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Migratory Responses to Air Pollution Reduction: Evidence from Large-scale Desulfurization Programme*

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This paper examines how improvements in air quality affect migration behavior. We exploit a natural experiment in the Czech Republic, where rapid desulfurization of coal-fired power plants in the 1990s led to a sharp reduction in SO_2 pollution - from extremely high levels to below EU/WHO limits - without directly impacting economic activity. Using a difference-in-differences approach, we find that cleaner air reduced emigration from previously heavily polluted municipalities by 24% and increased net migration by 78%, with effects strongest in the most polluted areas. The impact was particularly pronounced among highly educated individuals. Migration responses were strongest in municipalities with weaker social capital and fewer public amenities, suggesting that environmental improvements matter most where other local advantages are limited. In contrast, anti-emigration monetary subsidies—such as those offered during the socialist period in polluted areas—had no effect. Overall, our findings highlight the potential of environmental policies to support re-population and regional revitalization—especially when combined with investments in infrastructure and public services.

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1 Introduction

Air pollution is widely recognized as harmful to human health, affecting both physical and mental well-being and contributing to excess mortality across all age groups (see, e.g., Graff Zivin and Neidell 2013; Currie and Neidell 2005; Currie et al. 2009; Chay and Greenstone 2003; Newell et al. 2018; Selevan et al. 2018; Currie et al. 2014; Greenstone and Hanna 2014; Tanaka 2015; Schlenker and Walker 2015; Pun et al. 2017; Ng et al. 2024). A growing body of research has documented detrimental impacts of air pollution on a range of socio-economic outcomes, including health expenditures, labor supply, productivity, long-run earnings, cognitive development, and educational attainment (e.g., Hanna and Oliva 2015; Aragon et al. 2017; Isen et al. 2017; Chang et al. 2019; Fu et al. 2021; Bishop et al. 2023; Graff Zivin and Neidell 2012; Bharadwaj et al. 2017; Liu and Salvo 2018). Such evidence suggests that individuals may prefer to live and raise their children in cleaner environments and avoid polluted areas when possible.

Recent studies point to air pollution as a strong push factor for migration. For instance, Xu and Sylwester (2016) find that higher pollution levels are associated with greater emigration from low- and middle-income countries, particularly in Eastern Europe and Sub-Saharan Africa, while Chen et al. (2022) use thermal inversions as an instrument to show that air pollution drives substantial internal migration in China.[1] Yet the question of how migration responds to improvements in air quality remains largely unanswered. As a matter of fact, in response to the growing awareness of the socio-economic and health costs of environmental pollution, many countries have implemented policies and reforms aimed at improving air quality.[2] Consequently, air quality has improved in many parts of the world over time. Understanding the demographic and migratory responses to such environmental improvements is crucial for policymakers, particularly for regions facing population decline or economic disadvantage.

This paper provides, to the best of our knowledge, the first causal evidence on the migration response to a rapid and substantial improvement in air quality. We study a large-scale environmental intervention in North Bohemia, Czech Republic, where historically

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

2. For instance, the Gothenburg Protocol to Abate Acidification, Eutrophication and Ground-level Ozone (1999, revised 2012) aims at limiting air emissions of particulate matter, sulphur dioxide, nitrogen oxides, VOCs, ammonia, setting national emission ceilings for the main air pollutants. At the EU level, there is, for instance, the 2005 EU Thematic Strategy on Air Pollution, which set out strategic policy objectives; the 2001 National Emission Ceilings Directive (NECD), which established national emission ceilings for 2010 for all Member States on four main pollutants, or finally the Ambient Air Quality Directives, which are setting local air quality limits, which may not be exceeded anywhere in the EU.

high sulfur dioxide (SO_2) emissions from multiple lignite-burning power plants made the region one of the most polluted in Europe. Between 1992 and 1998, in compliance with new environmental regulations, coal-burning power plants installed modern desulfurization technologies. This technology-driven intervention sharply reduced SO_2 concentrations from levels far exceeding EU and WHO limits to levels below both standards, without directly affecting the region's economic activity *per se*. This technology-driven reduction in SO_2 emissions in the Czech Republic has been described, in fact, as one of the most dramatic historical examples of pollution reduction in Europe (Vestreng et al. 2007), offering a unique opportunity to identify the migration effects of cleaner air.

We estimate the effects of this environmental improvement using a difference-in-differences approach that compares changes in migration rates in municipalities with historically high versus low SO_2 exposure before and after desulfurization. Our results show that improved air quality significantly reduced emigration from formerly polluted municipalities. The effect is large: emigration rates declined by approximately 24%, with effects particularly pronounced in municipalities that experienced the highest levels of pre-desulfurization pollution. Net migration increased by 1.7 percentage points—equivalent to a 78% increase relative to less polluted areas. These effects are robust across a wide range of specifications, controls for local economic conditions and demographic structure. Further, we find that while immigration responses were smaller overall, cleaner air attracted more newcomers to municipalities with weaker labor markets, consistent with the idea that environmental quality acts as a compensating amenity in economically disadvantaged areas.

We then examine potential mechanisms. First, we show that anti-emigration governmental policy in the form of monetary benefits had no impact on emigration decisions. Second, we find stronger migration responses in municipalities with weaker social capital and fewer public amenities, suggesting that clean air matters most where other local advantages are scarce. Finally, the highly educated responded most to improved environmental quality, underscoring the potential of clean air to attract individuals important for long-term regional development.

In sum, by documenting the causal link between environmental improvements and migration, this study contributes to the literature on environmental migration and to broader research on migration determinants. Our findings suggest that environmental improvements can play a central role in reversing depopulation, especially when combined with strategic investments in local infrastructure, public services, and community resources.

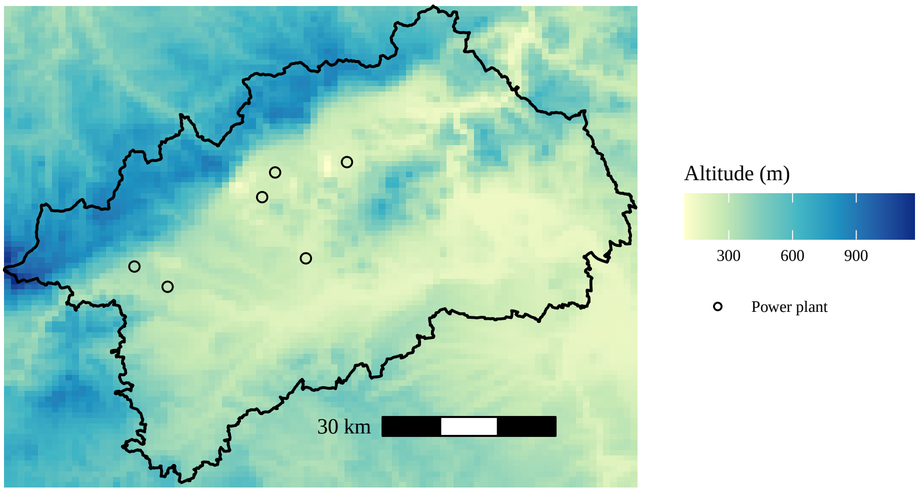


Figure 1: Altitude and power plant location in North Bohemia

Source: Shuttle Radar Topography Mission (SRTM) 1 Arc-Second Global (see Section 3.1).

2 Experimental setup: Historical Context

In the Czech Republic,[3] as in its Eastern European counterparts, the communist regime (1948–1989) prioritized heavy industry, fueling it with the region's abundant lignite reserves. North Bohemia, which contains the country's richest lignite deposits, became the center of energy production (see Appendix Figure A.1).[4] To minimize transportation costs, six lignite-burning power plant complexes (see Appendix Table A.1) were built close proximity to the mines, over an area of just 380 km^2, i.e. the equivalent of a 20×20 kilometer square. These power plants were often located near large cities, with little regard for environmental or health impacts on local residents. Energy production was so high a priority that the government even relocated most of the historical city of Most (a district capital) to allow mining expansion (see Appendix Figure A.2, and for details see Spurny (2016)).

About two-thirds of the lignite was consumed by power plants (Vaněk 1996); the rest was used in heating systems. The widespread use of sulfur-rich lignite resulted in high emissions of SO_2— a pollutant linked to severe health risks. The region's geography—surrounded by mountains, as can be seen from Figure 1—further limited the dispersion of unfiltered emissions, amplifying SO_2 pollution concentrations..

Figure 2 shows the long-term development of SO_2 concentrations in the region from 1970 onwards (see Section 3.1 for details on our data). The concentration levels were

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

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

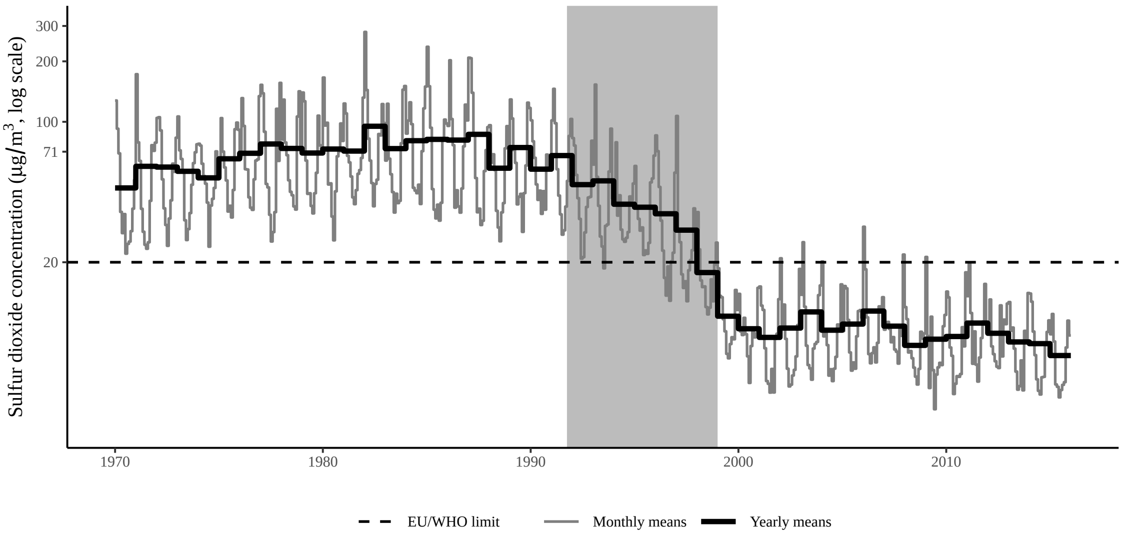


Figure 2: Development in SO_2 concentrations in the region over the period 1970–2015.

Source: Czech Hydrometeorological Institute (CHMI, see Section 3.1); Limits by: World Health Organization (2006).

remarkably stable from the beginning of the 1970s to the early 1990s. The annual mean SO_2 concentration reached 63 $\mu g/m^3$ in the 1970s and 78 $\mu g/m^3$ in the 1980s, surpassing even Beijing's average level of 71 $\mu g/m^3$ in 2000 (UNEP 2007) and almost four times exceeding the level of 20 $\mu g/m^3$[5], which is the EU annual limit (EU 2015) and World Health Organization (WHO) guideline for maximum 24-hour SO_2 exposition (World Health Organization 2006).[6]

The resulting environmental degradation had serious public health consequences. Several studies document lower life expectancy (Kotěsovec et al. 2000), higher risks of intrauterine growth retardation (Dejmek et al. 1999), and other adverse health outcomes in the region. Although the communist government was aware of these environmental issues as early as the 1960s (Glassheim 2006; Vaněk 1996), it took no action to mitigate them. Reducing pollution by decreasing energy production was not seen as an option among the communist leaders, as there were no alternative power sources available to fuel the planned industrial production, which grew steadily throughout the 1960s and 1970s. Technical means of desulfurization were also unavailable: the Soviet desulfurization technology was untested and not suitable for the Czech power plants (Kratochvíl 2011), while importing western technology would have been too expensive for a country struggling with a permanent lack of convertible currency (Vaněk 1996). As a result, the region became

5. Winter peak SO_2 concentrations were much higher. Pinto et al. (1998) report SO_2 concentrations in Teplice reaching 1600 $\mu g/m^3$ in 1993, comparable to London's 1952 smog levels of 1800 $\mu g/m^3$.

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

Figure 3: Net migration rate in North Bohemian municipalities (1971–2022)

Source: Czech Statistical Office (CZSO, see Section 3.1)

a symbol of industrial sacrifice–an "experiment" of the central government in maximizing energy output at minimal cost (Glassheim 2006).

The willingness of residents to tolerate —at least to some degree—such pollution, may have been linked to the region's unique post-war history: the North Bohemian region was originally primarily populated by ethnic Germans, who were forcibly expelled after WWII. The empty towns and villages were then resettled by people from other parts of the Czechoslovakia, many of whom had weak historical or emotional ties to the area (see Guzi et al. 2021, for details on this resettlement process, as well as the Section 5.5.2 for more details). The state's propaganda helped forge a new regional identity around coal and mining, which may have temporarily increased tolerance for environmental degradation (see Glassheim 2006). Nonetheless, the region experienced consistent out-migration throughout the 1970s and 1980s, see Figure 3.

This steady de-population tendency posed a threat to the regime's production goals. Consequently, the government implemented a series of monetary and non-monetary policies to counter the population decline. The most generous benefits targeted newcomers, particularly high-skilled professionals. For example, newcomers could receive house-building subsidies of up to 186% of the average annual wage in 1985 or recruitment bonuses worth 29% of the average wage.[7] For an overview of benefits, see Appendix Textbox A.1. On the other hand, the benefits designed to keep workers in the region were more universal, but far less generous. Anyone who worked in the basin districts (four of the six districts in

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).

the region) for at least 10 years was eligible for an annual retention benefit of 5.7% of the average annual wage in 1985. Locals used to call it "burial benefit" *("pohřebné").*

While these various benefits initially raised the income of workers in North Bohemia above the national average (Vaněk 1996), wage convergence in the late 1980s fueled local dissatisfaction (Vaněk 1996). Growing frustration culminated in environmental protests: in May 1989, the first environmental demonstration in Czechoslovakia took place. Following a severe temperature inversion on November 8th 1989 mass protests erupted in Teplice with slogans like *"We want healthy children!"* and *"We want clean air!"*. Other cities in the North Bohemian coal basin later joined the protests (Vaněk 1996). Shortly afterwards, on November 17th 1989, the major anti-regime demonstration, which marked the beginning of the Velvet Revolution and the fall of the communist regime in Czechoslovakia, took place in Prague. It was thus not the Communist Party but rather the new government, sworn in on December 10th 1989, whose task it was to respond to these demands.

2.1 Policy Response and Desulfurization

The new government launched a complex process of political and economic transition, a fundamental part of which was to introduce legislation aimed at improving environmental conditions and the Czech population's quality of life. These environmental reforms replaced rather than complemented earlier government efforts to retain or attract residents through monetary benefits.[8] Two major policies were adopted in the early years after the revolution that helped to reduce pollution in North Bohemia:

- *Regulation of SO_2 emissions*: Act no. 309, passed in 1991, set an obligation for the government to provide the general public with full and up-to-date information on air quality and emission sources and established a framework for the regulation of emissions and immissions. The law effectively required rapid installation of modern desulfurization technologies before December 31st 1998—i.e. within seven years.[9] This strict deadline forced existing power plants to implement desulfurization technologies swiftly. The first power plant (Komořany) commenced desulfurization in 1993. Others followed in 1994 and later. The last power plant in the region implemented desulfurization technologies in early 1999 (see Table A.1 in the Appendix).

8. The immigration and anti-emigration benefits previously introduced in North Bohemia were abandoned alongside the implementation of new environmental regulations. While retention benefits were initially maintained under Acts No. 276/1991 and 471/1991, they were abolished shortly thereafter by Act No. 1/1992, passed in December 1991.

