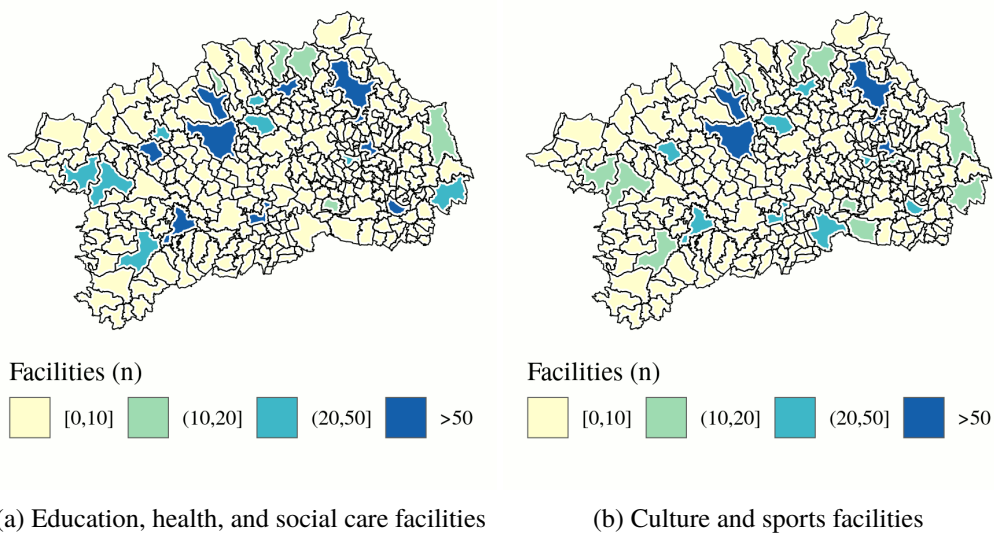
Figure 11: Distribution of ethnic Germans in 1930

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

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

	Sample split by share of ethnic Germans in 1930			
	$\leq 50\%$	$> 50\%$	$\leq 75\%$	$> 75\%$
	(1)	(2)	(3)	(4)
Pre-desulfurization SO ₂ concentration = 40 $\mu\text{g}/\text{m}^3$ × Post-desulfurization period	-0.307 (0.338)	-1.558* (0.831)	-0.558* (0.334)	-1.518 (1.043)
Pre-desulfurization SO ₂ concentration = 50 $\mu\text{g}/\text{m}^3$ × Post-desulfurization period	-1.154* (0.615)	-2.104*** (0.714)	-0.898*** (0.306)	-2.351*** (0.858)
Pre-desulfurization SO ₂ concentration = 60 $\mu\text{g}/\text{m}^3$ × Post-desulfurization period	-1.583** (0.658)	-1.982** (0.812)	-0.698* (0.364)	-2.216** (1.085)
Adjusted R2	0.183	0.351	0.279	0.353
Observations	2,207	3,999	3,469	2,737

Notes: Table reports coefficients γ from Equation (1). All model specifications include constant, 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 SO₂ concentration is 30 $\mu\text{g}/\text{m}^3$.



(c) Public administration facilities and public utilities

Figure 12: Spatial distribution of man-made amenities availability

Source: CZSO, ArcCR 500 v3.3. For details see Section XXX.

Table 8: Impact of man-made amenities availability on shaping migratory response to air pollution