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

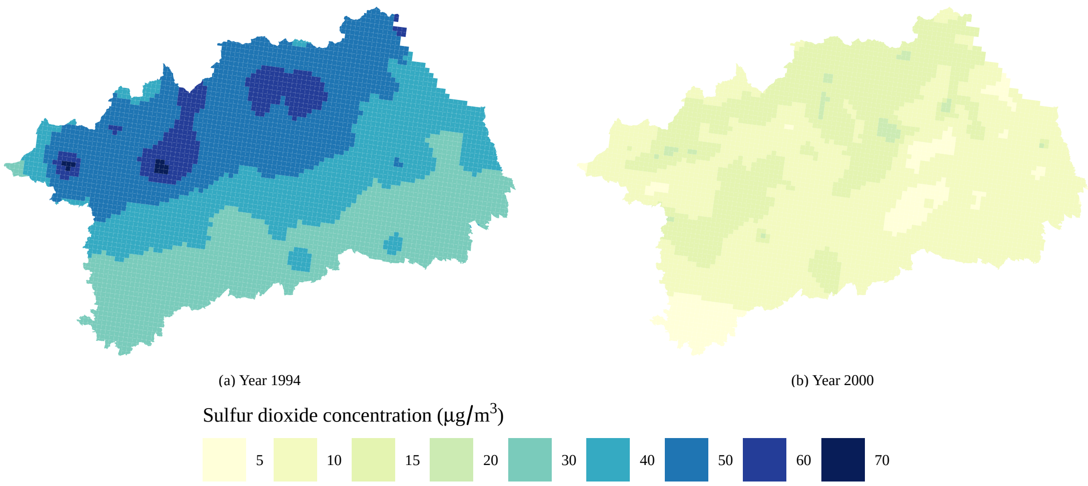


Figure 4: Spatial distribution of SO_2 concentrations in North Bohemia, year 1994 and 2000
Source: Czech Hydrometeorological Institute (CHMI, see Section 3.1)

- *Limits on lignite mining*: Government Resolution No. 444/1991 set limits on mining activity which, together with the drop in demand caused by the economic downturn during the transition period, led to a decrease in coal production during the 1990s, from 67 million metric tons in 1989 to 40 million metric tons in 2000 (see Figure A.6 in the Appendix).

As shown in Figure 4, these policies led to a dramatic improvement in air quality. Figure 4 shows the spatial distribution of SO_2 concentrations in North Bohemia in 1994, at the beginning of the desulfurization period (older data are not available) and after the completion of the desulfurization period, in 2000. In 1994, all municipalities still exceeded the EU/WHO limit of $20\,\mu g/m^3$, with average SO_2 concentrations ranging widely from 30 to $70\,\mu g/m^3$. By 2000, following desulfurization, average SO_2 concentrations in the region had dropped below $20\,\mu g/m^3$, and according to the CHMI dispersion model, all municipalities—regardless of their initial pollution levels—benefited from this decline, with concentrations ranging from 5 to $20\,\mu g/m^3$ and meeting the EU/WHO limit. The decline in SO_2 pollution was tightly correlated with pre-desulfurization levels (Figure 5; Pearson's $\rho = -0.95$), reflecting the uniform effectiveness of the intervention across municipalities.

3 Conceptual Framework and Data

Improvements in air quality are expected to reduce immediate health risks—such as respiratory and cardiovascular diseases, and premature mortality (e.g., Graff Zivin and Neidell 2013)—which in turn can enhance the livability of a region. These benefits are

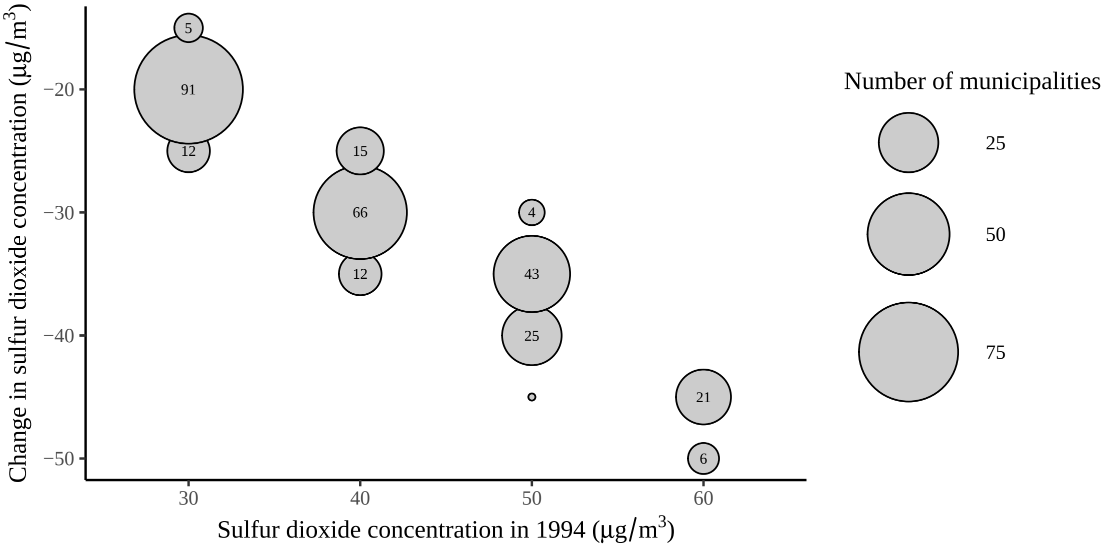


Figure 5: Change in SO_2 concentration between 1994 and 2000 categorized by 1994 SO_2 concentration

particularly salient for vulnerable populations such as children, the elderly, and individuals with pre-existing health conditions. As a result, cleaner air enhances perceived quality of life, which can lower the incentive to emigrate from polluted regions in search of better health or living conditions.

In addition to direct health effects, cleaner environments can indirectly, *ceteris paribus*, improve socio-economic outcomes, such as employment opportunities, labor supply/hours worked (Hanna and Oliva 2015), labor productivity (Graff Zivin and Neidell 2012), long-run earnings (Isen et al. 2017). These improvements may further reduce out-migration by increasing the opportunity cost of leaving.

Improved air quality may also attract in-migration by enhancing the perceived quality of life in formerly polluted regions. Cleaner air makes areas that once had high pollution levels attractive to people who might have previously avoided them due to health concerns. However, the decision to move is typically more costly and uncertain than the decision to stay. Therefore, the influence of environmental quality on in-migration may be more conditional—it may become a decisive factor only when accompanied by favorable economic conditions or when the quality-of-life benefits from cleaner air offset weaker local labor markets. In this context, migration costs and perceived economic opportunities can moderate the responsiveness of immigration flows to environmental improvements.

In summary, improved air quality in polluted regions can reduce out-migration by by improving local livability and economic performance, and may attract immigration where migration costs are low or offset by environmental or economic benefits. Both channels contribute to greater net migration and support re-population in formerly polluted areas.

Theoretically, the majority of studies investigating determinants of migration is rooted in the human capital investment theory of migration, wherein immigration is seen as a form of investment in human capital (Sjaastad 1962; Todaro 1969; Adserà and Pytliková 2015; Adunts and Pytliková 2023). Potential migrants assess the expected discounted returns to and costs of migration and move to destinations where the discounted net return to migration is greatest (Massey et al. 1993).

Below we present a simple human capital migration model adjusted for environmental concerns. In our model, the individual maximizes the net present value (NPV) of staying versus migrating by evaluating the present value of income and environmental quality across locations while accounting for migration costs.

Let individual k choose between staying in region i or migrating to region j. First, let's assume that the individual compares the present value (PV) of expected future incomes in regions i and j:

- Stay in i:

$$\mathrm{PV}_{ki} = \sum_{t=0}^{T} \frac{Y_{ki}(t)}{(1+r)^t} \tag{1}$$

- Move to j:

$$\mathrm{PV}_{kj} = \sum_{t=1}^{T} \frac{Y_{kj}(t)}{(1+r)^t} \tag{2}$$

Where $Y_{kj}(t)$ denotes expected income of individual k in location j at time t, r denotes a discount rate (reflecting time preference) and T the time horizon over which decisions of individuals are evaluated.

Second, the individual k considers the quality of the environment such as air quality, treated here as a "non-monetary amenity" that contributes to his/her utility. Thus, the individual compares the present discounted value of environmental quality, EV, in regions i and j:

- Stay in i:

$$\mathrm{EV}_{ki} = \sum_{t=0}^{T} \frac{Q_{ki}(t)}{(1+r)^t} \tag{3}$$

- Move to j:

$$\text{EV}_{kj} = \sum_{t=1}^{T} \frac{Q_{kj}(t)}{(1+r)^t} \tag{4}$$

Where $Q_{kj}(t)$ denotes perceived environmental quality in location j at time t.

The total net present value, NPV, of migrating from i to j is then a combination of income and environmental quality differences adjusted for the costs of moving:

$$\text{NPV}_{kij} = \left(\sum_{t=1}^{T} \frac{Y_{kj}(t)}{(1+r)^t} + \Phi \sum_{t=1}^{T} \frac{Q_{kj}(t)}{(1+r)^t} \right) - \left(\sum_{t=0}^{T} \frac{Y_{ki}(t)}{(1+r)^t} + \Phi \sum_{t=0}^{T} \frac{Q_{ki}(t)}{(1+r)^t} \right) - C_{kij} \tag{5}$$

Where:

- Φ: preference weight on environmental quality, i.e. parameter capturing how strongly the individual values environmental quality
- C_{kij}: cost of moving from i to j, which can be in the form of direct out-of-pocket costs of migrating and psychological costs of leaving family and friends, and the existing community and childhood places.

The individual is more likely to move if the expected income and amenity gains outweigh the costs. If individuals value environmental quality (i.e. $\Phi > 0$), then a more polluted environment in i compared to j increases emigration from i. Conversely, environmental improvements in i increase the incentive to stay. However, in evaluating whether to migrate to a cleaner region j, the cost of moving, C_{kij}, plays a crucial role. Migration involves both direct monetary and indirect psychological costs as well as uncertainty, so individuals will only relocate if the expected net benefits are substantial. Due to the cost of moving, improvements in j may not necessarily attract large numbers of newcomers unless accompanied by additional incentives, such as better economic prospects. However, environmental quality can also act as a compensating amenity that makes even economically weaker regions more attractive. This logic follows the classic compensating differentials framework developed by Rosen (1979) and Roback (1982), which suggests that individuals may accept lower wages in exchange for higher non-monetary amenities such as cleaner air, safer neighborhoods, or better climate. In this spirit, our model allows for the possibility that cleaner air can partially offset poor labor market conditions, especially when the environmental improvement is large or highly salient.

The discount rate, r, affects relative importance of future benefits: if r is high, i individuals are less likely to move unless benefits from income or amenities are immediate.

Finally, high migration costs C_{kij} reduce migration unless income or environmental quality differentials are substantial.

In this extended human capital migration framework, individuals maximize their utility by evaluating the present value of income and environmental quality across locations while accounting for the costs of moving. Migration occurs if the expected net benefits of moving to a new location exceed the costs. Improved air quality acts both as a direct amenity (enhancing utility) and indirectly by improving health, employment, productivity and earnings, thereby influencing the income component. This conceptual framework provides an intuitive way to see the trade-offs between economic opportunities, living in a clean environment and the costs of migration that individuals face when making residential choices.

3.1 Data

The primary data sets used in our empirical analysis are municipality-level data on residential migration and sulfur dioxide concentrations. The annual data on residential migration are compiled by the Czech Statistical Office (CZSO) from administrative records on permanent residence changes in the period from 1971 onwards.[10] People in the Czech Republic were and are legally obliged to register their place of permanent residence. Moreover, they are motivated to keep this registration up to date, as preferential access to some public services is granted on the basis of permanent residence (such as kindergartens, elementary schools or local health care). The dataset contains information on the numbers of people who moved in and out of each municipal area in each year. For the purposes of our analysis, we calculate annual municipality-level emigration and immigration rates as the number of movers per resident population, using those gross emigration and immigration levels, and population as of January 1st. Some records on residential migration, mostly from smaller municipalities, are missing due to changes in municipality boundaries or because they were lost before the records were digitized.

We utilize two sources of data on municipality-level air pollution. First, concentrations of SO_2 and other pollutants are measured by a network of ground measuring stations run by the Czech Hydrometeorological Institute (CHMI). This network is unfortunately too sparse to provide reliable municipality-level pollution data and therefore not optimal for our empirical analysis, but it does at least enable us to observe the long-term development of overall SO_2 concentrations in the region for our descriptive evidence (as depicted in Figure

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

2).[11] Our second source of data on municipality-level pollution concentration comes from a proprietary CHMI dispersion model, which takes into account local meteorological and topographic conditions as well as pollution source characteristics. The detailed resolution of the dispersion model on a 1 km grid allows us to capture pollution distribution at municipality level, represented by coordinates of their reference points, and provides us with the richer data we need for our empirical analysis.[12] We use data from two iterations of the model: for 1994 (the oldest iteration available) and for the year 2000 (the year after the desulfurization programme completion). The CHMI dispersion model provides pollution-level categories rather than predictions on a continuous scale. The model categorizes municipalities into five groups by SO_2 concentrations in 1994: 30, 40, 50, 60, and 70 $\mu g/m^3$; and four groups in 2000: 5, 10, 15, and 20 $\mu g/m^3$ (see Figure 4).[13]

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

Lastly, we employ several other datasets in our analysis. We use the ArcČR 500 v3.3 map collection to define the administrative borders of the examined municipalities and to make geospatial visualizations.[16] Further, we obtain altitude data from remotely sensed elevation grid data from the Shuttle Radar Topography Mission (SRTM) 1 Arc-Second Global.[17] The altitude of each municipality is defined as the altitude at the municipality reference point. The driving distances between the municipalities are calculated using

11. Data from individual measuring stations are available from CHMI website: https://www.chmi.cz/files/portal/docs/uoco/historicka_data/OpenIsko_data/index.html. Frequent changes in the measuring network (in the locations, number of stations, and technology used) do not allow us to construct consistent long-term time series for the individual measuring stations.

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

13. Figure A.4 in the Appendix compares values predicted by the dispersion model with annual averages from ground measuring stations. The Figure shows that the dispersion model somewhat overestimate the pollution concentrations. On the other hand it correctly orders measuring stations by SO_2 concentrations.

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

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

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

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

Open street map (OSM) data[18] and GraphHopper navigation software (version 7.0). To capture the yearly municipality-level unemployment rate we use administrative data on registered unemployment. These data are unfortunately only for the periods 2001–2011 and 2013–2015.[19] Therefore, we impute missing values for each municipality in the following steps: (a) We assume the unemployment rate to have been equal to zero before the fall of communism – i.e., in the pre-desulfurization period, (b) the number of unemployed in 2012 is put equal to the the mean of 2011 and 2013 values, and (c) we use linear interpolation for missing values in post-desulfurization period based on the 2001–2004 period. Our data on man-made amenities come from the MOS database on regions and municipalities, administered by the CZSO.[20]

3.1.1 Estimation Sample

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

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

As we mentioned above, environmental concerns were one of the issues central to the 1989 protests. People expected the new government to take decisive measures to improve the environment. The government swiftly addressed this demand by passing several laws and regulations in 1991. To ensure that our results are not driven by (legitimate) expectations for the future improvement of the environment, we exclude the period 1990–1991 from our

18. The OSM database for the Czech Republic was downloaded from geofabrik.de on May 1st 2023.

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

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

estimation sample. Moreover, migration behavior in the 1990s is likely to have been driven by expectations of a future cleaner environment, fueled by the ongoing desulfurization process, rather than by actual pollution levels. As a result, we define the pre-desulfurization period as the years 1983–1989 and the post-desulfurization period as the years 2000–2015.

The CHMI dispersion model calculates SO_2 concentrations in five levels between 30 and 70 $\mu g/m^3$ in 1994, which we use to essentially categorize municipalities based on their pre-desulfurization pollution levels. The highest level of 70 $\mu g/m^3$ is calculated for only one municipality: the district capital Chomutov. As we estimate the effect of desulfurization for each pollution level to reflect the potentially non-linear effect of air pollution, the effect for this pollution level would be estimated using only one independent observation. Therefore, we exclude Chomutov from the estimation sample used in our main analysis, and work with only four 1994 SO_2 concentration levels (30, 40, 50 and 60 $\mu g/m^3$) to categorize the municipalities according to pollution[21]. Overall, our baseline estimation sample thus contains data for 301 municipalities for the years 1983–1989 and 2000–2015, a total of 6,229 data-points.[22]

3.1.2 Descriptive Evidence

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

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

Regarding population movement, both emigration and immigration rates differed between the pre- and post-desulfurization periods, see Table 2, Panel A and B. The mean emigration rate in the pre-desulfurization period reached 5.2‰ and the immigration rate 3.1‰. After desulfurization, which reduced the SO_2 concentration to below EU and WHO

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

22. Due to administrative reforms six data-points are missing in regressions controlling for population and education structure.

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

	Year	Municipalities in estimation sample					
		All	By SO_2 concentration (1994)				
			30 $\mu g/m^3$	>30 $\mu g/m^3$			
				All	40 $\mu g/m^3$	50 $\mu g/m^3$	60 $\mu g/m^3$
		(1)	(2)	(3)	(4)	(5)	(6)
SO_2 concentration ($\mu g/m^3$)	1994	40.63		46.58			
		(0.56)		(0.51)			
	2000	11.11	9.68	11.92	10.16	13.42	13.89
		(0.17)	(0.19)	(0.23)	(0.28)	(0.35)	(0.41)
Population	1980	2189.87	880.11	2870.08	1526.87	4129.21	3771.27
		(457.29)	(182.86)	(683.48)	(438.12)	(1476.15)	(2062.93)
	1991	2327.62	886.37	3130.13	1615.58	4748.40	3598.15
		(530.05)	(176.41)	(813.91)	(497.38)	(1848.96)	(2016.66)
	2001	2110.81	824.90	2830.39	1393.43	4355.64	3656.07
		(464.42)	(162.69)	(714.02)	(402.67)	(1654.62)	(1973.76)
	2011	2145.70	865.46	2862.10	1409.48	4394.44	3722.59
		(457.30)	(162.45)	(702.80)	(387.07)	(1630.81)	(1944.76)
Altitude (m)		286.32	242.96	310.57	266.52	350.31	354.89
		(8.08)	(9.38)	(11.10)	(12.32)	(19.49)	(36.19)
Terrain roughness index (TRI)		2.48	1.78	2.87	2.70	3.20	2.56
		(0.082)	(0.072)	(0.11)	(0.17)	(0.16)	(0.25)
Share of ethnic Germans (%)	1930	54.24	26.81	69.66	60.56	77.84	79.28
		(2.23)	(3.73)	(2.07)	(3.60)	(2.11)	(3.30)
Share of small municipalities (%)		83.7	89.8	80.3	86.0	76.7	70.4
Municipalities (n)		301	108	193	93	73	27

Notes: Table reports means and standard errors in parentheses. Small municipalities are municipalities with mean population lower or equal to 1500.

Table 2: Migration rates by period and SO_2 concentration

	Municipalities in estimation sample					
	All	By SO_2 concentration (1994)				
		$30\,\mu g/m^3$	$>30\,\mu g/m^3$			
			All	$40\,\mu g/m^3$	$50\,\mu g/m^3$	$60\,\mu g/m^3$
	(1)	(2)	(3)	(4)	(5)	(6)
	Panel A: Emigration rate					
Post-desulfurization period (%)	3.46	3.09	3.67	3.56	3.84	3.62
	(0.074)	(0.092)	(0.10)	(0.12)	(0.20)	(0.21)
Pre-desulfurization period (%)	5.21	3.77	5.85	5.08	6.46	5.89
	(0.22)	(0.15)	(0.30)	(0.41)	(0.48)	(0.69)
Difference (p.p.)	-1.74^{***}	-0.68^{***}	-2.18^{***}	-1.52^{***}	-2.62^{***}	-2.27^{***}
	(0.20)	(0.15)	(0.27)	(0.40)	(0.42)	(0.54)
	Panel B: Immigration rate					
Post-desulfurization period (%)	4.58	4.05	4.88	4.54	5.26	5.01
	(0.11)	(0.13)	(0.16)	(0.19)	(0.32)	(0.27)
Pre-desulfurization period (%)	3.05	2.59	3.26	3.48	2.99	3.46
	(0.12)	(0.18)	(0.16)	(0.27)	(0.22)	(0.43)
Difference (p.p.)	1.53^{***}	1.46^{***}	1.62^{***}	1.06^{***}	2.27^{***}	1.55^{***}
	(0.17)	(0.21)	(0.23)	(0.32)	(0.39)	(0.55)
	Panel C: Net migration rate					
Post-desulfurization period (%)	1.12	0.96	1.21	0.99	1.42	1.39
	(0.074)	(0.081)	(0.11)	(0.12)	(0.22)	(0.19)
Pre-desulfurization period (%)	−2.16	−1.18	−2.60	−1.60	−3.47	−2.43
	(0.25)	(0.19)	(0.35)	(0.41)	(0.57)	(0.89)
Difference (p.p.)	3.28^{***}	2.14^{***}	3.80^{***}	2.58^{***}	4.89^{***}	3.82^{***}
	(0.29)	(0.21)	(0.40)	(0.46)	(0.71)	(0.94)
Municipalities (n)	301	108	193	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%.

limits, the emigration rate dropped by 1.7 percentage points, while the immigration rate rose by 1.5 percentage points (see column (1) in Table 2).

These changes in emigration and immigration are reflected in the development of the net migration rates[23], see Table 2, Panel C, which shows that in the pre-desulfurization period, the region experienced a negative net immigration rate with a mean of −2.2% per year despite the pro-immigration and anti-emigration policies in place at the time. The mean net migration rate in the post-desulfurization period rose by 3.3 percentage points to 1.1%. Further, Figure 3 shows long-term development in the average net migration rate over the years 1971–2015. As can be seen, the net migration rate turned to positive after the beginning of the desulfurization process. This evidence suggests that the substantial

23. Defined as immigration minus emigration by population.

reduction in air pollution brought about through desulfurization increased the region's attractiveness.

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

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

Figure 6 shows development in the emigration and immigration rates, respectively, by pollution levels, from 1983 through to 2015, including the whole of the desulfurization period (1994–1999). As Figure 6 reveals, there was a strong decline in emigration rates shortly after the fall of communism; that decline was particularly sharp in 1991, when the new environmental legislation was adopted. The emigration rates dropped at this stage for all groups of municipalities, even those whose pollution levels were still high at that time. This could be due to expectations of a future reduction in pollution supported by the new legislation.

On the contrary, the fall of communism seems not to have any clear immediate effect on immigration rates, as can be seen in Figure 6: the overall increase in immigration rates did not start until mid-nineties, once the implementation of desulfurization technology at the power-plants was already effective.

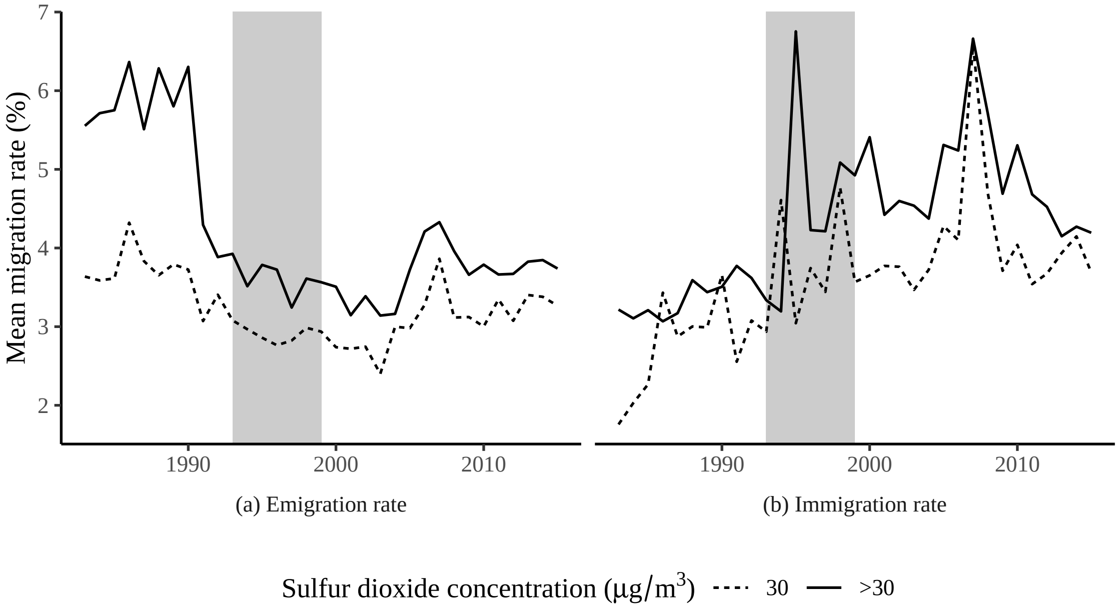


Figure 6: Migration rates in municipalities in North Bohemia by 1994 SO_2 concentration, years 1983–2015

Source: CZSO (see Section 3.1)

4 Identification Strategy and Empirical Specification

To isolate the causal effects of air pollution reduction on migration, we estimate difference-in-differences (DiD) model that compares migration rates across municipalities with different pre-desulfurization SO_2 concentration, before and after desulfurization program (1983–1989) vs. (2000–2015). Our baseline specification is:

$$mig_{it} = \alpha + \beta_i \left(Post_t \times SO2_i\right) + Post_t + \delta_i + \mathbf{X}'_{it-1}\boldsymbol{\theta} + \varepsilon_{it} \tag{6}$$

where mig_{it} is the migration rate in municipality i and in year t (we estimate separate models for emigration, immigration and net migration rate), $Post_t$ is a a dummy variable, which is equal to 1 for the post-desulfurization period (2000–2015) and 0 for the pre-desulfurization period (1983–1989), and ($SO2_i$) stands for a dummy variable for municipalities whose SO_2 concentrations in the pre-desulfurization period were greater than or equal to 40 $\mu g/m^3$.

To capture the overall effect of the reduction in air pollution due to desulfurization, we interact the dummy variable for the post-desulfurization period, $Post_t$, with $SO2_i$ air pollution indicator[24]. The β_i DiD coefficient is the coefficient of our interest.

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

The vector ($\mathbf{X}'_{it-1}$) includes controls for local time-variant characteristics. First, we use unemployment rate in municipality i, time $t-1$, as a proxy for local labor market conditions.[25] The unemployment rate is lagged by one year in the specification to capture local economic conditions while treating it as predetermined with respect to current migration decisions, thereby mitigating concerns about simultaneity or reverse causality. In addition to using lagged unemployment rates as a proxy for local economic conditions, we also estimate specifications that include regional linear time trends. To do so, we divide the study area into three subregions (areas) that are orthogonal to the spatial distribution of pollution exposure.[26] For each area, we incorporate an area-specific linear trend, ($\gamma_{r(i)}t$). This approach allows us to flexibly control for unobserved, gradually evolving regional characteristics—such as changes in economic structure, demographic dynamics, or public investment—that may vary over time but are unrelated to pollution levels. Including these trends helps mitigate concerns that time-variant local shocks or region-specific trajectories could confound our estimated effects of air quality improvement on migration behavior. Finally, it contains controls for municipality demographic and educational structure, i.e. share of age groups (0–19; 20–29; 30–39; 40–49; 50–59; 60–69) and share of secondary and tertiary educated among those aged 15+. All those controls enter the regression lagged by one year. We obtain the data on population characteristics primarily from decennial censuses held in 1980, 1991, 2001, and 2011. In order to make use of the entire wealth of our data, we use interpolate yearly values for the years between census years. For the population structure between 1991 and 2015, we use census data adjusted with population registry data from the CZSO.[27] We interpolate the remaining missing values using nearest-neighbor interpolation. These controls account for compositional differences across municipalities that may influence both the propensity to migrate and the sensitivity to environmental or economic conditions, as migration behavior might vary systematically by age and education level. We further explore this heterogeneity in migratory responses by demographic group in Section 6 of the paper.

Specification (6) also includes a full set of municipality fixed effects, δ_i, and a dummy for the post-desulfurization period, $Post_t$. The municipality fixed effects control for all time-invariant characteristics of each municipality—such as geographic location, natural amenities, or historical settlement patterns like post–World War II resettlement—that may

25. The municipality-level unemployment rate is defined as the share of registered unemployed on the working-age population (15–64) in the given municipality in the previous year. The municipality-level unemployment data are available for the period after year 2001. We assume the unemployment rate to have been equal to zero before the fall of communism—i.e., in the pre-desulfurization period.

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

27. The dataset is not publicly available but can be purchased from the CZSO for academic use.

influence migration independently of air quality. The $Post_t$ dummy captures structural shifts common to all municipalities after desulfurization began, allowing us to net out general post-treatment changes unrelated to differential exposure to pollution. This setup ensures that the estimated effects are identified from differential changes across pollution exposure groups, rather than from uniform trends or permanent differences across municipalities.

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

$$mig_{it} = \alpha + \sum_{p} \beta_i \left(Post_t \times SO2Group_i^p\right) + Post_t + \delta_i + \mathbf{X}'_{it-1}\boldsymbol{\theta} + \varepsilon_{it} \tag{7}$$

where the effect is estimated separately for each category of municipalities (a vector of indicator variables $SO2Group_i^p$) defined by pre-desulfurization SO_2 concentrations (40, 50, and 60 $\mu g/m^3$). The category of the least polluted municipalities (30 $\mu g/m^3$) is our reference group in both specifications. The reference category exceeds the EU/WHO 20 $\mu g/m^3$ limits for developed countries by 50%. The parameters, therefore, represent a lower bound estimate of the true effect of desulfurization, which decreased pollution levels to or below the 20 $\mu g/m^3$ limit in all municipalities.[28]

28. In an alternative specification, we define the treatment variable as a change in SO_2 concentration levels between pre- and post-desulfurization period. Results reported in Table A.6 in Appendix are numerically almost identical to our baseline estimates. This is due to the close correlation ($\rho = -0.95$) between the pre-desulfurization SO_2 levels and the air pollution reduction the municipalities experienced during the desulfurization period (see Figure 5).

5 Empirical Results

5.1 Main Results

Table 3 reports estimates from our baseline difference-in-differences specification (Model 6), which evaluates the impact of pollution reduction on migration outcomes. The key coefficient of interest captures the interaction between the post-desulfurization period and an indicator for municipalities with pre-1994 SO_2 concentrations of 40 $\mu g/m^3$ or higher. This coefficient identifies the change in migration outcomes in more polluted municipalities relative to less polluted ones after desulfurization technologies were introduced.

The most parsimonious specification (Column 1, 6 and 9) contains DD term, municipality and period FE, and controls for regional/area linear time trends, which account for unobserved local changes. In Column (1), we find that the desulfurization-induced reduction in pollution significantly reduced emigration: treated municipalities experienced a decline of approximately 1.4 percentage points, equivalent to a 24% reduction relative to their pre-treatment emigration rate. This suggests that improved air quality strongly discouraged residents from leaving formerly polluted areas. The estimated effect on immigration is positive but statistically insignificant (Column 5), while the effect on net migration is large and significant: an increase of approximately 1.7 percentage points (Column 9), equivalent to a 78% improvement compared to the baseline, indicating a strong re-population effect driven primarily by the reduction in out-migration. Overall, the results suggest that the reduction in air pollution made previously heavily polluted municipalities more attractive for people to live in.

In Columns (2), (6), and (10), we add lagged unemployment rates to proxy for local economic conditions, alongside area-specific linear time trends. This addition is particularly relevant given that the environmental reforms of the early 1990s pushed both for desulfurization and, at the same time, limited lignite mining. While desulfurization was implemented through the adoption of new technologies and therefore had little or no direct labor market impact, the mining limits—combined with the broader transition recession—led to mine closures and potential job losses, especially in heavily polluted municipalities near mining areas. Despite this, the estimated DiD coefficients remain stable and statistically significant, suggesting that the identified treatment effects are not confounded by contemporaneous labor market shifts. Additionally, the unemployment coefficients themselves are small and statistically insignificant.

In Columns (3), (7), and (11) of Table 3, we include interaction terms between the pollution reduction treatment and local unemployment rates. These models offer further insight into how environmental improvements interact with economic conditions to shape migration responses. For emigration, the interaction is negative but statistically insignificant, indicating that the retention effect of air quality improvements applies broadly—individuals are less likely to leave, regardless of the strength of local labor markets. In contrast, for immigration, the interaction term is positive and marginally significant, suggesting that environmental improvements are more likely to attract new residents in areas facing weaker economic conditions. That is, improved air quality may serve as a compensating amenity that offsets economic disadvantages. A similar pattern holds for net migration: while the main treatment effect of pollution reduction is positive but not statistically significant, the interaction with unemployment is positive and marginally significant, indicating that net population inflows are more pronounced in economically weaker areas benefiting from environmental improvements.[29]

Columns (4), (8), and (12) introduce the full set of controls, including demographic composition (age shares) and educational structure. These specifications also include area linear time trends and fixed effects. The results show that treatment effects remain quantitatively similar, indicating that the results are robust to differences in population composition across municipalities.

Taken together, these results highlight the important role of environmental quality in both emigration and immigration decisions, though via different mechanisms. Improvements in air quality consistently reduce emigration from formerly heavily polluted municipalities, and this retention effect appears largely independent of local labor market conditions. By contrast, the positive effects of environmental improvements on immigration and net migration are more pronounced in municipalities with higher unemployment rates. This pattern suggests that clean air may act as a compensating amenity in economically weaker areas, where it can partially offset limited job opportunities and enhance the attractiveness of the locality to potential newcomers.

These findings underscore the broader importance of environmental quality in residential location choices and regional development. Cleaner air not only reduces out-migration but can also help attract population inflows—particularly in areas experiencing economic disadvantage. In this way, environmental improvements contribute to regional stabilization and revitalization, especially where other economic pull factors are weak.