	Sample split by median of man-man amenities availability					
	Education, health, and social care facilities		Culture and sports facilities		Public administration facilities and public utilities	
	Below	Above	Below	Above	Below	Above
	(1)	(2)	(3)	(4)	(5)	(6)
<i>Panel A: Amenities in the municipality</i>						
Pre-desulfurization SO ₂ concentration = 40 µg/m ³ × Post-desulfurization period	-1.686* (0.884)	-0.331 (0.281)	-0.804 (0.883)	-0.516 (0.328)	-0.978 (1.046)	-0.798** (0.323)
Pre-desulfurization SO ₂ concentration = 50 µg/m ³ × Post-desulfurization period	-2.601*** (0.828)	-0.630** (0.286)	-1.148* (0.643)	-1.624*** (0.547)	-2.186*** (0.771)	-1.332*** (0.413)
Pre-desulfurization SO ₂ concentration = 60 µg/m ³ × Post-desulfurization period	-1.159 (0.715)	-1.544** (0.777)	-1.403* (0.815)	-0.978** (0.406)	-2.316 (1.448)	-1.178*** (0.370)
Adjusted R2	0.348	0.416	0.375	0.311	0.373	0.333
Observations	3,168	3,061	3,050	3,179	3,310	2,919
<i>Panel B: Amenities within 20 km</i>						
Pre-desulfurization SO ₂ concentration = 40 µg/m ³ × Post-desulfurization period	-1.267* (0.670)	-0.471 (0.324)	-1.533* (0.784)	-0.350 (0.289)	-1.242 (0.782)	-0.485 (0.334)
Pre-desulfurization SO ₂ concentration = 50 µg/m ³ × Post-desulfurization period	-1.422** (0.562)	-1.694*** (0.590)	-2.624*** (0.808)	-0.948*** (0.332)	-1.550*** (0.585)	-1.805*** (0.643)
Pre-desulfurization SO ₂ concentration = 60 µg/m ³ × Post-desulfurization period	-2.994** (1.304)	-0.865** (0.418)	-2.309** (0.992)	-1.029** (0.411)	-1.960** (0.763)	-1.121** (0.455)
Adjusted R2	0.389	0.327	0.384	0.261	0.383	0.271
Observations	3,141	3,088	3,103	3,126	3,132	3,097

Notes: Table reports coefficients γ from Equation (1). All model specifications include constant, 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 SO₂ concentration is 30 µg/m³.

A Appendix

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
Pruněčov	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.

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. The subsidy could reach up to 65,000 Czechoslovak crowns (CSK) (186% of average annual wage as of 1985). Highly-skilled professionals could also get preferential access to public housing.
- Individual enterprises also often paid recruitment benefits up to 10,000 CSK (29% of average annual wage as of 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, 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 worked in basin districts for at least 10 years were eligible for a monetary benefit of 2,000 CSK per year (5.7% of average annual wage as of 1985).
- Government limited mobility of highly-qualified workers (medical doctors, pharmacists, teachers, and selected technical professions) from the region. Vaněk (1996) states that professional who tried to move out from the area could find themselves unable to find a job or housing in their destination region. Vaněk (1996) claims that this policy was executed on an informal basis from the beginning of 1980s. In 1984 the policy was incorporated into a government act No. 37/1984 (only for medical doctors and pharmacists). The regulation was abolished (both *de facto* and *de iure*) in 1986.
- The authorities did not inform the public regarding health risks or pollutant concentrations. Only by 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 heavily subsidized or free stays in clean mountain areas to children during inversions.