29. While Figure 2 shows that SO_2 concentrations flattened after the sharp drop in 1994-1999 drop, net migration rates remained consistently positive in the following years (Figure 3). This may suggest that environmental quality was no longer improving in a measurable sense, yet migration remained dynamic. Our interpretation is that the initial environmental shock captured by our DiD framework triggered an immediate migratory response, especially in terms of reduced out-migration. In subsequent years, migration is likely shaped by a blend of standard economic push-pull factors plus the lasting amenity, health, and reputational benefits that cleaner air offers. Thus, the flat SO_2 levels and continued net immigration are not contradictory but reflect different phases of the migration response.

Table 3: Main results

	Dependent variable											
	Emigration rate (%)				Immigration rate (%)				Net migration rate (%)			
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
Pre-desulfurization SO_2 concentration ≥ 40 μg/m^3	−1.381***	−1.370***	−1.104**	−1.371***	0.313	0.304	−0.432	0.357	1.695***	1.674***	0.673	1.728***
× Post-desulfurization period (DD)	(0.282)	(0.280)	(0.351)	(0.334)	(0.335)	(0.335)	(0.419)	(0.316)	(0.470)	(0.465)	(0.509)	(0.440)
Unemployment rate (%)		−0.023	0.004	−0.016		0.020	−0.055	−0.001		0.043	−0.059	0.015
		(0.020)	(0.023)	(0.019)		(0.022)	(0.038)	(0.028)		(0.030)	(0.040)	(0.032)
Unemployment rate $\times DD$(%)			−0.038				0.105*				0.143*	
			(0.035)				(0.048)				(0.063)	
0–19 age group (%)				0.002				0.017				0.015
				(0.055)				(0.056)				(0.076)
20–29 age group (%)				−0.051				0.020				0.070
				(0.058)				(0.050)				(0.079)
30–39 age group (%)				−0.092*				0.071				0.163**
				(0.055)				(0.064)				(0.079)
40–49 age group (%)				−0.048				0.076				0.124
				(0.057)				(0.078)				(0.084)
50–59 age group (%)				−0.010				0.083				0.093
				(0.060)				(0.069)				(0.073)
60–69 age group (%)				−0.062				0.139				0.201**
				(0.064)				(0.090)				(0.100)
70–79 age group (%)				−0.032				−0.014				0.018
				(0.035)				(0.038)				(0.045)
Share of secondary educated (%)				−0.039**				0.066***				0.105***
				(0.016)				(0.018)				(0.023)
Share of tertiary educated (%)				−0.023				−0.305***				−0.282***
				(0.053)				(0.087)				(0.077)
Observations	6,229	6,229	6,229	6,223	6,229	6,229	6,229	6,223	6,229	6,229	6,229	6,223
Area linear time trends	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Municipality and period FE	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓

Notes: Table reports β coefficients from Equation (6). 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 below 40 μg/m^3.

5.2 Non-linear Effects

Table 4 presents estimates from our non-linear specification (Equation 7), allowing the effects of pollution reduction to vary by the level of pre-desulfurization SO_2 concentrations. The reference group includes municipalities with pre-1994 SO_2 levels below $40\,\mu g/m^3$.

The results suggest that the impact of environmental improvements on migration outcomes is strongly non-linear. In particular, the reduction in air pollution significantly decreased emigration rates in municipalities with initially high pollution levels. For municipalities with pre-desulfurization concentrations of $50\,\mu g/m^3$ and $60\,\mu g/m^3$, emigration rates declined by 1.7 and 1.6 percentage points, respectively, relative to the reference group. These effects are statistically significant at the 1% level and correspond to approximately 26–27% lower emigration, highlighting that residents in the most heavily polluted areas were especially responsive to improvements in air quality.

In contrast, the response of immigration to pollution reduction is less consistent. Municipalities with initial SO_2 levels of $50\,\mu g/m^3$ experienced a statistically significant increase in immigration—around 1.1 percentage points. However, for the most polluted municipalities ($60\,\mu g/m^3$), the immigration response is small and statistically insignificant, suggesting that air quality improvement alone was not sufficient to fully reverse prior deterrents to in-migration in these areas.[30]

The estimates for net migration combine these two effects. Municipalities with $50\,\mu g/m^3$ and $60\,\mu g/m^3$ concentrations prior to desulfurization show increases in net migration of 2.8 and 1.8 percentage points, respectively, relative to the least polluted reference group. Both effects are statistically significant and substantively meaningful. This reinforces the conclusion that air pollution reduction supported re-population, primarily by reducing emigration, but also—at least in moderately polluted areas—by attracting new residents.

The mixed findings on immigration responses may be driven by two underlying factors. First, generous financial incentives offered before desulfurization may have compensated potential migrants for the negative effects of pollution, thereby weakening the observable impact of later environmental improvements. Second, areas with historically high pollution levels may have developed a persistent negative reputation, which continued to discourage immigration even after air quality improved. Taken together, these factors suggest that while cleaner air can help reduce population outflows, it may not be sufficient on its own

30. We acknowledge that estimates must be interpreted with caution as the reduction in air pollution took place in parallel to the abolition of anti-depopulation policies. The analysis presented in Section 5.5.1 shows that the abolition of these policies had no impact on emigration rates. Therefore, we interpret our estimates on emigration rates as causal effects. However, our estimates for immigration and net migration rates cannot be interpreted as such, as we cannot disentangle the effects of reducing air pollution from the effects of abolishing substantial pro-immigration benefits due to the lack of individual-level data.

Table 4: Main results: non-linear

	Dependent variable					
	Emigration rate (%)		Immigration rate (%)		Net migration rate (%)	
	(1)	(2)	(3)	(4)	(5)	(6)
Pre-desulfurization SO_2 concentration = 40 $\mu g/m^3$	−0.879**	−0.928**	−0.533	−0.478	0.346	0.450
× Post-desulfurization period	(0.397)	(0.411)	(0.378)	(0.367)	(0.562)	(0.560)
Pre-desulfurization SO_2 concentration = 50 $\mu g/m^3$	−1.700***	−1.644***	1.061**	1.068**	2.760***	2.712***
× Post-desulfurization period	(0.419)	(0.433)	(0.484)	(0.444)	(0.729)	(0.672)
Pre-desulfurization SO_2 concentration = 60 $\mu g/m^3$	−1.588***	−1.554***	0.171	0.241	1.760**	1.795**
× Post-desulfurization period	(0.469)	(0.438)	(0.567)	(0.515)	(0.856)	(0.736)
Unemployment rate (%)		−0.015		−0.005		0.010
		(0.019)		(0.027)		(0.032)
Observations	6,229	6,223	6,229	6,223	6,229	6,223
Shares of age and education groups (%)		✓		✓		✓
Area linear time trends	✓	✓	✓	✓	✓	✓
Municipality and period FE	✓	✓	✓	✓	✓	✓

Notes: Table reports β coefficients from Equation (7). 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 below 40 $\mu g/m^3$.

to attract new residents or fully reverse deep-rooted migration patterns—especially in the areas most affected by past pollution.

5.3 Robustness Checks and Validation of Identification Assumptions

In this section, we present a series of tests to assess the credibility of our identification strategy and the robustness of the main results. We begin by evaluating the parallel trends assumption, followed by placebo tests, and conclude with a range of robustness checks examining alternative model specifications, controls, and sample definitions.

5.3.1 Assessing the Parallel Trends Assumption

A core assumption of our difference-in-differences (DiD) identification strategy relies on the assumption that, absent the desulfurization reform, migration trends in municipalities with high pre-1994 SO_2 concentrations (treated group) and low pollution levels (control group) would have followed similar trajectories. To evaluate this assumption, we estimate the following regression for the pre-treatment period (1983–1989):

$$mig_{it} = \sum_{j} \gamma_{jt} \mathrm{SO2}_i \theta_t + \delta_i \mathrm{SO2}_i + \xi_{it} \quad (8)$$

Here we interact the SO2, dummy equal to one for air pollution level greater than or equal to $40\,\mu\mathrm{g/m}^3$, with year fixed effects (θ_t) with the year 1989 used as a reference. We estimate regression (8) on a sub-sample limited to the pre-treatment period. Point estimates with 95% confidence intervals (calculated using robust standard errors clustered by municipality) for coefficient γ are reported in Figure 7. The estimates are small and statistically insignificant in most years, supporting the parallel trends assumption. A marginally significant estimate for net migration in 1986 is noted but does not indicate a systematic deviation. These findings bolster the validity of our empirical design.[31]

In addition to the binary treatment specification with SO2 >= $40\,\mu\mathrm{g/m}^3$, we examined pre-treatment migration trends for each pollution category used in the non-linear specification in Table 4 (40, 50 and $60\,\mu\mathrm{g/m}^3$). Appendix Figure A.5 plots, for the pre-desulfurization years 1983–1989, differences in migration rates relative to the $30\,\mu\mathrm{g/m}^3$, baseline for the pre-desulfurization period. The coefficients for all pollution groups are small and statistically insignificant across all years, indicating no evidence of divergent

31. The test reveals no divergence in trends in the pre-desulfurization period (1983–1989) for emigration and immigration rate, whereas for net migration rate the test is weaker. However, we note that there is a ten-year gap between the pre- and post-desulfurization period due to the lengthy and costly desulfurization process. Such a long gap could jeopardize the validity of the parallel trends assumption.

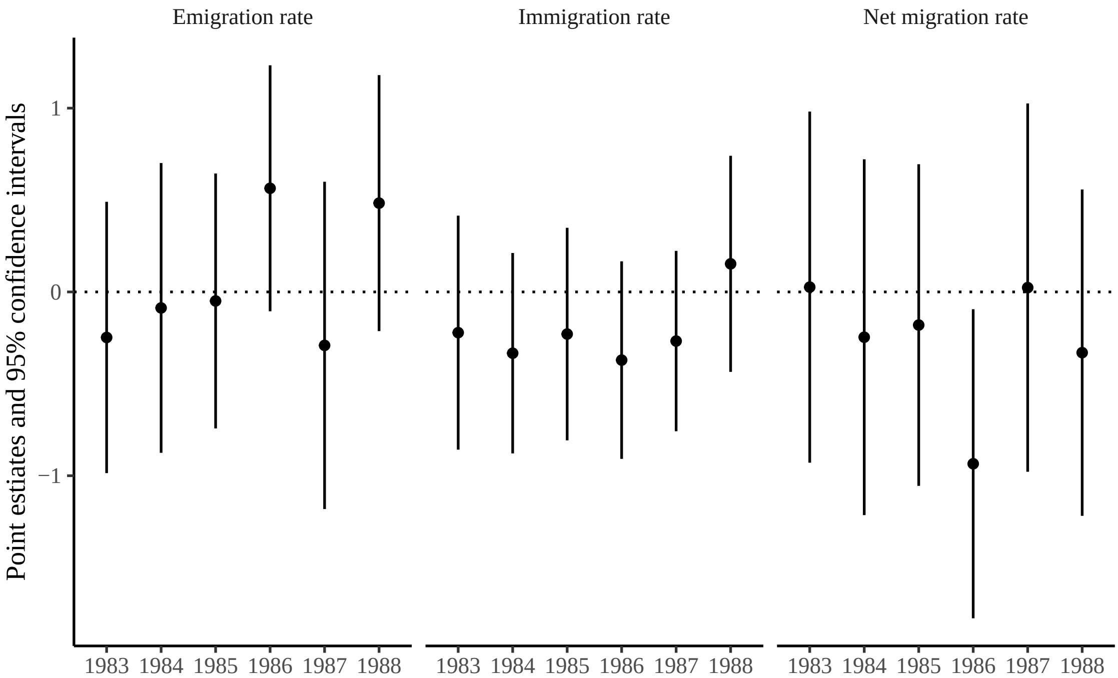


Figure 7: Parallel trend assumption test

pre-trends. This supports the interpretation that the larger post-treatment effect for the 50 μg/m^3 group in Table 4 is not driven by differential pre-trends.

5.3.2 Placebo tests

To rule out the possibility that our main results are not driven by spurious correlations or other concurrent events, we perform a set of placebo DiD analyses. First, we conduct a pre-reform placebo test by assigning a fictitious treatment period to the years 1986–1989—well before the actual implementation of desulfurization technologies. Using data from 1983 to 1989, we re-estimate our baseline difference-in-differences model (7) under the false assumption that desulfurization occurred in 1986. If our identification strategy is valid, we should not detect any treatment effects in this period. Second, we implement a post-reform placebo test by applying the same method to a later period (2000–2015), pretending that desulfurization began in 2006. Again, the idea is to test for spurious treatment effects in a period when the actual desulfurization had already ended.

The results of both placebo tests are presented in Table 5, with *Panel A* showing estimates for the Pre-Reform 1983–1989 window and *Panel B* for Post-Reform 2000–2015 period. Across all three migration outcomes—emigration, immigration, and net migration—the estimated treatment effects are small and statistically insignificant in both placebo periods. These results indicate that no systematic changes in migration occurred in high-pollution

Table 5: Placebo tests

	Dependent variable		
	Emigration rate (%)	Immigration rate (%)	Net migration rate (%)
	(1)	(2)	(3)
Panel A: Pre-desulfurization period (placebo cutoff at 1987)			
Pre-desulfurization SO_2 concentration ≥ 40 $\mu g/m^3$	−0.006	−0.291	−0.284
× Post-desulfurization period	(0.260)	(0.253)	(0.332)
Observations	1,413	1,413	1,413
Panel B: Post-desulfurization period (placebo cutoff at 2007)			
Pre-desulfurization SO_2 concentration ≥ 40 $\mu g/m^3$	−0.095	−0.340	−0.245
× Post-desulfurization period	(0.130)	(0.223)	(0.223)
Observations	4,816	4,816	4,816
Municipality unemployment; demogr. and edu. structure	✓	✓	✓
Municipality and period FE	✓	✓	✓
Area linear trends	✓	✓	✓

Notes: Table reports β_i coefficients from Equation (6). 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 below 40 $\mu g/m^3$.

municipalities during the placebo periods, supporting the validity of our parallel trends assumption and reinforcing the causal interpretation of the main post-1994 results.

5.4 Robustness to Alternative Specifications

To assess the robustness of our findings, we estimate a series of alternative specifications and subsample regressions. Across all models, we maintain the focus on three distinct migration outcomes: emigration (Panel A), immigration (Panel B), and net migration (Panel C). Table 6 and Table 7 present these robustness checks.

5.4.1 Controlling for Local Employment Structure and Post-treatment Pollution

Columns (1)–(2) of Table 6 extend our baseline specification with controls for local occupational structure, using sectoral employment shares from the 1991 and 2001 censuses. While worse-polluted municipalities saw a greater shift from manufacturing to agriculture (Appendix Table A.4), the estimated treatment effects remain statistically significant and even slightly larger than in the baseline (Table 3). Adding full demographic and unemployment controls in column (2) yields nearly identical results.

Next, we look at whether post-desulfurization SO_2 concentrations explain residual variation in migration outcomes. The environmental policies introduced in the 1990s decreased SO_2 concentrations to below the EU/WHO limits in the post-desulfurization period, yet some variation in the pollution load across the examined municipalities remained (see Figure 4 and Table 1). To test whether post-desulfurization SO_2 concentrations played any role in migration behavior, we re-estimate Equation (6) including post-treatment pollution levels as controls. Results in columns (3)–(4) show negligible deviation from the baseline for emigration and net migration. The estimated effect on immigration rate is close to zero and insignificant similarly to our baseline specification when controlling for post-desulfurization pollution levels.

5.4.2 Weighting by Population and Heterogeneity by Municipality Size

Since more polluted municipalities are generally larger (Table 1), we examine whether results are driven by small or large municipalities. This is of particular importance as the Czech municipal structure is dominated by a large number of small municipalities. In columns (5)–(6) of Table 6, we re-estimate regressions using population weights. Results indicate weakening of the emigration effect and a negative immigration response, implying that smaller municipalities drive the baseline patterns. To explore this further, we split the sample into small (population <1,500) and large municipalities and re-estimate the model separately (columns (7)–(10)).[32] The estimated effects for small municipalities align closely with the baseline, confirming that the main results reflect dynamics among smaller localities, while larger municipalities may exhibit distinct compensatory mechanisms (see Section 5.5.3).

5.4.3 Additional Robustness Checks

Table 7 presents a battery of further robustness tests. First, including the outlier municipality of Chomutov—an industrial district capital with extremely high pre-treatment pollution (the only municipality with a pre-desulfurization SO_2 concentration of 70 $\mu g/m^3$)—yields results consistent with the baseline (columns (1)–(2) of Table 7). Second, we restrict our data sample to a balanced panel of municipalities and exclude municipalities with incomplete migration records. As can be seen from columns (3) and (4) of Table 7, balancing the panel has no impact on our results.