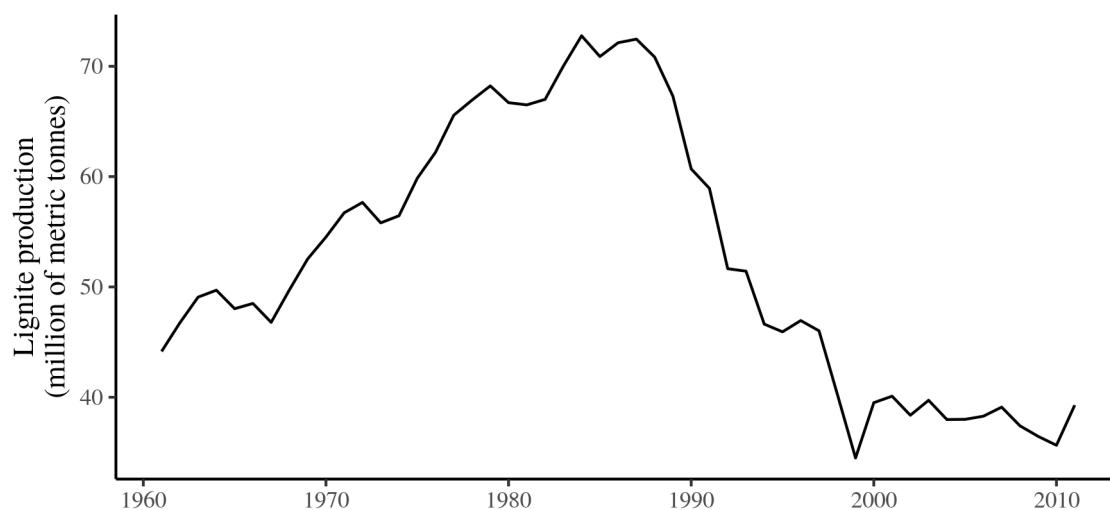


Figure A.1: Lignite mining in North Bohemia

Table A.2: Education structure by SO₂ concentration in 1994

		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
	Census	(1)	(2)	(3)	(4)	(5)
Primary educated (%)	1980	59.77 (0.47)	59.38 (0.79)	59.26 (0.88)	60.86 (1.00)	60.14 (1.26)
	1991	47.72 (0.45)	46.94 (0.75)	48.94 (0.88)	47.61 (0.90)	46.90 (1.19)
	2001	32.43 (0.37)	31.74 (0.66)	33.03 (0.70)	32.97 (0.73)	31.73 (0.80)
	2011	23.65 (0.31)	23.30 (0.51)	24.11 (0.60)	23.78 (0.61)	23.13 (0.70)
Secondary educated (%)	1980	37.59 (0.45)	38.06 (0.75)	38.15 (0.80)	36.64 (0.94)	36.37 (1.24)
	1991	49.43 (0.42)	50.57 (0.69)	48.27 (0.80)	49.05 (0.80)	49.85 (1.10)
	2001	62.76 (0.34)	63.86 (0.55)	62.21 (0.66)	61.93 (0.64)	62.47 (0.89)
	2011	64.17 (0.31)	65.69 (0.47)	63.80 (0.57)	62.38 (0.66)	64.25 (0.80)
Tertiary educated (%)	1980	1.32 (0.07)	1.38 (0.12)	1.32 (0.13)	1.29 (0.15)	1.17 (0.19)
	1991	1.82 (0.09)	1.98 (0.16)	1.77 (0.17)	1.72 (0.17)	1.68 (0.24)
	2001	2.99 (0.10)	2.94 (0.17)	3.02 (0.20)	3.03 (0.21)	2.99 (0.32)
	2011	5.86 (0.17)	5.48 (0.28)	5.89 (0.32)	6.15 (0.34)	6.42 (0.46)

Notes: All shares are defined for population age group 15+. Table reports means and standard errors in parentheses.

Table A.3: Age structure by SO₂ concentration in 1994

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

Notes: All shares are defined as shares on total population. Table reports means and standard errors in parentheses.

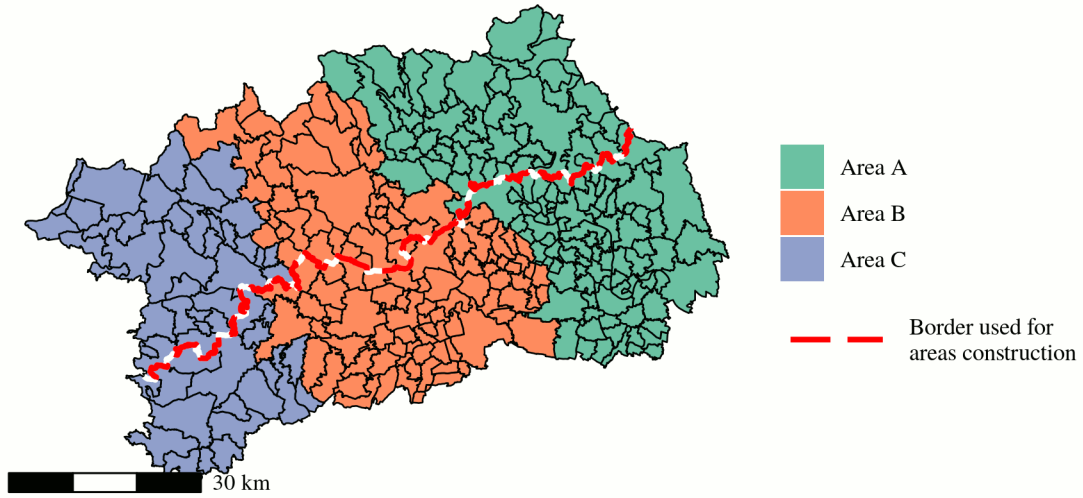


Figure A.2: Definition of areas

Table A.4: Main results of SO₂ concentration' decreases on immigration and net immigration rates

	Dependent variable	
	Immigration rate (%)	Net immigration rate (%)
	(1)	(2)
Pre-desulfurization SO ₂ concentration = 40 μg/m ³ × Post-desulfurization period	-0.533 (0.389)	0.344 (0.580)
Pre-desulfurization SO ₂ concentration = 50 μg/m ³ × Post-desulfurization period	1.061** (0.498)	2.756*** (0.751)
Pre-desulfurization SO ₂ concentration = 60 μg/m ³ × Post-desulfurization period	0.170 (0.583)	1.756** (0.882)
Adjusted R2	0.164	0.146
Observations	6,229	6,229

Notes: Table reports coefficients γ from Equation (1). All model specifications include constant, 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 SO₂ concentration is 30 μg/m³.

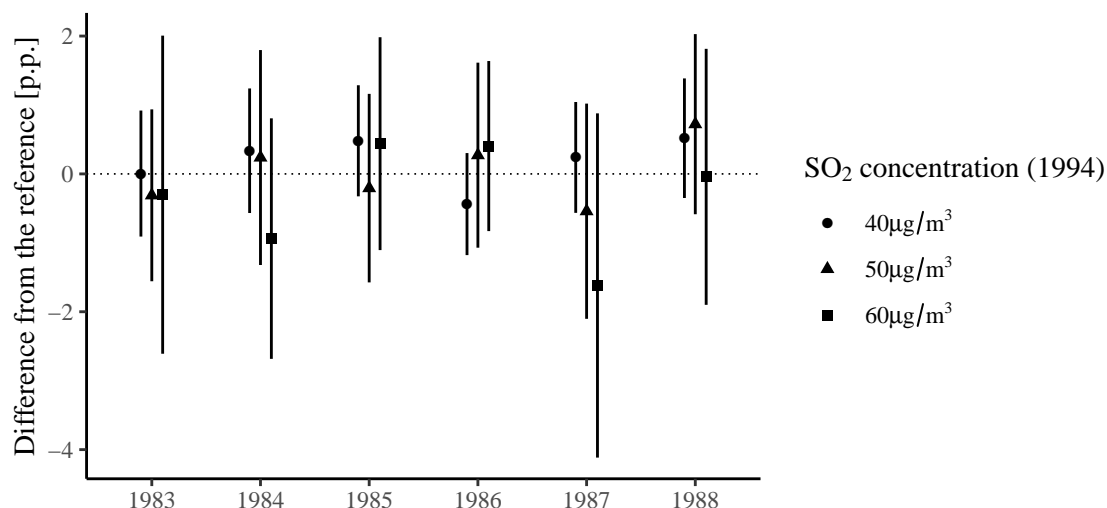


Figure A.3: Parallel trends assumption test

Points represent γ coefficients from the regression $mig_{it} = \gamma\theta_t SO_{ip} + \theta_t + \theta_i + \theta_a \times \theta_t + \varepsilon_{it}$, where the outcome is the emigration rate. The regression is estimated on the sample covering pre-desulfurization period (1983–1989) with year 1989 and pollution level $30 \mu\text{g}/\text{m}^3$ category used as a reference. Vertical lines depict 95% confidence intervals. All parameters are insignificant indicating no divergence in trends.

Table A.5: Impact of social capital on shaping migratory response to air pollution: controlling for education and age structure

	Sample split by share of ethnic Germans in 1930			
	$\leq 50\%$	$> 50\%$	$\leq 75\%$	$> 75\%$
	(1)	(2)	(3)	(4)
<i>Panel A: Nearest-neighbor interpolation</i>				
Pre-desulfurization SO_2 concentration = $40 \mu\text{g}/\text{m}^3$	-0.369	-1.604**	-0.647*	-1.643
× Post-desulfurization period	(0.348)	(0.810)	(0.338)	(1.023)
Pre-desulfurization SO_2 concentration = $50 \mu\text{g}/\text{m}^3$	-1.137*	-2.035***	-0.890***	-2.470***
× Post-desulfurization period	(0.619)	(0.703)	(0.285)	(0.841)
Pre-desulfurization SO_2 concentration = $60 \mu\text{g}/\text{m}^3$	-1.600**	-1.883**	-0.741**	-2.222**
× Post-desulfurization period	(0.706)	(0.818)	(0.357)	(1.080)
Adjusted R2	0.186	0.360	0.281	0.363
Observations	2,207	3,999	3,469	2,737
<i>Panel B: Linear interpolation</i>				
Pre-desulfurization SO_2 concentration = $40 \mu\text{g}/\text{m}^3$	-0.373	-1.610*	-0.708*	-1.631
× Post-desulfurization period	(0.363)	(0.822)	(0.370)	(1.042)
Pre-desulfurization SO_2 concentration = $50 \mu\text{g}/\text{m}^3$	-1.191*	-2.024***	-0.919***	-2.455***
× Post-desulfurization period	(0.627)	(0.699)	(0.286)	(0.833)
Pre-desulfurization SO_2 concentration = $60 \mu\text{g}/\text{m}^3$	-1.811**	-1.906**	-0.830**	-2.260**
× Post-desulfurization period	(0.714)	(0.788)	(0.382)	(1.006)
Adjusted R2	0.212	0.378	0.302	0.378
Observations	1,880	3,426	2,959	2,347