Third, we limit the post-desulfurization period to 2000–2006 to isolate short-run migration responses (Table 7, columns 5 and 6). This shorter window captures the years immediately following the environmental reform, before potential longer-term structural or reputational effects took hold. Emigration and net migration effects remain negative and statistically significant (Panels A and C), though their magnitude is somewhat smaller than

32. As no relevant pre-pollution population count is available, we use the mean population from the estimation sample. The category of small municipalities contains 84% of municipalities in our estimation sample, see also Table 1 and Share of small municipalities in%.

Table 6: Robustness analysis I

	Employment structure		SO_2 conc. in post-def. per.		Weighted by population		Small municipalities		Large municipalities	
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
Panel A: Emigration rate										
Pre-desulfurization SO_2 concentration $\geq 40\,\mu g/m^3$	-1.467^{***}	-1.445^{***}	-1.144^{***}	-1.179^{***}	-0.135	-0.383^{**}	-1.251^{***}	-1.252^{***}	-0.132	-0.219
$\times$ Post-desulfurization period	(0.389)	(0.396)	(0.283)	(0.293)	(0.213)	(0.151)	(0.274)	(0.289)	(0.227)	(0.191)
Observations	6,229	6,223	6,229	6,223	6,229	6,223	6,229	6,223	6,229	6,223
Panel B: Immigration rate										
Pre-desulfurization SO_2 concentration $\geq 40\,\mu g/m^3$	0.810^{**}	0.710^{*}	-0.008	0.124	-1.222^{***}	-1.015^{***}	0.096	-0.035	-1.203^{***}	-1.343^{***}
$\times$ Post-desulfurization period	(0.400)	(0.362)	(0.354)	(0.345)	(0.305)	(0.298)	(0.154)	(0.341)	(0.356)	(0.368)
Observations	6,229	6,223	6,229	6,223	6,229	6,223	6,229	6,223	6,229	6,223
Panel C: Net migration rate										
Pre-desulfurization SO_2 concentration $\geq 40\,\mu g/m^3$	2.277^{***}	2.153^{***}	1.136^{**}	1.303^{***}	-1.087^{***}	-0.632^{**}	1.347^{***}	1.217^{***}	-1.071^{**}	-1.125^{**}
$\times$ Post-desulfurization period	(0.623)	(0.577)	(0.478)	(0.450)	(0.406)	(0.320)	(0.311)	(0.290)	(0.465)	(0.456)
Observations	6,229	6,223	6,229	6,223	6,229	6,223	6,229	6,223	6,229	6,223
Unemployment		✓		✓		✓		✓		✓
Education and age structure		✓		✓		✓		✓		✓
Area linear trends	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Municipality and period FE	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓

Notes: Table reports β_i coefficients from extended Equation (6). In columns (1) and (2) the baseline specification (6) is extended with the employment structure (occupation shares) in the municipality, and in columns (3) and (4) with SO_2 concentrations in the post-desulfurization period (with $5\,\mu g/m^3$ as the reference level). Columns (5) and (6) presents results of regression weighted by population, and columns (7)–(10) for subsamples of small and large municipalities respectively with the cutoff at 1,500. Robust standard errors clustered by municipality are reported in parentheses: *, ** and *** denote statistical significance at 10%, 5% and 1%. The reference category for SO_2 concentration in the pre-desulfurization period is below $40\,\mu g/m^3$.

in the full 2000–2015 sample. Immigration effects are positive and statistically significant when estimated without controls (Panel B, column 5), but become statistically insignificant when controlling for unemployment and population structure (column 6). These results suggest that environmental improvements may have triggered an immediate response, particularly in terms of reduced out-migration, but the full migratory adjustment likely evolved over a longer horizon.

Fourth, to ensure results are not driven by outliers,[33] we exclude the top 1% of emigration and immigration rates and top/bottom 1% of net migration rates each year. As shown in columns (7)–(8) in Table 7, estimates remain significant and stable, with slightly reduced magnitudes. Fifth, The CHMI dispersion model tend to overestimate the pollution levels (see Figure A.4 in the Appendix) which could lead to a contamination of the treated group by municipalities which actually suffered from lower pollution levels. To mitigate concerns about pollution misclassification due the overestimation by the CHMI dispersion model, we exclude the 40 $\mu g/m^3$ category from the sample (columns (9)–(10)). Results remain robust.

Finally, we account for spatial autocorrelation in the error structure using Conley standard errors with a 40 km cutoff Conley (1999). As reported in columns (11)–(12) in Table 7, the Conley standard errors increase somewhat, but the treatment effect on emigration remains statistically significant at the 1% level. This further supports the robustness of our identification.

5.5 Mechanisms Shaping the Migration Response to Air Quality Improvements

Having established that reductions in air pollution significantly influenced migration patterns, we now turn to the mechanisms underlying this relationship. Specifically, we examine whether the observed effects vary across institutional, social, and infrastructural dimensions that may shape individuals' willingness or ability to respond to environmental change. We focus on three potential mechanisms: (i) government policies that may have suppressed emigration in the pre-reform period; (ii) the strength of local social capital and historical attachment to place; and (iii) the availability of man-made amenities that could offset the dis-utility of pollution or enhance the value of environmental improvements. By exploring these channels, we aim to better understand the heterogeneous migration response to improved air quality across municipalities.

33. These outliers may occur due to mine expansions (as in the case of the city of Most) or other unobserved factors such as natural disasters. To the best of our knowledge, there is no comprehensive database of such events that would enable us to control for them.

Table 7: Robustness analysis II

	Inclusion of Chomutov		Balanced panel		Limited bal. panel		Exclusion of outliers		Exclusion of 40 $\mu g/m^3$ cat.		Adj. std. errors	
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
Panel A: Emigration rate												
Pre-desulfurization SO_2 concentration $\geq 40\,\mu g/m^3$ × Post-desulfurization period	−1.357***	−1.354***	−1.344***	−1.336****	−1.156***	−0.821**	−1.068***	−1.052***	−1.667***	−1.645***	−1.381***	−1.371***
	(0.280)	(0.298)	(0.292)	(0.313)	(0.295)	(0.338)	(0.207)	(0.214)	(0.337)	(0.357)	(0.506)	(0.504)
Observations	6,252	6,243	4,485	4,485	2,730	2,730	6,164	6,158	4,387	4,383	6,229	6,223
Panel B: Immigration rate												
Pre-desulfurization SO_2 concentration $\geq 40\,\mu g/m^3$ × Post-desulfurization period	0.298	0.351	0.482	0.478	0.792**	0.452	0.285	0.300	0.788*	0.743**	0.313	0.357
	(0.333)	(0.315)	(0.341)	(0.325)	(0.399)	(0.396)	(0.260)	(0.252)	(0.405)	(0.356)	(0.666)	(0.671)
Observations	6,252	6,243	4,485	4,485	2,730	2,730	6,164	6,159	4,387	4,383	6,229	6,223
Panel C: Net migration rate												
Pre-desulfurization SO_2 concentration $\geq 40\,\mu g/m^3$ × Post-desulfurization period	1.655***	1.705***	1.826***	1.814***	1.947***	1.273**	1.386***	1.365***	2.455***	2.388***	1.695	1.728
	(0.464)	(0.436)	(0.488)	(0.467)	(0.559)	(0.544)	(0.342)	(0.324)	(0.588)	(0.545)	(1.196)	(1.183)
Observations	6,252	6,243	4,485	4,485	2,730	2,730	6,099	6,094	4,387	4,383	6,229	6,223
Municipality unemployment, demogr. and edu. structure		✓		✓		✓		✓		✓		✓
Municipality and period FE	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Area linear trends	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓

Notes: Table reports β_i coefficients from Equation (6). In columns (1) and (2) the estimation sample includes the city of Chomutov. In columns (3) and (4) the estimation sample is balanced by excluding municipalities for which migration records are missing. In columns (5) and (6) we limit the post-desulfurization period in the balanced panel to 2000–2006. In columns (7) and (8) municipality-year data-points within each year's top 1% values for emigration and immigration rate are excluded from the sample. In case of net migration rate each year's top and bottom 1% values are excluded. Next, in columns (9) and (10) we exclude 40 $\mu g/m^3$ category from the estimation sample. Columns (11) and (12) contain baseline parameter estimates with Conley standard errors with 40 km cutoff reported in parentheses. Robust standard errors clustered by municipality are reported in parentheses in columns (1)–(10): *, ** and *** denote statistical significance at 10%, 5% and 1%. The reference category for SO_2 concentration in the pre-desulfurization period is below 40 $\mu g/m^3$.

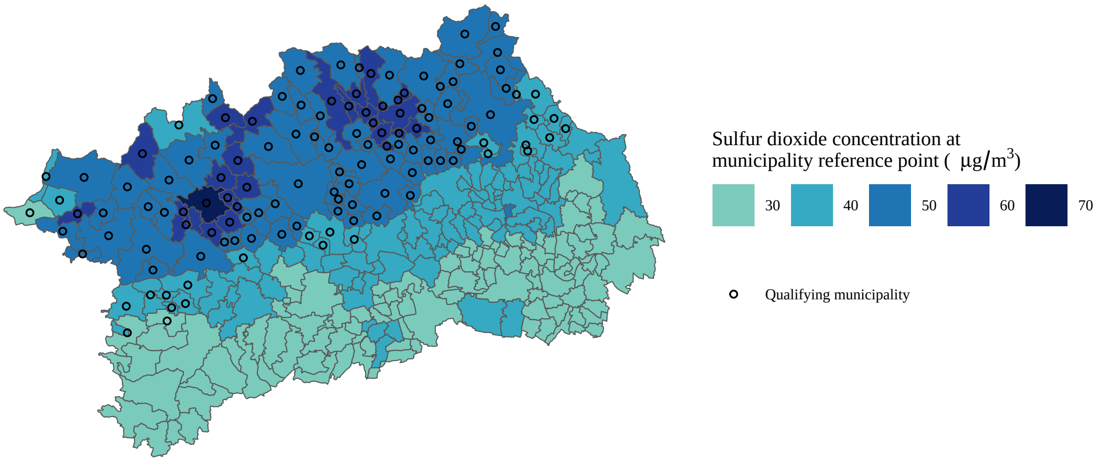


Figure 8: SO_2 concentrations in 1994 and qualifying municipalities in the pre-desulfurization period

Source: Czech Hydrometeorological Institute (CHMI), ArcČR 500 v3.3, see Section 3.1.

5.5.1 The Role of Anti-Emigration Government Policies

The baseline results in Table 3 indicate that higher pollution loads made remaining in a municipality less desirable—pollution acted as a strong push factor. However, this effect may have been weakened by government policies in the pre-desulfurization era that aimed to retain workers in the region and may have offset the dis-utility associated with poor environmental quality.

Eligibility for anti-emigration benefits was determined by location and employment tenure in the area. Specifically, workers who had been employed for at least 10 years in designated municipalities were eligible for an annual monetary benefit of 2,000 Czechoslovak crowns, approximately 5.7% of the average annual wage in 1985—equivalent to nearly three weeks' pay. These benefits were abolished in early 1992 along with the introduction of new environmental regulations.

To disentangle the impact of these benefits from the effects of air pollution reduction, we exploit the fact that eligibility varied across municipalities. Some municipalities in our sample were covered by the benefit scheme (hereafter "qualifying municipalities"), while others were not ("non-qualifying municipalities"). Figure 8 shows that the qualifying municipalities were geographically concentrated in the northern part of North Bohemia and that eligibility was correlated with pollution levels. All municipalities with pre-desulfurization SO_2 concentrations of $50\,\mu g/m^3$ or higher were eligible, while among municipalities at the $40\,\mu g/m^3$ level, 74% were eligible. Among the least polluted municipalities, only 32% qualified.

Table 8: Impact of monetary benefits on migratory response to cleaner air

	Eligibility for benefits			
	Indicator variable		Treatment intensity	
	(1)	(2)	(3)	(4)
Pre-desulfurization SO_2 concentration = 40 $\mu g/m^3$ × Eligibility for benefits × Post-desulfurization period	−1.138 (1.619)	−1.607 (1.888)	−0.587 (1.933)	−0.709 (1.797)
Pre-desulfurization SO_2 concentration = 40 $\mu g/m^3$ × Post-desulfurization period	−0.683** (0.314)	−0.659** (0.325)	−0.583* (0.313)	−0.545* (0.308)
Post-desulfurization period × Eligibility for benefits	0.500 (1.150)	0.908 (1.447)	−0.422 (1.346)	−0.438 (1.095)
Municipality unemployment; demogr. and edu. structure		✓		✓
Municipality and period FE	✓	✓	✓	✓
Area linear trends	✓	✓	✓	✓
Observations	4,007	4,002	4,007	4,002

Notes: Table reports γ_i, β_i and σ_i coefficients from Equation (9) with the emigration rate as a dependent variable. 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 below 40 $\mu g/m^3$.

To examine whether the observed emigration responses may have been influenced by the abolition of anti-emigration government benefits, we extend our baseline DiD specification into a triple differences framework. Specifically, we estimate the following model:

$$\begin{aligned} mig_{it} = \alpha &+ \beta_i\,(Post_t \times SO2_i) + \gamma_i\,(Post_t \times SO2_i \times Ben_i) \\ &+ \sigma_i\,(Post_t \times Ben_i) + Post_t + \delta_i + \mathbf{X}'_{it-1}\boldsymbol{\theta} + \varepsilon_{it} \end{aligned} \tag{9}$$

Here, Ben_i is either a binary indicator for benefit eligibility or a continuous measure of treatment intensity. The coefficient γ_i on the triple interaction captures whether the effect of pollution reduction differs systematically between municipalities with and without benefit coverage. We restrict estimation to municipalities with pre-desulfurization SO_2 concentrations of 40 $\mu g/m^3$ or below, where benefit eligibility varied. As in the baseline specification, δ_i and $Post_t$ represent municipality and period fixed effects, respectively, and $\mathbf{X}_{it-1}$ includes lagged control variables.

The results of our triple difference empirical specification are presented in columns (1) and (2) of Table 8. As can be seen, the triple difference terms are small and statistically insignificant in all specifications. These results suggest that the abolition of anti-emigration benefits did not drive the observed decline in emigration following desulfurization.

To account for the possibility that benefit eligibility depended on workplace location rather than residence, we construct a continuous exposure measure based on the share of economically active residents employed in qualifying municipalities (using 1991 census data). Figure 9 shows minimum variation in the intensity measure across all groups of

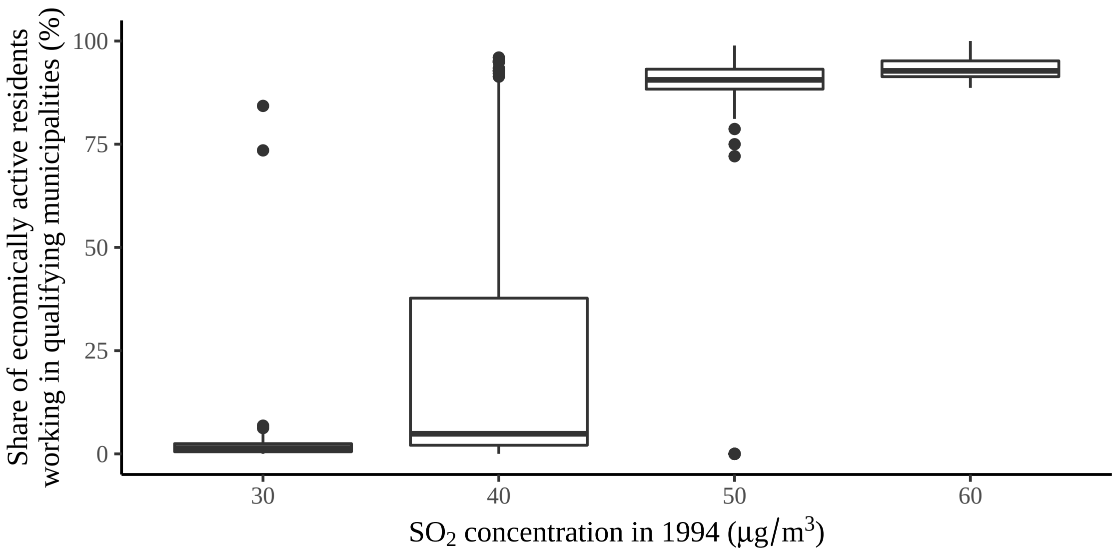


Figure 9: Share of population working in qualifying municipalities on economically active population (1991) by SO_2 concentration in municipality of residence (1994).

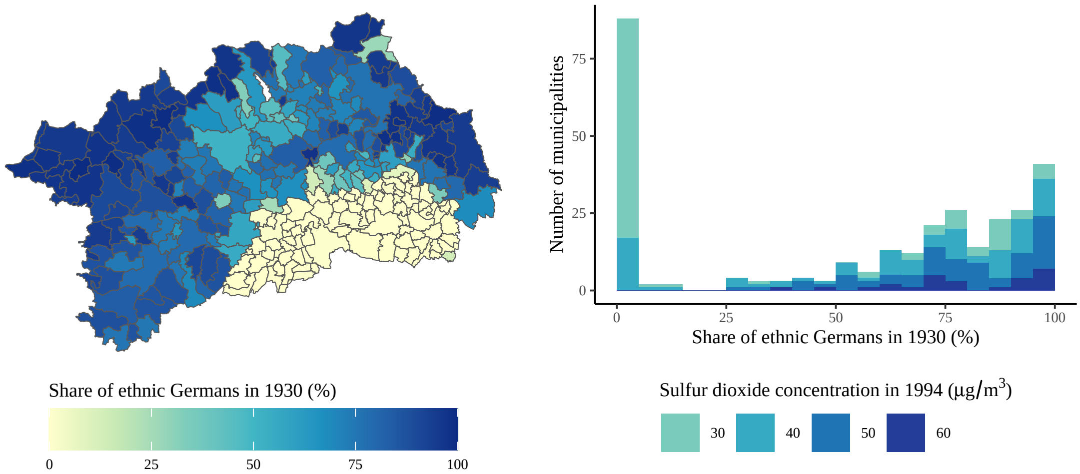
municipalities except those with pre-desulfurization SO_2 concentrations of 40 μg/m^3. This is not surprising, since those municipalities are typically located on the border between qualifying and non-qualifying areas (see Figure 8). This outcome suggests that the region's inhabitants commuted short distances (i.e., their municipalities of work and residence had similar levels of pollution).

Finally, we re-estimate Equation (9) using the continuous treatment intensity measure. The results, presented in columns (3) and (4) of Table 8, also show no significant triple difference effect. Taken together, our findings suggest that the observed reductions in emigration following air quality improvements were not driven by changes in the availability of anti-emigration benefits.

5.5.2 The Role of Social Capital and Attachment to Local Communities

Residents' willingness to migrate in response to air pollution depends not only on their tolerance for environmental disamenities but also on their attachment to local communities. Stronger social ties can increase the psychological and social costs of moving, thereby reducing sensitivity to local shocks, including environmental improvements.

We explore this mechanism using a natural experiment rooted in the region's history. North Bohemia was heavily affected by the post–World War II expulsion of ethnic Germans, who made up 64% of the local population in 1930. The vacated municipalities were resettled by ethnic Czechs, who seized abandoned properties but often lacked strong social



(a) Spatial distribution of ethnic Germans in 1930

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

Figure 10: Distribution of ethnic Germans in 1930

Source: Czech Hydrometeorological Institute (CHMI), ArcČR 500 v3.3, Guzi et al. (2021). For details see Section 3.1.

ties to each other or the region. These resettled municipalities, which had previously been ethnically segregated, remained socially fragmented in the following decades (see Figure 10).

As noted above, government propaganda during socialism promoted a regional identity centered around coal mining, possibly increasing tolerance to pollution. However, in municipalities resettled after the war, both regional identity and local social capital—defined as strong interpersonal networks and community cohesion—were weak or absent. Theoretical models by David et al. (2010) and Bräuninger and Tolciu (2011) suggest that such a negative shock to social capital can create a stable equilibrium with lower social capital and higher emigration.

Guzi et al. (2021) provide evidence that the expulsion and resettlement led to persistently higher emigration in affected municipalities. Using municipality-level data for 1971–2015, they show that municipalities with a pre-war ethnic German share above 90% had emigration rates 0.6–0.7 percentage points higher than comparable nearby municipalities with shares below 10%. This effect appears to be driven by lower local social capital: residents of resettled towns are less likely to participate in local associations or organize community events, even though their values and pro-social attitudes are otherwise similar.

Building on Guzi et al. (2021), we use the pre-war (1930) share of ethnic Germans as a proxy for local social capital. In North Bohemia, this measure may also capture attachment to coal-mining identity—likely pulling effects in opposite directions. To examine how social capital moderates the impact of pollution reduction on migration, we split municipalities

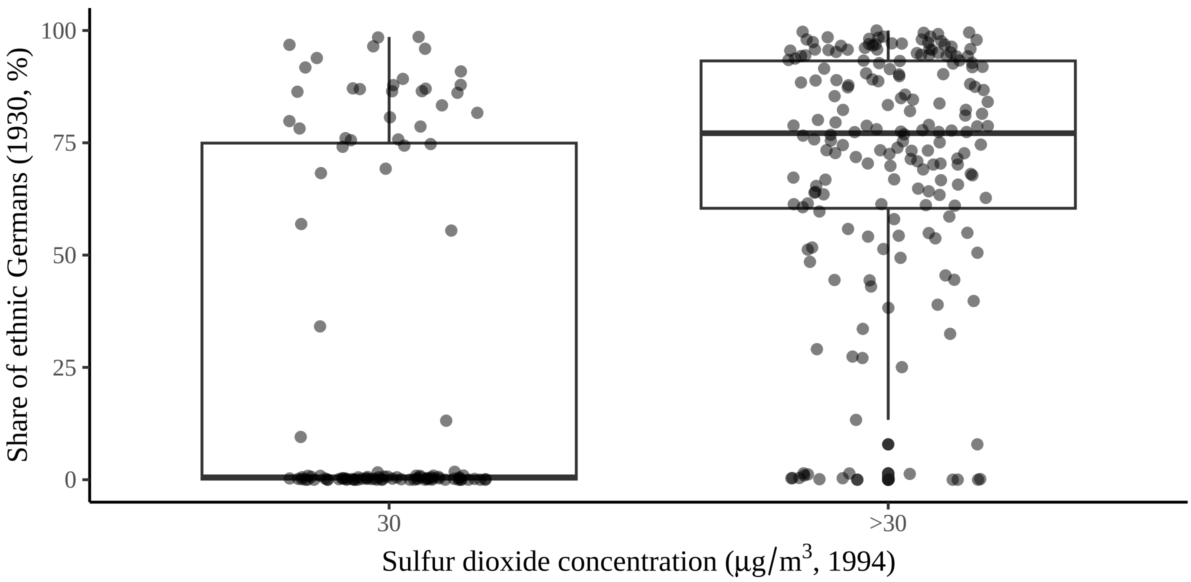


Figure 11: Pollution in 1994 and share of ethnic Germans in 1930

by whether their ethnic German share in 1930 was below (Panel A) or above 50% (Panel B) and estimate equation (6) separately for both groups.

The results, presented in Table 9, show that the reduction in emigration following desulfurization is more pronounced in municipalities with higher ethnic German shares in 1930 (Panel B, columns 1 and 2). This indicates that cleaner air had a larger impact in municipalities with weaker social capital—from which residents were more willing to emigrate and hence more responsive to changes in environmental quality. By contrast, in municipalities with stronger social capital (Panel A), emigration was less responsive to pollution reduction, suggesting that tight-knit communities help buffer the disutility from poor environmental conditions. Results for immigration rate presented in columns (3) and (4) show that pollution reduction appears to increase immigration more in historically resettled areas (Panel B), i.e., areas with lower local social capital, whereas immigration reponse to cleaner air seems to be negative in areas with stronger social capital (Panel A).

The net migration results (columns 5 and 6) reinforce this interpretation. Municipalities with high ethnic German shares (Panel B) experienced a large and statistically significant increase in net migration following desulfurization. In contrast, municipalities with stronger social capital (Panel A, column 5) show no statistically significant effect. This suggests that environmental improvements had a more pronounced effect on overall demographic change in socially fragmented areas. The results are consistent with the view that strong local social capital can both reduce the incentive to leave and reduce the attractiveness of cleaner but unfamiliar areas to potential immigrants. Taken together, our findings support the idea that social capital can make people more willing to tolerate poor environmental conditions, placing greater value on social relationships than on cleaner air. In contrast, people in less cohesive communities appear more likely to respond to improvements in air quality.

5.5.3 The Role of Man-Made Amenities

Just as social capital may influence how residents respond to changes in their local environment, the presence of man-made amenities—such as schools, healthcare facilities, libraries, or sports centers—can also shape residential preferences. These amenities may improve the overall quality of life in a municipality, making it a more attractive place to live. As a result, improvements in air quality may lead to smaller migration responses in areas where such amenities are already abundant, since these places were relatively desirable even before environmental conditions improved.

To explore this mechanism, we use data from the Czech Statistical Office (CZSO) on the number of facilities in each municipality in 1993—the earliest year available. For some public administration facilities, 1994 data are used due to missing earlier information.[34] We group amenities into three categories: (i) education, health, and social care facilities (e.g., schools, hospitals, retirement homes); (ii) cultural and sports facilities (e.g., libraries, cinemas, football fields); and (iii) public administration and infrastructure (e.g., job centers, courts, sewerage, water supply systems).[35].

As expected, municipalities with larger populations tend to have more amenities (Spearman's ρ ranges from 0.72 to 0.86). Availability is also positively correlated across the three amenity groups (Spearman's ρ between 0.67 and 0.74). While one might expect that more polluted municipalities received more amenities to offset poor environmental quality during the socialist period, we find only weak correlations between pre-desulfurization SO_2 concentrations and amenity availability (Spearman's ρ between 0.05 and 0.24).

Similarly, one could imagine that municipalities richer in local social capital could be able to lobby more efficiently and to obtain more (often government-funded) man-made amenities. However, municipalities with stronger social capital—proxied by the pre-war share of ethnic Germans—do not appear to have systematically more amenities either (correlations range from −0.08 to 0.13).[36]

To test whether man-made amenities moderated the migration response to improved air quality, we split municipalities into two groups—above and below the median level

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

35. For the full list of amenities included, see Appendix Textbox A.2.

36. For descriptive statistics on the availability of man-made amenities see Appendix Table A.5.

Table 9: Social capital and migratory response to air pollution reduction

	Dependent variable					
	Emigration rate (%)		Immigration rate (%)		Net migration rate (%)	
	(1)	(2)	(3)	(4)	(5)	(6)
Panel A: Municipalities with 1930 share of ethnic Germans $\leq$ 50%						
Pre-desulfurization SO_2 concentration $\geq 40\,\mu g/m^3$	-0.681^{**}	-0.666^{**}	-0.896^{*}	-0.844^{*}	-0.215	-0.178
$\times$ Post-desulfurization period	(0.313)	(0.302)	(0.455)	(0.457)	(0.494)	(0.483)
Observations	2,207	2,204	2,207	2,204	2,207	2,204
Panel B: Municipalities with 1930 share of ethnic Germans > 50%						
Pre-desulfurization SO_2 concentration $\geq 40\,\mu g/m^3$	-1.921^{***}	-1.871^{***}	1.604^{**}	1.733^{**}	3.526^{***}	3.605^{***}
$\times$ Post-desulfurization period	(0.661)	(0.643)	(0.719)	(0.751)	(1.137)	(1.085)
Observations	3,999	3,996	3,999	3,996	3,999	3,996
Municipality unemployment and demogr. and edu.structure		✓		✓		✓
Municipality and period FE	✓	✓	✓	✓	✓	✓
Area linear trends	✓	✓	✓	✓	✓	✓

Notes: Table reports β_i coefficients from Equation (6). 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 below $40\,\mu g/m^3$.

of amenities within each amenity category—and re-estimate our baseline DiD model (Equation 6) separately for each subgroup.

Table 10 presents results using the number of amenities located within each municipality. In an alternative specification, shown in Table 11, we account for access to amenities in neighboring municipalities by summing amenities located within a 20 km driving distance. These two measures provide bounds for the estimates we would expect using a distance-weighted amenity index that declines with distance and drops to zero beyond 20 km.

Overall, the results align with our main findings on the effects of air quality improvements. In both specifications, the estimated effects of pollution reduction are consistently larger in municipalities with fewer man-made amenities. This pattern is evident for emigration, immigration, and net migration outcomes, and it holds across all three amenity categories. The findings suggest that residents in less well-equipped municipalities were more responsive to environmental improvements, while those in more amenity-rich areas had fewer incentives to move in response to better air quality.

These results also help explain the smaller or statistically insignificant effects found in population-weighted regressions and in subsamples of large municipalities (see Table 6). Larger municipalities tend to have more amenities, which may have reduced the perceived disutility from pollution and thus weakened migration responses to environmental improvements.

To summarize, this section shows that the migration response to improved air quality is shaped by broader local conditions rather than being uniform across space. We find no evidence that the observed decline in emigration was affected by the removal of pre-reform anti-emigration monetary benefits. However, both the strength of social capital and the availability of man-made amenities play a role in shaping how residents respond to environmental improvements. Specifically, municipalities with weaker social ties—proxied by a high historical share of ethnic Germans—and those with fewer public amenities experienced a more pronounced migratory response to cleaner air, consistent with the interpretation that air quality matter more where other local advantages are limited. Conversely, in more connected communities or better-equipped municipalities, people are more willing to tolerate poor environmental conditions, placing greater value on social relationships and better facilities in their migration decisions. These findings reinforce the view that the full impact of environmental improvements depends not only on pollution levels but also on the broader social and infrastructural environment, in which people live.

Table 10: Man-made amenities and migration response to improved air quality

	Dependent variable											
	Emigration rate (%)				Immigration rate (%)				Net migration rate (%)			
	Sample				Sample				Sample			
	Below median		Above median		Below median		Above median		Below median		Above median	
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
Panel A: Education and health facilities												
Pre-desulfurization SO_2 concentration $\geq 40\,\mu g/m^3$	-2.115^{***}	-2.151^{***}	-0.703^{**}	-0.603^{**}	0.213	-0.013	0.102	-0.022	2.328^{***}	2.138^{***}	0.805^{*}	0.581^{*}
× Post-desulfurization period	(0.508)	(0.600)	(0.301)	(0.257)	(0.529)	(0.574)	(0.320)	(0.290)	(0.620)	(0.673)	(0.468)	(0.330)
Observations	3,152	3,146	3,061	3,061	3,152	3,146	3,061	3,061	3,152	3,146	3,061	3,061
Panel B: Culture and sports facilities												
Pre-desulfurization SO_2 concentration $\geq 40\,\mu g/m^3$	-1.128^{***}	-0.995^{*}	-1.106^{***}	-1.216^{***}	0.957	1.033	-0.449	-0.371	2.085^{**}	2.028^{**}	0.657	0.845^{*}
× Post-desulfurization period	(0.423)	(0.526)	(0.330)	(0.359)	(0.712)	(0.710)	(0.337)	(0.335)	(0.851)	(0.778)	(0.426)	(0.438)
Observations	3,034	3,028	3,179	3,179	3,034	3,028	3,179	3,179	3,034	3,028	3,179	3,179
Panel C: Public administration facilities and public utilities												
Pre-desulfurization SO_2 concentration $\geq 40\,\mu g/m^3$	-1.855^{***}	-1.733^{***}	-1.100^{***}	-1.182^{***}	1.652^{**}	1.505^{**}	-0.317	-0.520	3.507^{***}	3.238^{***}	0.783^{**}	0.662^{*}
× Post-desulfurization period	(0.517)	(0.568)	(0.278)	(0.277)	(0.713)	(0.661)	(0.328)	(0.318)	(0.906)	(0.831)	(0.374)	(0.341)
Observations	3,294	3,288	2,919	2,919	3,294	3,288	2,919	2,919	3,294	3,288	2,919	2,919
Municipality unemployment, and demogr. and edu. structure		✓		✓		✓		✓		✓		✓
Municipality and period FE	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Area linear trends	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓

Notes: Table reports γ_j coefficients from Equation (7). 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 below $40\,\mu g/m^3$.