Notes: Table reports coefficients γ from Equation (1). All model specifications include constant, 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 $30 \mu\text{g}/\text{m}^3$.

Textbox A.2: Man-made amenities by group

- **Education, health and social care facilities:** Adult protective service facility; Community health center; Emergency medical service facility; Hospitals; Child protective service facility; Kindergartens; Language schools; Primary and secondary schools; Retirement houses; Spas; Universities; Vocational education institutes
- **Culture and sports facilities:** Amphitheatre (natural); Athletic fields; Cinema; Free time centers (for children); Gallery; Gyms; Museum; Other sport facilities; Public library; Sport stadiums; Swimming pools; Theater; Zoo (animal park)
- **Public administration facilities and public utilities:** Courts and legal system facilities; Firefighters squad; Firefighting facilities; Gas supply network; Job centers; Other offices; Police station; Post office; Urban planning offices; Waste management facilities; Water supply network

Table A.6: 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 (1)	30-39 (2)	40-49 (3)	50-59 (4)	60-69 (5)	Primary (6)	Secondary (7)	Tertiary (7)
<i>Panel A: Nearest-neighbor interpolation</i>								
Pre-desulfurization SO ₂ concentration = 40 μg/m ³ × Post-desulfurization period	-0.341 (0.328)	0.008 (0.360)	0.227 (0.372)	0.334 (0.393)	0.526 (0.377)	-0.062 (0.824)	-0.503 (0.822)	0.383 (0.283)
Pre-desulfurization SO ₂ concentration = 50 μg/m ³ × Post-desulfurization period	-0.388 (0.372)	0.110 (0.348)	0.186 (0.413)	-0.033 (0.433)	0.758 (0.496)	-0.243 (0.858)	-1.141 (0.896)	0.606** (0.299)
Pre-desulfurization SO ₂ concentration = 60 μg/m ³ × Post-desulfurization period	-0.367 (0.596)	-0.194 (0.571)	0.772 (0.504)	0.284 (0.411)	-0.237 (0.543)	-0.446 (1.163)	-0.130 (1.155)	0.794** (0.374)
Adjusted R2	0.544	0.518	0.411	0.419	0.581	0.932	0.889	0.799
Observations	6,923	6,923	6,923	6,923	6,923	6,923	6,923	6,923
<i>Panel B: Linear interpolation</i>								
Pre-desulfurization SO ₂ concentration = 40 μg/m ³ × Post-desulfurization period	-0.368 (0.323)	-0.013 (0.352)	0.205 (0.365)	0.384 (0.399)	0.541 (0.358)	0.056 (0.803)	-0.552 (0.794)	0.344 (0.262)
Pre-desulfurization SO ₂ concentration = 50 μg/m ³ × Post-desulfurization period	-0.440 (0.365)	0.062 (0.343)	0.185 (0.409)	0.068 (0.448)	0.771 (0.469)	-0.189 (0.844)	-1.005 (0.864)	0.537* (0.276)
Pre-desulfurization SO ₂ concentration = 60 μg/m ³ × Post-desulfurization period	-0.434 (0.609)	-0.205 (0.557)	0.781 (0.524)	0.340 (0.408)	-0.219 (0.528)	-0.439 (1.146)	-0.115 (1.116)	0.698** (0.344)
Adjusted R2	0.589	0.539	0.409	0.556	0.612	0.951	0.923	0.822
Observations	5,719	5,719	5,719	5,719	5,719	5,719	5,719	5,719

Notes: Table reports coefficients γ from Equation (1). All model specifications include constant, 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 SO₂ concentration is 30 μg/m³.

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- 2) reform of EU policies and the EU budget,
- 3) capital markets and the regulation of the financial sector and
- 4) governance and macroeconomic policy in the European Monetary Union.

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