Table 11: Man-made amenities within a 20 km driving distance

	Dependent variable											
	Emigration rate (%)				Immigration rate (%)				Net migration rate (%)			
	Sample				Sample				Sample			
	Below median		Above median		Below median		Above median		Below median		Above median	
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
Panel A: Education and health facilities												
Pre-desulfurization SO_2 concentration ≥ 40 $\mu g/m^3$	−1.438***	−1.186***	−0.837**	−1.155***	1.082*	0.843*	−1.175***	−1.069**	2.520***	2.029***	−0.338	0.086
× Post-desulfurization period	(0.465)	(0.447)	(0.359)	(0.403)	(0.590)	(0.470)	(0.410)	(0.465)	(0.840)	(0.671)	(0.389)	(0.413)
Observations	3,052	3,048	3,161	3,159	3,052	3,048	3,161	3,159	3,052	3,048	3,161	3,159
Panel B: Culture and sports facilities												
Pre-desulfurization SO_2 concentration ≥ 40 $\mu g/m^3$	−1.547***	−1.442***	−1.123***	−1.314***	1.224**	1.177**	−0.932**	−0.895**	2.771***	2.619***	0.191	0.419
× Post-desulfurization period	(0.494)	(0.497)	(0.293)	(0.324)	(0.590)	(0.521)	(0.358)	(0.376)	(0.864)	(0.779)	(0.404)	(0.398)
Observations	3,029	3,025	3,184	3,182	3,029	3,025	3,184	3,182	3,029	3,025	3,184	3,182
Panel C: Public administration facilities and public utilities												
Pre-desulfurization SO_2 concentration ≥ 40 $\mu g/m^3$	−1.944***	−1.990***	−0.817***	−0.723**	1.476**	1.675***	−0.548	−0.556	3.420***	3.665***	0.269	0.166
× Post-desulfurization period	(0.555)	(0.578)	(0.274)	(0.285)	(0.590)	(0.613)	(0.356)	(0.346)	(0.965)	(0.940)	(0.378)	(0.334)
Observations	3,144	3,141	3,069	3,066	3,144	3,141	3,069	3,066	3,144	3,141	3,069	3,066
Municipality unemployment; demogr. and edu. structure		✓		✓		✓		✓		✓		✓
Municipality and period FE	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Area linear trends	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓

Notes: Table reports γ_j coefficients from Equation (6). 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 below 40 $\mu g/m^3$.

6 Air Pollution Reduction and Changes in Population Structure by Age and Education

In the following section we explore whether improvements in air quality influenced the demographic and educational composition of local populations. If migration responses to environmental improvements vary by individual characteristics, we would expect stronger responses among younger and more educated groups—either because these individuals are more mobile or because they might be more aware of the health risks associated with air pollution.

Due to data limitations, we cannot observe individual-level migration decisions by age or education. Instead, we use municipality-level census data to study whether air quality improvements affected the age and educational structure of municipal populations over time. Specifically, we estimate Equation (6) with the shares of different age and education groups as dependent variables. For age, we consider six population groups (0–19, 20–29, 30–39, 40–49, 50–59, and 60–69). For education, we examine the shares of adults (aged 15 and older) with primary, secondary, and tertiary education.

Data on population structure are available from the decennial censuses conducted in 1980, 1991, 2001, and 2011. We associate the 1980 and 1991 censuses with the pre-desulfurization period and the 2001 and 2011 censuses with the post-desulfurization period. This setup allows us to assess whether municipalities more affected by air quality improvements saw different changes in their population composition relative to cleaner municipalities.

Table 12 reports the results. The estimates indicate some evidence of population aging in municipalities that experienced greater improvements in air quality. Specifically, the shares of individuals aged 20–29 and 30–39 declined relative to cleaner areas, while the share of those aged 60–69 increased. Although not all estimates are statistically significant, this pattern suggests that younger cohorts may have been more likely to migrate away from previously polluted areas, even after air quality improved. Conversely, older residents may have remained or moved in, perhaps due to a combination of stronger place attachment and improved living conditions.

Turning to education, we find a small but statistically significant increase in the share of tertiary-educated residents in municipalities with larger pollution reductions. This finding is consistent with the hypothesis that more educated individuals are more responsive to environmental quality.

Overall, while the magnitude of the estimated changes is modest, the results suggest that air quality improvements may have contributed to subtle shifts in the composition of local populations—reducing the outflow of older and more educated individuals, or

Table 12: Impact of air pollution reduction on age and education structure

	Dependent variable								
	Age structure (shares of age groups on total population, %)						Education structure (shares on 15+ population, %)		
	0–19	20–29	30–39	40–49	50–59	60–69	Primary	Secondary	Tertiary
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
Pre-desulfurization SO_2 concentration $\geq 40\,\mu g/m^3$	-1.505^{***}	-0.304	-0.009	0.129	0.373	0.542^{*}	0.046	-0.882	0.443^{**}
$\times$ Post-desulfurization period	(0.392)	(0.285)	(0.272)	(0.283)	(0.310)	(0.327)	(0.709)	(0.658)	(0.216)
R^2 Adj.	0.723	0.403	0.285	0.345	0.290	0.427	0.918	0.883	0.725
Observations	1,151	1,151	1,151	1,151	1,151	1,151	1,151	1,151	1,151
Municipality and period FE	✓	✓	✓	✓	✓	✓	✓	✓	✓
Area linear trends	✓	✓	✓	✓	✓	✓	✓	✓	✓

Estimates in columns (1)–(9) are based on data from decennial censuses. 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 below $40\,\mu g/m^3$.

potentially attracting them. These patterns are consistent with heterogeneous migration responses to environmental quality and align with previous findings that the benefits of clean air are more salient for some demographic groups than others.

7 Conclusions

This paper makes a novel contribution to the literature on environmental migration by examining how improvements in air quality affect residential mobility. By exploiting the large-scale desulfurization of coal-fired power plants in North Bohemia as a natural experiment, we provide causal evidence that reductions in air pollution significantly influenced migration patterns.

Our difference-in-differences estimates show that cleaner air led to a substantial decline in emigration from previously highly polluted municipalities. Emigration rates fell by approximately 24%, with effects particularly pronounced in areas that had experienced the highest levels of SO_2 pollution. The response was non-linear: municipalities with extreme pre-reform pollution levels ($\geq 50\,\mu g/m^3$) experienced migration effects twice as large as those with moderate pollution ($40\,\mu g/m^3$). Net migration also increased significantly in these areas, rising by 1.7 percentage points—equivalent to a 78% increase relative to the baseline of the least polluted municipalities. These results suggest that improvement in air quality even in the most extreme polluted areas can make them more attractive to live in. Further our results are robust to the inclusion of controls for local labor market conditions and municipal population structure, including lagged unemployment and age-education composition, are validated by numerous robustness checks and supported by zero effects from placebo tests.

Importantly, we show that the observed effects are not confounded by concurrent economic shocks, such as mine closures during the transition period. Even after controlling for local unemployment and allowing treatment effects to vary by economic conditions, we find that air quality improvements had strong and consistent effects on migration behavior—particularly in reducing out-migration. However, immigration and net migration responses were more sensitive to local unemployment, suggesting that cleaner air may function as a compensating amenity that offsets weak labor markets. This finding highlights an important mechanism: in economically disadvantaged municipalities, improvements in environmental quality can help attract newcomers even when job prospects are limited.

We also explore heterogeneity in migration responses by age and education. Our results suggest that highly educated individuals were especially responsive to environmental improvements, likely reflecting stronger preferences for health and well-being of their families. This is valuable information for policy makers as highly educated individuals tend to be the drivers of economic growth and innovation, making their settlement decisions critical for regional development.

Beyond the main results, this study also shows how the impact of cleaner air on migration depends on local conditions. We find that municipalities with weaker social capital—such as those resettled after World War II–and those with fewer public services and facilities—like schools, hospitals, or cultural centers—saw larger migration responses to air quality improvements. In contrast, places with stronger communities or more local amenities had smaller responses, likely because they were already more attractive places to live, even when pollution was high. This suggests that in more disadvantaged areas, clean environment plays a bigger role in people's decisions about where to live.

In contrast, our results, based on a triple difference estimator, show that financial incentives to stay in polluted areas—such as those offered during the socialist period—had no meaningful effect on people's migration decisions. This underlines that money alone is not enough to convince people to stay in places with poor living conditions. What matters more are deeper factors like environmental quality, public services, and social ties.

These findings suggest that clean air is especially important in areas that lack other advantages. Improving the environment in such places can help stop people from moving away and even attract new residents. But cleaner air on its own is not enough. To support long-term population stability and economic recovery, governments also need to invest in local infrastructure and strengthen community life. These efforts may not make the migration response to cleaner air bigger—but they help create the conditions for lasting improvement.

Our study offers several generalized lessons for policymakers seeking to prevent regional depopulation or encourage re-population in formerly polluted areas: First, improving air quality can substantially reduce out-migration. Environmental policies that reduce pollution—especially in areas that were heavily affected—can make these places attractive to live in. Second, the benefits of cleaner air are greatest in disadvantaged municipalities with fewer local amenities or economic opportunities. In such areas, environmental improvements play a particularly important role in shaping migration decisions. Third, stronger community ties are associated with lower migration responsiveness to environmental change. This suggests that building and maintaining local social capital can support population stability, even when other local conditions are less favorable. Fourth, given the non-linear effects observed in our study, policymakers should prioritize interventions in areas with the most severe pollution histories. Finally, long-term success depends on sustained effort. Cleaner air alone will not transform struggling regions—but when combined with investments in infrastructure and community life, it can serve as a foundation for lasting demographic and economic revitalization. Policymakers should therefore view environmental improvements as one pillar of a broader regional development strategy—alongside strong public services, community engagement, and continued commitment to maintaining livable conditions.

To sum up, this paper provides robust evidence that improving environmental quality in heavily polluted areas can reverse out-migration and attract new residents. However, the size of this effect is shaped by local context: cleaner air matters most in places where social capital and infrastructure are limited. Policymakers should view environmental improvements not as a stand-alone solution, but as a powerful tool that is most effective when combined with broader strategies to address regional disparities and support community resilience.

These findings have important implications for regions around the world facing similar environmental and demographic challenges. Environmental improvements should be seen as a cornerstone of comprehensive development strategies, with cleaner air forming the basis for demographic stabilization and renewed regional vitality. By adopting an integrated approach that combines environmental, economic, and social investments, policymakers can help transform depopulating regions into thriving, sustainable communities. While this study focuses on the Czech Republic, its insights offer a valuable road-map for addressing environmental and migration challenges in diverse settings globally.

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A Appendix

A.1 Additional Figures and Tables

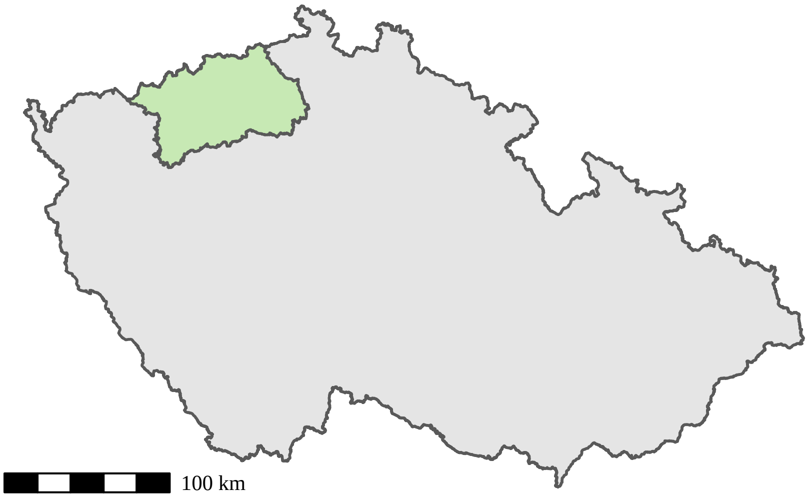

Figure A.1: Location of the region in the Czech Republic

Source: ArcČR 500 v3.3

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

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

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

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

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

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

Table A.2: Descriptive statistics: Population structure by year and SO_2 concentration

	Year	Municipalities in estimation sample					
		All	By SO_2 concentration (1994)				
			30 $\mu g/m^3$	>30 $\mu g/m^3$			
				All	40 $\mu g/m^3$	50 $\mu g/m^3$	60 $\mu g/m^3$
		(1)	(2)	(3)	(4)	(5)	(6)
Share of 0–19 age group (%)	1980	30.40	28.87	31.20	31.09	31.75	30.07
		(0.26)	(0.39)	(0.33)	(0.50)	(0.51)	(0.82)
	1991	29.03	27.90	29.65	29.33	30.29	29.01
		(0.26)	(0.40)	(0.33)	(0.51)	(0.56)	(0.46)
	2001	23.07	22.45	23.42	23.22	23.96	22.67
		(0.21)	(0.33)	(0.27)	(0.37)	(0.50)	(0.57)
	2011	21.12	20.64	21.38	20.89	22.08	21.17
		(0.22)	(0.34)	(0.28)	(0.45)	(0.38)	(0.63)
Share of 20–29 age group (%)	1980	14.47	14.03	14.71	14.53	14.96	14.59
		(0.16)	(0.28)	(0.19)	(0.30)	(0.27)	(0.50)
	1991	11.64	11.72	11.59	11.43	11.94	11.19
		(0.16)	(0.23)	(0.20)	(0.27)	(0.32)	(0.67)
	2001	16.61	16.64	16.60	16.64	16.74	16.08
		(0.15)	(0.27)	(0.18)	(0.26)	(0.30)	(0.55)
	2011	11.98	11.94	12.01	11.93	12.25	11.61
		(0.17)	(0.25)	(0.22)	(0.33)	(0.35)	(0.49)
Share of 30–39 age group (%)	1980	13.93	13.32	14.25	14.07	14.34	14.58
		(0.16)	(0.24)	(0.20)	(0.32)	(0.30)	(0.54)
	1991	13.53	13.43	13.58	13.33	13.65	14.18
		(0.14)	(0.23)	(0.18)	(0.26)	(0.31)	(0.42)
	2001	12.29	11.91	12.51	12.30	12.64	12.83
		(0.13)	(0.22)	(0.17)	(0.27)	(0.25)	(0.39)
	2011	16.65	16.18	16.92	16.66	17.17	17.19
		(0.16)	(0.28)	(0.20)	(0.32)	(0.30)	(0.47)
Share of 40–49 age group (%)	1980	10.33	10.06	10.47	10.15	10.76	10.76
		(0.12)	(0.22)	(0.14)	(0.19)	(0.25)	(0.28)
	1991	15.15	14.53	15.49	15.34	15.53	15.85
		(0.19)	(0.26)	(0.25)	(0.40)	(0.38)	(0.44)
	2001	14.57	14.08	14.85	14.46	15.01	15.73
		(0.14)	(0.23)	(0.17)	(0.24)	(0.28)	(0.50)
	2011	13.33	12.70	13.68	13.46	13.71	14.33
		(0.14)	(0.21)	(0.18)	(0.31)	(0.26)	(0.26)
Share of 50–59 age group (%)	1980	12.50	12.70	12.40	12.05	12.59	13.01
		(0.15)	(0.26)	(0.18)	(0.27)	(0.31)	(0.39)
	1991	10.83	10.78	10.85	10.64	11.10	10.88
		(0.14)	(0.25)	(0.17)	(0.24)	(0.31)	(0.34)
	2001	15.13	14.85	15.28	15.05	15.38	15.80
		(0.19)	(0.28)	(0.25)	(0.36)	(0.45)	(0.46)
	2011	14.34	14.46	14.26	14.24	14.14	14.67
		(0.15)	(0.29)	(0.18)	(0.29)	(0.24)	(0.42)
Share of 60–69 age group (%)	1980	8.99	9.72	8.61	8.99	7.96	9.14
		(0.15)	(0.24)	(0.18)	(0.25)	(0.31)	(0.35)
	1991	11.38	11.97	11.04	11.32	10.70	11.06
		(0.20)	(0.32)	(0.25)	(0.38)	(0.43)	(0.40)
	2001	9.18	9.55	8.97	9.25	8.71	8.68
		(0.13)	(0.21)	(0.17)	(0.23)	(0.31)	(0.27)
	2011	13.49	13.94	13.24	13.43	13.13	12.87
		(0.18)	(0.26)	(0.24)	(0.32)	(0.48)	(0.38)

Notes: Table reports means and standard errors in parentheses.

Table A.3: Descriptive statistics: Education structure by year and SO_2 concentration

	Year	Municipalities in estimation sample					
		All	By SO_2 concentration (1994)				
			30 μg/m^3	>30 μg/m^3			
				All	40 μg/m^3	50 μg/m^3	60 μg/m^3
		(1)	(2)	(3)	(4)	(5)	(6)
Share of primary educated (%)	1980	59.76	59.76	59.76	58.90	60.81	59.71
		(0.49)	(0.82)	(0.61)	(0.91)	(1.02)	(1.23)
	1991	47.72	47.06	48.09	48.98	47.50	46.90
		(0.47)	(0.74)	(0.60)	(0.97)	(0.93)	(1.19)
	2001	32.43	31.74	32.83	33.03	32.97	31.73
		(0.37)	(0.66)	(0.45)	(0.70)	(0.73)	(0.80)
	2011	23.65	23.30	23.85	24.11	23.78	23.13
		(0.31)	(0.51)	(0.38)	(0.60)	(0.61)	(0.70)
Share of secondary educated (%)	1980	37.64	37.80	37.56	38.53	36.70	36.80
		(0.45)	(0.76)	(0.56)	(0.82)	(0.96)	(1.21)
	1991	49.45	50.45	48.89	48.26	49.26	49.85
		(0.43)	(0.69)	(0.55)	(0.88)	(0.84)	(1.10)
	2001	62.76	63.86	62.14	62.21	61.93	62.47
		(0.34)	(0.55)	(0.42)	(0.66)	(0.64)	(0.89)
	2011	64.17	65.69	63.32	63.80	62.38	64.25
		(0.31)	(0.47)	(0.39)	(0.57)	(0.66)	(0.80)
Share of tertiary educated (%)	1980	1.31	1.31	1.30	1.33	1.30	1.21
		(0.073)	(0.12)	(0.092)	(0.14)	(0.15)	(0.19)
	1991	1.89	2.00	1.82	1.89	1.79	1.68
		(0.095)	(0.16)	(0.12)	(0.19)	(0.18)	(0.24)
	2001	2.99	2.94	3.02	3.02	3.03	2.99
		(0.10)	(0.17)	(0.13)	(0.20)	(0.21)	(0.32)
	2011	5.86	5.48	6.06	5.89	6.15	6.42
		(0.17)	(0.28)	(0.21)	(0.32)	(0.34)	(0.46)

Notes: Table reports means and standard errors in parentheses.

Table A.4: Changes in economical activity and occupation structure between 1991 and 2001

	Dependent variable						
	Economic activity (n)	Manufacturing (%)	Agriculture (%)	Construction (%)	Transportation (%)	B. services, R&D (%)	Education (%)
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Pre-desulfurization SO_2 concentration > 30 $\mu g/m^3$ × Post-desulfurization period	−84.07** (40.33)	−15.92*** (2.50)	18.46*** (3.16)	−1.60* (0.92)	0.64 (0.84)	0.31 (0.74)	−0.95* (0.53)
Municipality demographic and educational structure	✓	✓	✓	✓	✓	✓	✓
Municipality and period FE	✓	✓	✓	✓	✓	✓	✓
Area linear trends	✓	✓	✓	✓	✓	✓	✓
Observations	390	390	390	390	390	390	390

Notes: Table reports γ coefficients from Equation: $E_{it} = \gamma \text{SO40}_i p_t + \theta_t + \theta_i + \varepsilon_{it}$, where E is a measure of economic activity in municipality i and in year t (we estimate separate models for emigration, immigration and net migration rate), p_t is a a dummy variable, which is equal to 1 for the post-desulfurization period (2001) and 0 for the pre-desulfurization period (1991). The regressions are estimated using municipality level data from 1991 and 2001 censuses. The dependent variable is defined as the number of economically active persons (column (1)) or percentage share of occupations on economically active (columns (2)–(7)). 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 below 40 $\mu g/m^3$.

Table A.5: Descriptive statistics: Man-made amenities availability

	Year	Municipalities in estimation sample					
		All	By SO_2 concentration (1994)				
			30 $\mu g/m^3$	>30 $\mu g/m^3$			
				All	40 $\mu g/m^3$	50 $\mu g/m^3$	60 $\mu g/m^3$
		(1)	(2)	(3)	(4)	(5)	(6)
Education and health facilities in the municipality (n)	1993	5.29	2.75	6.72	4.67	9.23	7.19
		(0.96)	(0.64)	(1.45)	(1.42)	(3.15)	(3.57)
Culture and sports facilities in the municipality (n)	1993	5.76	3.48	7.03	4.28	11.75	4.11
		(1.08)	(0.38)	(1.66)	(0.85)	(4.25)	(1.29)
Public administration and utilities in the municipality (n)	1993	6.59	5.72	7.07	6.53	7.45	7.96
		(0.21)	(0.30)	(0.27)	(0.35)	(0.49)	(0.63)
Education and health facilities within 20 km driving distance (n)	1993	287.44	236.88	315.76	291.41	334.68	349.89
		(6.22)	(7.37)	(8.09)	(9.99)	(15.50)	(17.61)
Culture and sports facilities within 20 km driving distance (n)	1993	307.42	269.39	328.72	319.65	341.51	326.37
		(7.91)	(8.92)	(11.00)	(12.82)	(21.95)	(28.51)
Public administration and utilities within 20 km driving distance (n)	1993	350.29	378.99	334.21	375.20	295.96	293.59
		(6.69)	(9.76)	(8.70)	(11.03)	(15.02)	(20.06)

Notes: Table reports means and standard errors in parentheses.

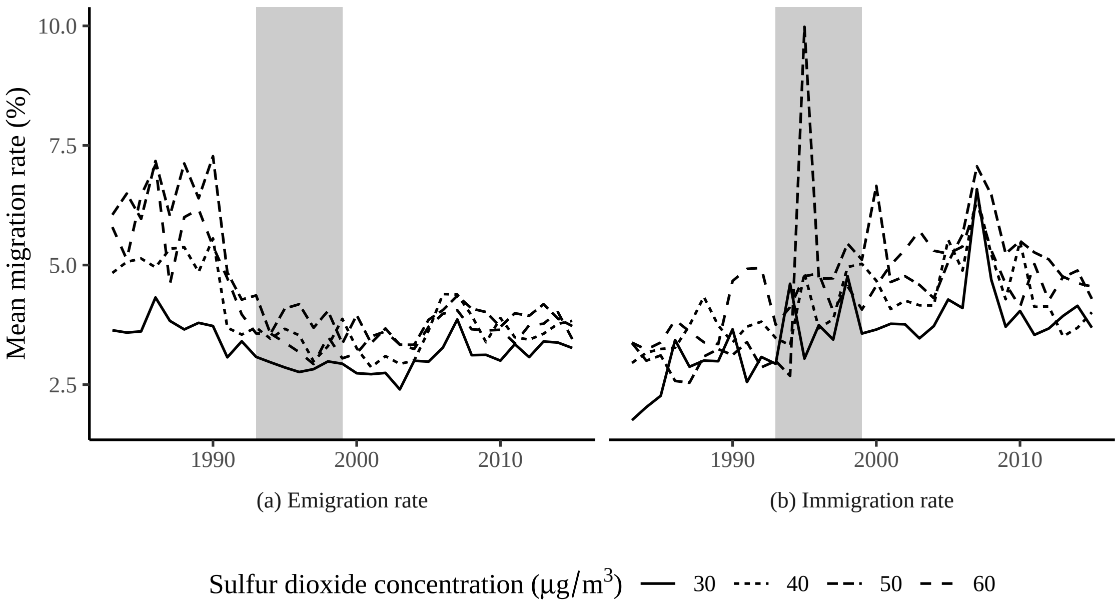

Figure A.3: Migration rates in municipalities in North Bohemia by 1994 SO_2 concentration category, years 1983–2015

Source: CZSO (see Section 3.1)

Table A.6: Results of an alternative specification with treatment variable being specified as a change in SO_2 concentration levels

	Dependent variable		
	Emigration rate (%)	Immigration rate (%)	Net migration rate (%)
	(1)	(2)	(3)
Decrease in SO_2 concentration × Post-desulfurization period	−0.067*** (0.016)	0.025 (0.019)	0.091*** (0.029)
Adjusted R^2	0.337	0.139	0.134
Municipality demographic and educational structure	✓	✓	✓
Municipality and period FE	✓	✓	✓
Area linear trends	✓	✓	✓
Observations	6,229	6,229	6,229

Notes: Table reports γ coefficients from Equation (6) with treatment variable being defined as a change between pre- and post-desulfurization SO_2 concentration (i.e., SO_2 in 1994 − SO_2 in 2000). Robust standard errors clustered by municipality are reported in parentheses: *, ** and *** denote statistical significance at 10%, 5% and 1%.

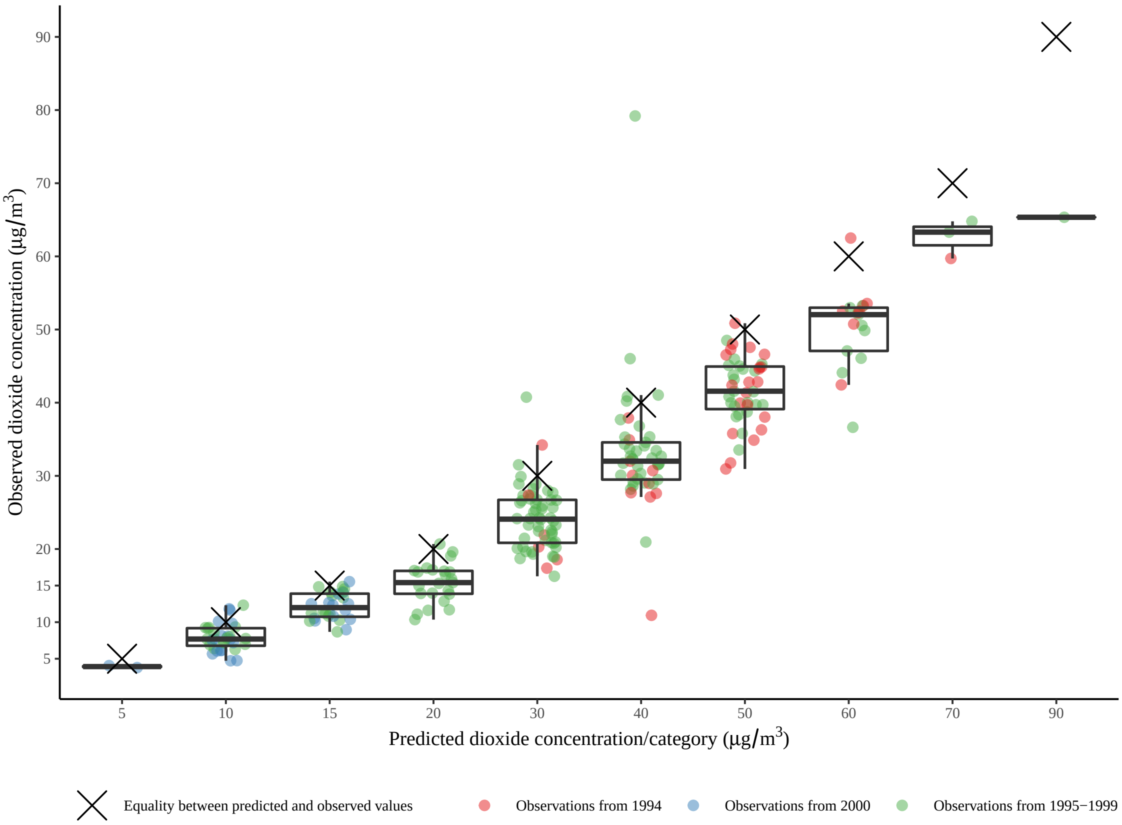

Figure A.4: Predicted and observed SO_2 concentrations

Source: Czech Hydrometeorological Institute

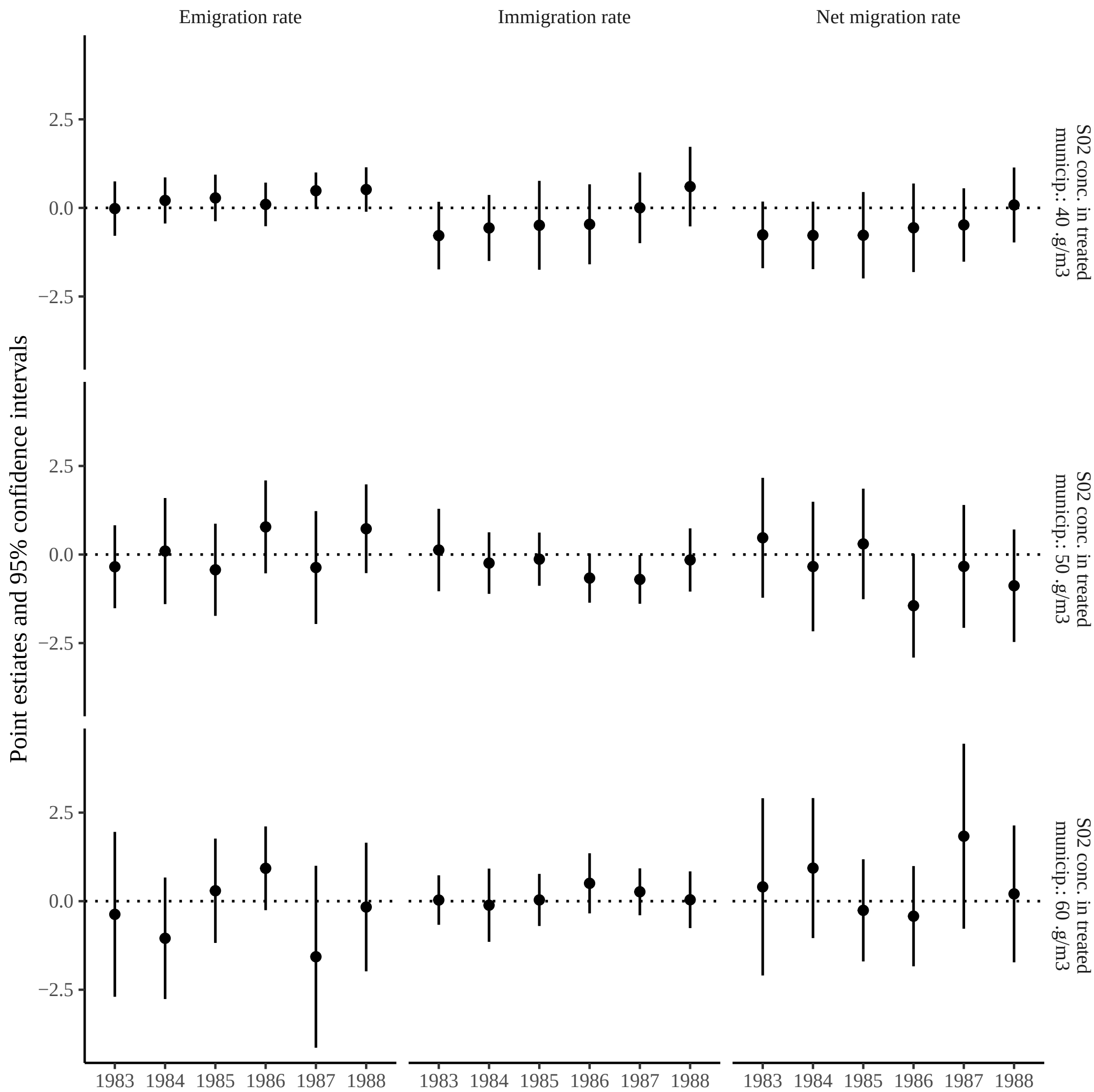

Figure A.5: Parallel trend assumption test

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

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

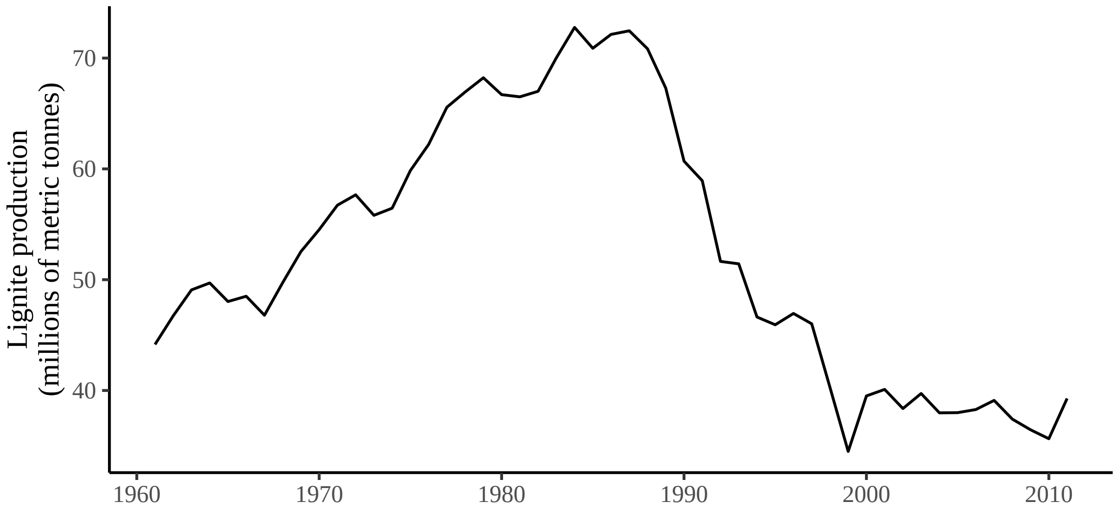

Figure A.6: Lignite mining in North Bohemia

Textbox A.2: Man-made amenities by group

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